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Flying Qualities of Multi-rotor UAVs: market analysis and parameter definition

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Abstract

Unmanned Aerial Vehicles (UAVs) are currently one of the most promising frontiers of technological development for our society. Some applications of this technology have been in use for a long time in military scenarios and in specific civil applications but only in recent years drones achieved a significant market diffusion. Unfortunately, their employment is still restricted by some constraints, limiting their applicability in many industrial environments. These limitations are mainly related to the safety and reliability of UAVs and to the management and acquisition of sensitive data in terms of privacy. In order to enhance the market diffusion of UAVs, scientific research can optimise their technical characteristics, making them both a safer, more reliable technology and an optimally performing solution for completing specific missions and industrial tasks. The development of this thesis is built around two main points: the definition of the industrial environments which could benefit the most from the implementation of UAV-based services, and the presentation of a method to improve the performance of a specific multirotor drone with respect to its operative environment. Therefore, in the first chapter, the concept of flying qualities is introduced as a reference for improving both aircraft and UAV performance. Accordingly, a method to evaluate and enhance the flying qualities of UAVs is presented. In the second part of the introduction the UAV market is investigated to define which main industries demand drone-based services. Additionally, the main characteristics UAVs are required to possess in order to effectively complete the assigned missions are outlined. In the second chapter, the operative scenarios are analysed to decide which category of UAV is the most promising for future market applications and, consequently, the most interesting to discuss as application in the thesis. In the third chapter the flight dynamics of a chosen drone is studied by means of its natural modes, eigenvalues and aerodynamic derivatives. At this point, a parametric analysis is conducted to highlight which influence each design parameter has on the UAV flight dynamics and, accordingly, on its flying qualities. Therefore, an adequate tool to enhance the flying qualities of the selected UAV is provided. Consequently, in the fourth chapter the parametric analysis is exploited to suitably modify the design of the UAV in order to mitigate the most critical aspects of its flight dynamics. Each mission implies different problems to deal with, and it may require a different design set-up with a degradation of the drone dynamics. In the fourth chapter it is showed how, by acting on specific design parameters, it is possible to improve the UAV flying qualities with respect to the assigned mission. It is important to underline that the target of this thesis is not to optimize the design of the considered drone, but rather to propose a simple and general strategy that allows the enhancement of UAVs flying qualities with respect to the operational requirements of the assigned mission.

Sommario

I droni o Unmanned Aerial Vehicle (UAV) sono attualmente una delle più promettenti frontiere di sviluppo tecnologico per la nostra società. Alcune applicazioni di questa tecnologia sono da tempo in uso in scenari militari o in specifiche applicazioni civili, ma solo negli ultimi anni si è assistito ad una loro maggiore diffusione di mercato. Tuttavia, tale processo è limitato da restrizioni dovute sia a ragioni di sicurezza ed affidabilità della tecnologia, sia all' acquisizione e alla gestione di dati sensibili in materia di privacy. Per favorire un maggiore utilizzo degli UAV, la ricerca scientifica può cercare di ottimizzarne le caratteristiche tecniche, rendendoli sia un dispositivo più sicuro ed affidabile che una soluzione ottimamente performante nel compiere specifiche missioni in ambito industriale. Lo sviluppo di questa tesi ha due scopi principali: la definizione delle aree industriali che maggiormente potrebbero beneficiare dell'implementazione di tecnologie UAV, e la proposta di un metodo volto al miglioramento delle performance di uno specifico drone multi-rotore rispetto al suo contesto operativo. Nell'introduzione viene presentato il concetto di qualità di volo come punto di riferimento per il miglioramento delle prestazioni sia dei velivoli tradizionali che dei droni. Conseguentemente, sono riportati anche alcuni metodi per la definizione e per il miglioramento delle qualità di volo degli UAV. Successivamente viene studiato il mercato dei droni, al fine di comprendere quali aree industriali richiedano maggiormente il loro utilizzo e quali caratteristiche tecniche essi debbano possedere per assolvere le missioni assegnate nel modo più efficace possibile. Nel secondo capitolo i contesti operativi sono stati analizzati come riferimento per decidere quale categoria di UAV sia la più promettente per future applicazioni di mercato e, di conseguenza, sia la più interessante da analizzare nella successiva parte della tesi. Nel terzo capitolo, è stata studiata nel dettaglio la dinamica del volo del drone scelto, analizzandone i modi naturali tramite le derivate aerodinamiche e gli autovalori. Successivamente, è stata condotta un'analisi parametrica che ha evidenziato l'influenza di ciascun parametro di design sulla dinamica del volo del drone e, conseguentemente, sulle sue qualità di volo. Pertanto, è stato definito uno strumento adeguato a migliorare le qualità di volo del drone preso in esame. Infatti, nel quarto capitolo l'analisi parametrica è stata sfruttata per modificare opportunamente il design dell'UAV, così da intervenire sulle principali criticità della sua dinamica del volo. A seconda della missione assegnata le problematiche possono essere diverse e la configurazione di design imposta al drone può cambiare, inducendone il peggioramento di determinate caratteristiche dinamiche. Nel quarto capitolo è stato mostrato come, agendo su alcuni parametri di design, sia possibile raggiungere o quantomeno avvicinare i livelli di qualità di volo richiesti da una specifica missione. È opportuno precisare che lo scopo di questa tesi non sia ottimizzare il design del drone studiato, bensì proporre una metodologia semplice e facilmente scalabile che permetta di migliorare le qualità di volo del drone rispetto alle sue specifiche esigenze operative.

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Chapter 1
Introduction

One of the most promising frontiers of the technological development of our society are undoubtedly the Unmanned Aerial Vehicles (UAVs). They are not only an ingeneous engineering realization, but also a key player in the future development of the current industrial environment. As reported in [1], "Unmanned Aerial Systems (UAS - a.k.a. drones) have evolved over the past decade as both advanced military technology and off-the-shelf consumer devices. There is a gradual shift towards public use of drones, which presents opportunities for effective remote procedures that can disrupt a variety of built environment disciplines". The analysis [2], conducted by McKinsey and Company, highlights that the factors influencing the spread of drones within our society do not have just a technical or engineering nature, but they also concern the adequacy of legislation, infrastructure and public acceptance of this technology. Even though the market has a real need and demand about the implementation of drone based services (demonstrated by the programs elaborated by some of the largest high-tech companies [6], [7], [8]), the external factors previously mentioned are a significant limit to their diffusion. From an engineering perspective, the flying qualities of UAVs, which currently are not satisfactory enough to allow their application in sensitve environments such as urban areas, can be improved. In order to enlarge the number of operations that can be assigned to drones, the scientific community is putting much effort into the enhancement of the flying qualities of UAVs. Therefore, the motivation behind this work is that, even though there is an undenaiable necessity for drones to achieve better flying qualities, no standard criterion has already been developped to study and improve them. Consequently, it is diffuclt to enhance the applicability fields of UAVs satysftying the neccessities of the market. Hence, the objective of this thesis is to provide a simple but generalizable method to improve the flying qualities of one specific UAV with respect to the mission it has to perform. An exhaustive explanation of the concept of Flying Qualities, of the characteristics of the method applied in this thesis to improve them and of the reasons behind the selection of one specific UAV are reported in the introduction of this thesis.

The goal of this introduction is dual. From one side it aims at presenting the main factors which influence the future development and diffusion of UAVs, explaining how they relate with each other. From the other side, it wants to present the reasons behind the selection of a certain method to improve the flying qualities of a specific category of drone. Basically, there are three main aspects to consider while analysing both the current and future development of UAVs:

- The presence of industrial sectors which require this technology and are ready to invest time and money to implement UAVs within their operational lines.

- The technical adequacy of drones, which must be sophisticated enough to carry out the missions assigned by each industrial environment (condition stated in the previous point) with high standards of precision and safety. One of the most efficient way to improve the performance of the UAVs is represented by the analysis of its flying qualities.
- External factors that may influence the development and employment of UAVs, favouring their diffusion or setting barriers to their applicability. (i.e. Other technologies development, legislation, public acceptance).

Without one of these three elements, a positive development for the UAVs market is impossible. Depending on which industry requires the employment of an UAV, there are different missions it needs to perform. Consequently, the technical evolution of drones will be more focused on developing those characteristics required in the biggest possible number of operative situations. Without a proportional evolution of others technologies (like autopilots, flight control systems or batteries with improved performances), the employment of drones would be impossible and without a proper legislation it could be potentially dangerous for our society. The technical evolution of UAVs has the important role of making this technology attractive for the market but respectful of required standards for a sustainable and safe employment.

The first part of the introduction is focused on the concept of flying qualities. It explains what is their physic meaning, why they are important and how they are evaluated. Subsequently, two method used to improve the flying qualities of two different UAV categories are presented. This section is usefull to clarify the meaning of flying qualities and to set a reference for the numerical simulation section of the thesis. The second part of the introduction analyses the market-related factors influencing the development of drones. This section begins with an analysis of the main industries interested in the development and employment of UAV-based solutions and it continues with the analysis of external factors influencing the diffusion of drones. The goal of the industry analysis is to report the main applicability fields of UAVs and to define which missions they are required to perform. This step is essential to highlight their most valuable characteristics and to provide us with enough information to decide which category of UAVs is better to study in the simulative part of the thesis. At this point it is important to clarify which is the link between these market related issues and the study of the flying qualities. The industry analysis documented the existance of potential functions that today drones are not allowed to perform due to a lack of reliability and manouevrability. One of the main solutions which can be provided to this problem is represented by the study and the enhancement of their flying qualities. Obviously, the selection of the main improvements needed by UAVs depends on the main open problems indicated by the industry analysis. At the end of the introduction a brief overview of the thesis is reported.

1.1 Flying qualities

The first rudimental realizations of autonomous aircraft date back to the second half of the 19th century, when the Italian and Spanish armies used hot-air balloons to drop explosive devices in enemy territory [3]. Figure 1.1 shows how, throughout the 20th century, the developments of UAV were essentially finalized to military purposes and uses, while their commercial applications took place essentially during the 21st century. In the current technological landscape the main commercial applications of UAVs exploit their capability of performing aerial surveillance and inspection to work basically in the following industries: Agriculture, Construction and Engineering Sites, Media and Entertainment, Security [4], [5]. According with the aforementioned McKinsey report, and as can be easily imagined, one of the most ambitious goal regarding the use of drones concerns their employment to perform delivery and passenger transport functions in urban contexts. As evidence, some of the most influential and powerfull high-tech companies such as Amazon, Google and Uber, have taken steps to implement UAV solutions within their current business lines [6], [7], [8]. As reported by [9], "the increasing usage of unmanned aircrafts to accomplish both military and civilian missions has resulted in an increasing need to verify the airworthiness of these aircrafts". Obviously, the greater is the complexity of the tasks carried out by UAVs, the greater may become the external risk associated to these missions (i.e. urban environment, obstacles avoidance). For this reason, the improvement of the characteristics of manoeuvrability, stability and controllability of UAVs is a key step in order to increase the number of functions they can perform within our industrial and social environment.

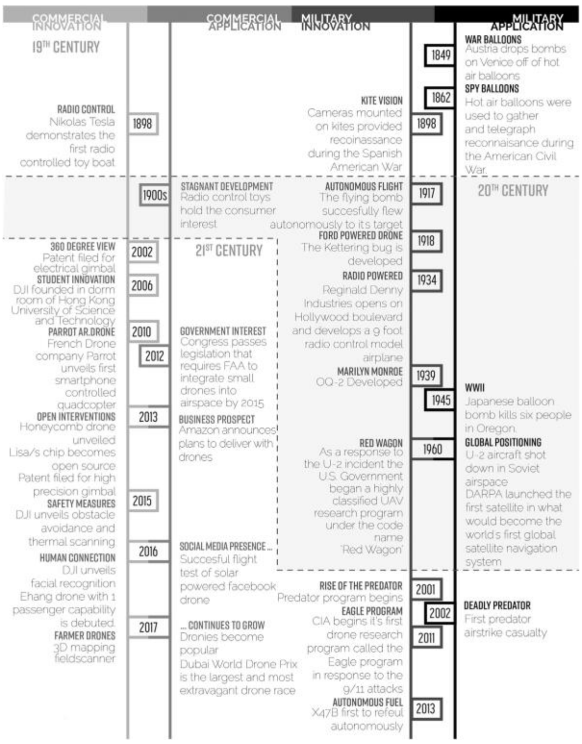

Figure 1.1 Historical timeline of UAVs technology development [1]

The main approach used to study and improve the manoeuvrability and reliability characteristics of both UAVs and traditional aircraft concerns the analysis of flying qualities. Flying Qualities can be defined in two most common ways, they are "a set of properties that describes the ease and the effectiveness with which an aircraft responds to command inputs in function of the designed mission" [9], but also as "those qualities or characteristics of an aircraft and sensor system that govern the ease and precision with which an operator is able to perform the tasks required in support of its mission role"[14]. A good explanation of the purposes and the objectives of studying flying qualities is given by [10]: Aircraft flying qualities design specifications are intended to enforce mission requirements and flight safety regardless of design implementation. Improving the flying qualities of UAVs can enlarge the number of missions UAVs are allowed to perform.

As described in [11], the accurate research of the flying qualities of traditional aircrafts promoted their rapid development and diffusion on a large scale, becoming the point of reference for their design process. The main advantages of using the flying qualities concern two main points: the safety and reliability of aircrafts designed with this method and the greater efficiency of their design process, with a consequent reduction of costs and time. As Coting stated in [14], "a historical case has been made that UAVs are at a similar point in their development to piloted aircraft when flying qualities were introduced". Therefore, in this moment UAV technology is mature enough to deal with the introduction of a dedicated flying qualities reference framework. This step could bring to the development and diffusion of UAVs the same advantages already experienced by standard aircrafts. From one side there is the possibility of faster and cheaper design process which could favour the commercial diffusion of UAVs; on the other side there is the opportunity of completing missions with increased safety and reliability. This last implication could allow the drones to be operative also in those contexts where high performances are fundamental (i.e. transport of goods and people in urban environments, high precision interventions in industrial contexts). However, the scientific community has highlighted some objective limits to the employment of standard criteria to study the flying qualities of UAVs. As stated in [12], "Flying qualities of manned aircraft, from which airworthiness requirements derived, are based on an extensive database of flying qualities and handling qualities assessments for a variety of aircraft types. For each aircraft, objective flying qualities criteria, such as modal frequency and damping, phase and gain margins, and bandwidth, are calculated or measured. (...). One of the reasons for the lack of flying qualities requirements for unmanned aircraft is that a database of flying and handling qualities is missing". Furthermore, as reported by [11], nowadays there is no effective reference in terms of flying qualities for UAVs. The attempts made by the scientific community to apply the criteria of traditional aircrafts to drones have often reported unsatisfactory and sometimes contradictory results. In the following pages, after a description of the theoretical basis of reference for the evaluation of flying qualities, some examples of papers which describe the application of traditional criteria to evaluate the flying qualities of drones are reported. Particularly, the reasons why these attempts were not completely successful are highlighted.

Very few elements are present in literature on the subject of the flying qualities of multirotor drones. Therefore, in order to elaborate a structured analysis that describes what the flying qualities represent and what is their importance, fixed-wing drones are taken as reference. Coherently, the considerations proposed on traditional aircrafts refer to aeroplanes and not to helicopters. Despite this differentiation, it should be clear that the purpose and the definition of flying qualities do not change depending on the aerial vehicle considered. What varies from airplanes to helicopters is only how the flying qualities are measured and evaluated.

As highlighted in [15], for the evaluation of the flying qualities of traditional aircrafts, reference is usually made to the Cooper-Harper scale. This is a very useful method to link the pilot's operational judgement regarding the manoeuvrability of the aircraft with its technical and engineering characteristics. The Cooper-Harper scale exploits a decision tree to induce the pilot to express a standardised and rationalised judgement to evaluate the manoeuvrability characteristics of the aircraft. This evaluation is expressed as a score which can vary from 10 to 1 (acceptable levels are only those between 3 and 1). Naturally, the judgements reported by the pilot depend on the type of aircraft being considered. An aircraft used for cargo missions has acceptable standards of manoeuvrability completely different from those of a military aircraft: the manoeuvrability characteristics that are worth a level 2 or 3 for the flying qualities of the second vehicle, would provide the first one with much better results. Through many experimental flights, several attempts have been made to align the frequency and time domains response of the aircraft to the pilots' judgement. Completed this step, it is sufficient to measure certain response parameters in order to predict with good confidence the pilot's operational judgement about a new aircraft. Obviously, the value of these target parameters, which marks the boundary between different levels of flying quality, depends on the type of aircraft and mission. For this reason, a classification of missions with its associated requirements and manoeuvres has been developed. This classification differentiates the flying quality levels with respect to the mission profile. Unfortunately, the method used to assess flying qualities of traditional aircraft cannot be applied in the same precise way to UAVs, because there are too many differences between their particular use and constituent parts. For example, negligible aerodynamic forces for traditional aircraft become extremely important for drones. Moreover, as recognised by W. Williams in [16], the small size of UAVs implies the absence of control stick force feedback, absence of vibration and higher sensitivities in the longitudinal and latero-directional planes manoeuvres. In this sense, Cotting proposes a modification of the Cooper-Harper scale which accounts the peculiar characteristics of UAVs. As a result, he provides a realistic framework for the evaluation of the flying qualities of UAVs [14]. By answering to the proposed questions, the operator is guided to relate his judgement about the operative characteristics of the UAV with a precise score in terms of flying qualities. As it happens to aircrafts, also drones need to be classified depending on the characteristics and requirements of the missions they have to perform. The evaluation of flying qualities levels is different for each of these groups. In order to carry out this analysis, two main factors are considered: the level of aggressiveness of the mission and the precision required for its completion. The judgment over the flying qualities of drones performing aggressive and precise manoeuvres is stricter and to get a good evaluation the requirements are more demanding.

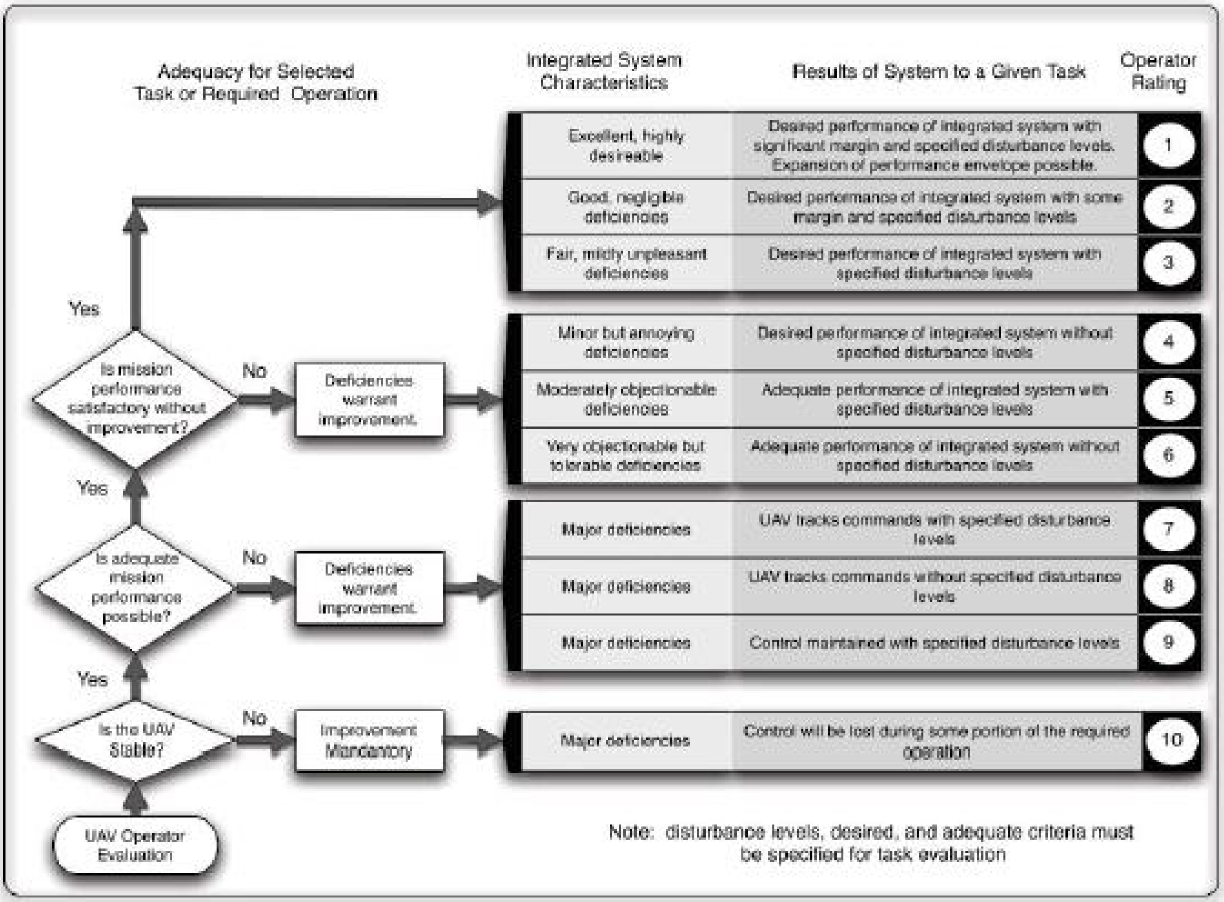

Figure 1.2 *Modified Cooper-Harper Rating Scale for UAVs [14]*

Non-Precision Tasks		Precision Tasks	
Non-Aggressive Category B	Aggressive Category D	Non-Aggressive Category C	Aggressive Category A
Reconnaissance	Gross Acquisition	Aerial recovery	Tracking
Climb	Anti-submarine	Close Formation	Ground attack
Takeoff	Max g Turn	Approach	Terrain Following
Non-precision Landing	“Herbst” Turn	Precision Landing	Precision Aerobatics

Figure 1.3 *Categorization of Mission Task Elements [15]*

At this point, it is presented how pilots judge the levels of flying qualities of UAVs and the criteria used to classify drones with respect to their assigned missions are reported. There are still two main points to clarify. The first one is the method used to evaluate the flying qualities of a specific drone from an engineering point of view. The second one regards the strategies which can be followed to improve the flying qualities of the selected UAV.

Starting with the evaluation of the flying qualities for one specific drone, it’s important to clarify that standard aircrafts refer to a reliable standard. It univocally matches values proper of the frequency and time domain responses with the judgment assigned by the pilot. Unfortunately, the evaluation of the flying qualities of drones is not so linear and the application of common criteria can lead to wrong and incoherent evaluations. To appreciate some examples of flying qualities evaluation of a drone, the example of two different works is reported below. Exploiting and suitably adapting some criteria proper of standard aircrafts, the authors evaluated the flying qualities of two different UAVs. The results obtained through the study of the flying qualities in terms of stability and manoeuvrability are compared to the results obtained through a more reliable and consolidated type of analysis. The two responses are compared so that is possible to understand if adapting the mentioned standard criteria can produce a realistic imagine of the stability, manoeuvrability, and controllability of the UAV.

A meaningful attempt of applying traditional aircraft criteria to assess the flying qualities of UAVs is described in [11]. The authors of this article considered a small fixed-wing UAV, which was tested both in its basic state and after the introduction of a control augment system. The response of the drone in both configurations was also studied in the frequency domain and time domain. The results are clear: the introduction of the control augment system improved the aircraft response, reducing the oscillatory behaviour in the time domain and increasing gain margin and phase margin in the frequency one. At this point, the authors applied the Control Anticipation Parameter (CAP) and Bandwidth criteria to the two configurations, with the goal of evaluating the flying qualities for the longitudinal plane. These two criteria, exhaustively explained in [15] and applied in [11], are traditionally used for manned aircrafts and should identify a level of flying qualities coherent with the real behaviour of the considered aircrafts, that is obtained through the study of the response in the time and frequency domains. In the beginning, the results obtained through the application of the CAP criterion are considered. This criterion is based on the evaluation of three fundamental parameters: natural frequency and damping of the short period mode and the vertical load factor with respect to the angle of attack. Depending on the values assumed by these parameters, the UAV is assigned to a specific level of flying qualities, which can vary from 3 to 1. If this criterion were consistent with the stability of the UAV determined by the analysis in the time and frequency domains, one would expect better performances when the UAV is equipped with the control augment system. Unfortunately, as illustrated in Figure 4, the exact opposite occurs. When the system is equipped with an augment control system, its flying qualities get worse, going from level 1 to level 2. Therefore, as it appears in literature, the CAP criterion cannot be applied to UAVs, especially due to their low inertia moment which always induces an extremely high natural frequency of the short period mode. However, the authors suggest a modification of the CAP criterion, based on the addition of a correction factor "N" which multiplies the short period frequency. In this way, the obtained flying qualities level is consistent with the analysis made in the time and frequency domains and an improvement of the flying qualities of the drone consequent to the addition of the control augment system was demonstrated. Although the authors managed to adapt the criterion to their specific case, obtaining a coherent rating of the flying qualities of the drone, the applied method does not seem to be well justified.

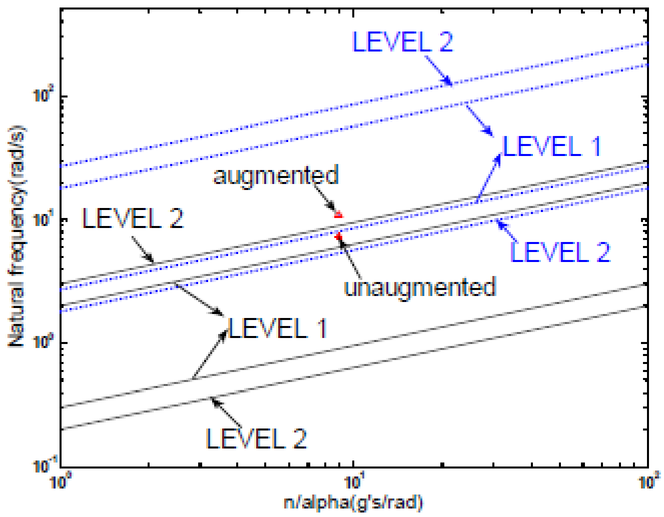

***Figure 1.4** CAP criterium [11]*

Particularly, it is not explained if the method used to calculate "N" could be adequate also to correct the properties of different category of UAV. Even if this strategy provided satisfying results in this circumstance, it could be not appropriate in different situations. The bandwidth criterion, instead, works by evaluating the bandwidth frequency and the time delay of the characteristic response of the UAV. Once these parameters are defined, the drone is assigned again to a level of flying qualities which can vary from 3 to 1. In this specific case, the author observes how the flying quality levels obtained with this criterion reflect the trend highlighted by the responses in frequency and time domains, resulting in an improvement of flying qualities when the drone is equipped with the augment control system. Even though the evaluation of the flying qualities adequately reflects the improvement in the performance of the aircraft, there is no criterion that defines the boundaries between different flying quality levels. In essence, this criterion does not allow to understand what values of bandwidth frequency and response delay cause a sensible modification of the pilots' judgement about the characteristics of the UAV.

From the analysis of this article, it emerges how it was possible to define for this specific UAV some flying qualities criteria that reflect the real behaviour of the UAV. The most complicated step is to generalize the defined criterion to every UAV. Without a criterion that can be generalised, there is no possibility of properly exploiting the concept of flying qualities. Therefore, the judgment of the pilot about the behaviour of the selected UAV cannot be correctly anticipated. Besides, it wouldn't be possible to create a database of information linked to the flying qualities, which would be fundamental to benefits UAV market with the same advantages that flying qualities brought to standard aircrafts market [12].

Another article that studies the applicability of standard criteria for evaluating the flying qualities of UAVs is [17]. The authors examined the MH850 fixed-wing mini-UAV, developed for low-cost alpine surveillance missions. This drone is assigned to mission category B, characterised by gradual manoeuvres without precise tracking but with accurate flying control. Therefore, the limits of the flying qualities levels are chosen with respect to this categorisation.

In this paper, the flying qualities of the UAV were studied by means of the CAP criterion. In order to evaluate its flying qualities, the relative damping and natural frequency values of the Phugoid and Short Period mode were plotted against the load factor derivative. By applying the standard version of the CAP criterion, the flying qualities of the UAV are assigned to level 3. Instead, evaluating the pilot feedback, the flying qualities should be in level 1. At this point, similarly to what happens in [11], the authors proposed the introduction of a scale factor so that they can consider the differences in size and inertia present between a drone and a standard aircraft. This scale factor takes a Cessna 152 aircraft as reference, and it accounts flying speed, wingspan and moment of inertia. At this point, in order to analyse how the score of the flying qualities is adapted to different flying conditions, the authors decided to vary the static margin. By changing the distance between the centre of mass and the neutral point, it can be induced a consequent variation of the values of natural frequency and relative damping of the short period mode. The score obtained with CAP criterion regarding the flying qualities should change accordingly to the variation of the static margin. For a correct predictive model, it is necessary that the flying qualities reflect the dynamic behaviour of the aircraft. In this paper, it is observed that the evaluation of the flying qualities approaches and reaches level 1 when the static margin is reduced. Unfortunately, the authors reported that practical tests showed an opposite situation: reducing the static margin causes a deterioration of the behaviour of the UAV. The authors demonstrated that the modified CAP is not adequate to reflect the behaviour assumed by the UAV with respect to the evolution of operative flying conditions. The authors reported how both scaling factors and boundaries between levels are not adequate to use standard criteria for evaluating flying qualities of UAVs.

The two articles mentioned above show, by using two different procedures, the consequences of adapting the standard flying qualities criteria to study UAVs. Unfortunately, they also show that these adaptations are singular and not generalizable. Both articles also proved how these solutions are not adequate to represent either the operational evolution of the flying conditions (variation of the static margin) or the adaptation of the drone to the insertion of an augment control system. These considerations motivate why it is extremely difficult to create a flying qualities database that allows to predict the pilot's judgement simply by measuring the response indicators in time and frequency domains. Even though the utilization of standard criteria is proved not appropriate to evaluate the flying qualities of UAVs, it is still possible to define some strategies to improve them. In order to get better flying qualities, one key step is analysing the characteristics of stability and manoeuvrability of the UAV, which are usually expressed by their aerodynamic derivatives and eigenvalues. These elements depend on flying conditions and on the design of the UAV. In the following pages, two different articles which studied the influence of flight conditions and design parameters over the flying qualities of the UAV by performing a parametric analysis are presented. Our goal is reporting a simple and generic methodology which can optimize the design of the UAV with respect to the specific goal one wants to achieve.

In the article [18] the author studies a fixed wing UAV, the Black Kite, characterized by reduced dimensions and weight with an operating range between 30 m/s and 40 m/s of forward speed and between 2000 ft and 6000 ft of flying altitude. The author is interested in evaluating the stability and manoeuvrability characteristics of the drone and in improving consequently its flying qualities by means of specific design variations. In this article, to evaluate the flying qualities, the behaviour and the controllability of the airplane is studied, defining if it is adequate for completing the mission without any complications. Firstly, the dynamic behaviour of the aircraft was evaluated by referring to its aerodynamic derivatives and, subsequently, by calculating its eigenvalues characteristic of the longitudinal plane. At this point, Samuelsson studied the stability of the oscillatory modes and their variation with respect to different operational contexts. In this phase, it emerges a first parametric approach: altitude and flying speed are varied so that the response of the drone can be studied. The goal of this step is to highlight which operative condition is the most compromising for the stability of its modes. In this specific case, the less favourable operating conditions for the UAV are represented by high altitude and low speed. Once the worst possible flying conditions had been defined, the stability of each natural mode is evaluated by calculating its associated eigenvalues. The first consideration is that all modes are stable except for the Phugoid one (the real part of Phugoid eigenvalues is positive). In order to improve the flying qualities of the drone (i.e. to increase its levels of stability and manoeuvrability) it is necessary to make the Phugoid mode stable, even at the cost of slightly decreasing the stability of the other modes. Two different ways to influence the stability of the Phugoid mode are identified: imposing a low lift to aerodynamic resistance ratio, or adding weight to the UAV, causing a consequent variation of the distance between the centre of mass and the neutral point. Since having a high L/D ratio is an absolute priority for the design of the UAV, the stability of the Phugoid mode is enhanced "by moving the position of the centre of gravity to keep sufficient static margin while adding weight to the airplane". Adding weight to the drone improves the stability of the Phugoid mode, but the resulting variation of the static margin affects the characteristics of the short period mode, whose natural frequency increases as the static margin decreases. The author justifies this strategy in the following way: "Since the critical stability mode was the Phugoid, the high priority was to make this mode stable within the highest level as possible while keeping the fairly good characteristics of the short period mode. This was done by relocating the centre of gravity to increase or decrease the static margin. By adding an extra balance weight in the aft of the UAV this could be achieved." This point highlights that the solutions adopted to improve the stability of one mode can influence the stability of the others, eventually decreasing it. Therefore, it is clever to consider how the variation of a certain design parameter, aimed at improving the stability of a specific mode, may deteriorate the global flying qualities of the UAV.

A similar approach to the improvement of flying qualities is shown is the paper [19]. The author wants to analyse how much the flying qualities of a specific UAV are influenced by the variation of its design. A fixed-wing UAV called ANTEX_M X03 is studied, and its design is adapted to achieve a desired improvement in its performances. This work starts with the definition of a

6DOF model which allows to study the stability characteristics of the UAV through the analysis of its eigenvalues. Naturally, the eigenvalues of the UAV depend on the value assumed by its aerodynamic derivatives. The procedure followed by the author to tackle this issue is actually very similar to the one described in [18]. In the beginning, the author identifies the specific stability and manoeuvrability characteristics that need to be improved and they are associated to the respective natural modes. Subsequently, it is evaluated which aerodynamic derivatives have the greatest influence on the chosen modes, and the design parameters that can most impact each derivative are ultimately identified. Therefore, a framework useful to study the variation of the stability just through a variation of a chosen design parameter is elaborated. Particularly, a set of 8 design parameters (shown in Figure 1.6) are identified, they are multiplied to a parametric element "a" which causes their gradual variation. Their variation generates a gradual evolution of the aerodynamic derivatives and of the stability of each natural mode. Each design parameter influences each derivative in a specific and unique way; a first important diversification can be made between the derivatives of the longitudinal plane and of the latero-directional one. Figure 1.5 shows how the variation of prominent design parameters impact the evaluation of the stability and flying qualities associated to each mode. In the mentioned figure, only the extreme values of the interval of variation of “a” are reported: this figure illustrates whether design parameter is better to increase or decrease in order to improve the stability of a specific mode. Once the variation interval for parameter "a" is identified, and once that is studied how the stability of each mode is influenced by the variation of the design parameters, it becomes possible to decide how to vary the design of the UAV in order to reach a specific goal. In this case, the relative damping of both the Phugoid mode and the Dutch Roll one is increased. The variations of the chosen design parameters and the results achieved are reported below. Parameters 2 and 3 are increased by 10%, parameter 1 by 5% and parameter 6 is reduced by 10%. In this way, the author manages to improve by the 7% the damping of the Phugoid mode and to increase by the 2.9% the damping of the Dutch Roll mode. By looking to Figure 6, the correct direction of variation for parameter “a” to generate the desired evolution in terms of damping ratio is deducted. The author also specifies that, even though this solution is not the optimal one, it has a significant impact on the overall stability of the UAV.

Design Parameters		Flying Qualities			
		$\omega_{n_{ph}}$	ξ_{ph}	$\omega_{n_{sp}}$	ξ_{sp}
1	$a = 0.2$	-2	3.8	9.7	4.7
	$a = -0.2$	2.5	-5.7	-10.4	-5.4
2	$a = 0.2$	-4.5	6.3	5.2	7.5
	$a = -0.2$	5	-7	-6.5	-8

Design Parameters		Flying Qualities				
		τ_{roll}	$t\|_{\phi=60^\circ}$	$T_{2_{spiral}}$	$\omega_{n_{dr}}$	ξ_{dr}
2	$a = 0.2$			5.6	11.6	9.6
	$a = -0.2$			-1.3	-14.7	-6
4	$a = 0.2$		-8.3			
	$a = -0.2$		9.9			
5	$a = 0.2$		-16.5			
	$a = -0.2$		24.2			
6	$a = 0.2$			-10.5	22.3	3.6
	$a = -0.2$			44.6	-35.8	1.8

Figure 1.5 *Design variation effects on Flying Qualities [19]*

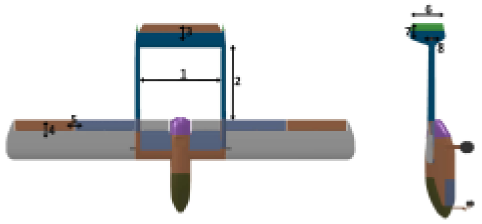

***Figure 1.6** Design Parameters of the ANTEX M03 X [19]*

In both [18] and [19] two examples of how the flying qualities of an UAV can be improved by acting on its design are presented. Obviously, the design variation of the UAV is not done randomly, but it is the consequence of the analysis of its aerodynamic derivatives and eigenvalues. Their evolution is studied and linked to the design variations by explointing a parametric analysis. With this method, the influence that each desing parameter has over each mode is comprehensively explicited. Even though the design modifications implemented are specific of both the studied drones and the desired improvements, the parametric approach has a general valence. For this reason we are more interested in the methodology proposed than in the results achieved. This method does not rely on specifc assumptions and it can be applied to study each UAV whose eigenvalues are known. Regardless of the specific UAV that one has to study, if its aerodynamic derivatives and its eigenvalues are known, a parametric analysis can be exploited to adapt its design, improving its flying qualities. These papers also highlight that design variations affect all the modes and not only the ones the authors desired to improve. Since the improvement of one mode can lead to the worsening of the others, in order to effectively improve the overall stability of the UAV, is better to be aware of potential collateral effects of a specific design variation.

In this first section of the introduction an explanation about the meaning and the utility of the flying qualities is provided, reporting the methods used to evaluate and improve them. By looking at some litterature examples, there are no fully satisfactory criteria to evaluate UAV flying qualities as it happens for standard aircrafts. Despite this problem, two works are also presented which studied the improvement of the flying qualities of specific UAVs. Since the main goal of this thesis is improving the flying qualities of one selected UAV, the papers [18] and [19] are key references for the improvement strategy performed in Chapter 4. As already reported, improving the flying qualities of drones is fundamental to increase the kind of flight missions they can perform through the industrial environemnt. In order to identify the requirements and open issues of the most common operative contexts for UAVs, in the prosecution of this introduction an industry analysis is elaborated. This study also provided important information to select the best category of drone to put at the centre of our focus.

1.2 UAVs Market – Industry analysis and external factors

The goal of this section is to present the main topics related to the characteristics and the development of the UAVs market. This section is divided in 2 main parts. The first one identifies the prevalent industries where UAVs could operate to bring significant advantages, solving open problems and needs. This procedure allows to identify the kind of missions which UAVs are more requested to perform. This information can be an important driver when it comes to decide the category of drone whose dynamic characteristics and flying qualities are better to be improved. Obviously, if the market requires a specific family of UAVs more than others, it makes sense to prioritize the development and engineering optimization of that specific category of drones. Moreover, the industry analysis documented the presence of several operations which are not performed yet by UAVs due to their poor flying qualities. The second part defines which are the external factors influencing the UAVs market and how they can impact over their development and diffusion.

The following industry analysis reports the main missions performed by UAVs within a specific industry and the features required to UAVs for delivering the best possible result. The selected industries are the ones with the biggest propension to employ UAVs and, for each industry, the main problems they have to solve and the solutions they provide are reported. Before inquiring the characteristics of each industry, according to [23], some of the technical features making UAVs so useful within the industrial environment are presented.

- Flying path planning support: the capability to fly from one point to another dealing with all kinds of obstacles encountered.
- Autonomous navigation: the ability to reckon its position and to fly through a given area without the need of any pre-assigned path.
- Swarm coordination is applied when various UAVs work together (team formation, task coordination, collision avoidance, etc.).

These features can be usually applied to perform the following operations:

- Object detection: automatic target recognition.
- Tracking: automatic target following.
- Surveillance of area, groups, etc. (this type of application can raise privacy right issues).
- Data collection (temperature, humidity, etc.).
- Item transport (commercial and emergency purposes).

In the following pages, the features and activities that can be applied to provide a unique value within specific Industrial compartments are reported. The information used to develop this industry analysis can be mostly found in [4] and [5].

1.2.1 Agriculture

The agriculture industry is put at the centre of our focus because it is one of the main opportunities for the employment of UAVs in the Italian market.

The main issues impacting the agriculture industry can be summarized as follow.

- Aggregate agricultural consumption will increase worldwide by 69% from 2010 to 2050, it is clear how the agriculture industry needs to innovate itself, improving its current functioning to keep up with such an increment of demand.
- Often the machines used in the agriculture market are extremely old and technologically backward, therefore they produce a high level of pollution. In order to respect European polices and prevent further environmental damages, the agriculture market will be obligated to introduce more sustainable technology solutions.
- There are high maintenance costs for all those tools which are used both to perform manual interventions and to carry out inspections and damages detection activities.
- The function of damages detection and plantation control and surveillance is solved, in the most technological advanced scenario, by satellite imagery. This solution has lots of problems and side effects and it is the easiest one to be substitute with UAVs.

The two main tasks that drones can perform to drive advantages in the agriculture market are surveying missions (both static and long range) and precise spraying missions. In the following lines, specific examples of these applications are addressed:

- High-resolution mapping for general crop monitoring and farm planning, useful to improve the effectiveness of the design of the plantations and to be constantly aware of their situation, discovering faster when and where certain damages took eventually place.
- NDVI, Thermal and multi-spectral camera analysis to evaluate crops, vineyards and orchards health status. UAVs have the big advantage of being able to carry different types of payload. Depending on the type of camera adopted, multiple information can be collected, like the presence of specific diseases and illness over plants and the growth and development ratio of the implanted crops. In addition, it is possible to map how herbicides are spread over the whole field, how specific plants react to them, and how they affect the life of the animals which populate the same areas.
- Drones can be also used in the process of defining the design of the plantation, for example the position and distribution of channels used both for irrigation and for managing big flows of water generated by flood or other types of inundation.
- Documentation of eventual loss or thefts within the plantation.
- Precise fertilizer and crop protection product spraying missions, used to make this procedure quicker, more precise and less polluting.

By looking at the profiles of the missions just defined, it can be noticed that, as far as the surveillance, disease detections, and design definition tasks are concerned, the employment of UAVs goes to integrate and substitute the information from satellite imagery. Then, UAVs can also substitute the employment of tractors and human workforce in all the spraying missions and in less sophisticated damage detection tasks, carried out manually by the farmers. About the spraying mission, substituting tractors with drones can surely lead to more efficient and effective fulfilment of the task, besides a significant reduction of pollution with a consequent higher environmental sustainability. More effort is spent to compare the results provided by UAVs or by Satellite imagery. UAVs suffer from limitations due to daily scene lighting conditions, weather/atmospheric condition and technical limitations related to the standard number of hours that UAVs should fly in a year to guarantee safety conditions [21]. Even though these are significant side effects, they still have important advantages with respect to the satellite employment. They come from the fact that, for fields smaller than 50 hectares in size, utilizing UAVs is much cheaper than using satellite imagery and UAVs can provide images with much higher resolution. Since the data provided by satellites needs more time to be elaborated and available, another advantage of UAVs is that the detection of damages is performed more often and quicker than by using satellite imagery, providing farmers with a faster and more efficient documentation of the current situation of their plantation [22].

In the end, the main advantages provided to the Agriculture industry by the employment of UAVs are: Increased efficiency in diseases detection and in the application and monitoring of remedies, optimized treatments with fertilizers with possible reduction of distributed product up to 20% or 40%, a decrease in the pollution generated by combustion engines (as UAVs use electric motors) and a reduction of the water waste, sometimes up to the 90%. Once the main missions performed by drones in the agriculture industry are defined, it’s possible to evaluate which characteristics they need in order to be effective. Surveying missions may require high level of endurance and range of the flight, depending on the size of the considered plantation. To perform adequately spraying missions, UAVs are requested to hover or to fly with very low forward speed. In the end, depending on the characteristics of the ground, the conditions for landing and taking-off could be quite hard for UAVs.

Figure 1.7 *Multirotor UAV performing a spraying mission [5]*

1.2.2 Infrastructure

Before describing the activities performed by UAVs within this sector, is better to describe what are the main industries involved in the wide infrastructure area.
The main infrastructure and engineering sites which could benefit quicker and easier by UAVs employment are reported. They are analysed together because they share common problems and common opportunities for the employment of drones.

- Renewable energy sites such as wind farms, solar panels and traditional power plants. Particularly, the oil and gas industry is an early adopter for the in-site inspections both in its extraction and treatment sites.
- Electric Power lines and aqueducts.
- Roads and Railway lines.
- Wide building sites.

The main problems these industries are dealing with are:

- Low and slow availability of data regarding all the different phases of the development of the working sites, from their initial conditions to the development of the project, ending with the final evaluation of discrepancies with the initial perspective.
- Needs of the infrastructure to be inspected and to deal with maintenance procedures as frequently as possible. These operations are usually very expensive and time-consuming (particularly for bridges and tunnels or power lines located in the mountains).
- Inspections of the machinery and of the inventory level in Construction and Engineering sites conducted without turning off the full installation, sparing economic loss.
- Human intervention to perform inspections and damage detection activities. These are very risky tasks which put in grave danger the lives of the operators involved and they often end up with the worst of the possible outcomes.

The main functions UAVs can have in these industries are divided into two main categories: surveying missions (more mature application and easier to perform) and actual in-loco interventions (mostly of them still need further technology before being assigned to drones).
The following are the main applications of UAVs in infrastructure industries:

- Accurate aerial mapping, which is useful to assist project planning; during the pre-construction phase, drones can significantly improve the speed and quality of the design process by providing better field data. They can also create Digital Elevation Models (DEMs) which increase the precision and detail of construction evaluations.
- They can be applied to monitor the status of the asset inventory. This is useful to immediately detect the absence of certain parts by gathering and handling data. Inspections to verify how raw materials are employed and checked by workers.

- Investors or other stakeholders can use UAVs to constantly monitor the advancement status of the works, having a precious tool to evaluate day by day the adequacy of the current status of the work with respect to the plan initially defined.
- Finally, UAVs could be employed to perform hazardous tasks which currently are completed by human workforce. For example, UAVs could be used to wash the windows of extremely high palaces. One possibility to make UAVs perform substitution interventions or damage repairs is to integrate their functions. Obviously, for this kind of employment incredibly high level of control and stability are requested, which has not been reached yet by the biggest number of existing solutions.

In the end, the main advantages coming from the employment of UAVs in these industries are highlighted. The cost and time effective procedure of data acquisition allows the companies to speed-up the planning project of the infrastructures. UAVs can also provide trustworthy documentation to monitor contractor engagement and it can be eventually useful to settle disputes in court. They can lead to significant saves in terms of cost and time of sites inspections, without the need of turning off the complete system; (i.e. standard wind turbine inspection costs are now about 1500€ for tower, UAV introduction could make the overall costs decrease up to 50%). To conclude, the most important advantage is proposed: greater protection of human life in the workplace. Many inspections activities are completed directly by workers, and these activities are often extremely dangerous and often end-up with tragic outcomes. Substituting human workforce with the employment of drones would spare a big number of tragic injuries.

Figure 1.8 *Quadcopter employment in construction site [4]*

In order to complete in a satisfactory way each application UAVs can perform within these industries, they need to possess a wide set of different features. For example, inspections of roads, railways and power lines require high endurance and long flight range. Inspections, maintenance operations and target observance require instead a better manoeuvrability and the possibility to hover. Besides, engineering sites often do not have big space for taking-off and landing.

1.2.3 Security and Delivery

Another sector which could gain significant benefits by the utilization of UAVs is the Public Safety and Security one. Due to their speed, size and manoeuvrability, drones are the perfect supplement for ground security teams seeking to perform monitoring tasks more quickly and efficiently. Drones can quickly cover large and difficult-to-reach areas, reducing staff numbers and costs, and do not require much space for their operators. They can also make it easier and more effective to conduct border security and maritime surveillance and extends into providing the capability to prevent dangerous events (e.g., forest fires, floods, earthquakes) with aerial views and monitoring. Drones also have the potential to assist at low altitudes first response teams (primarily fire-fighters and police) in identifying civilians, gathering evidence, tracking fugitives and assessing other safety hazards more promptly. UAVs can also perform remote reconnaissance and rapid accident assessments to ensure that an area is safe for a response team to enter, and to guarantee an immediate reaction to security alarms. UAVs can also expand their function beyond basic monitoring and can ensure the safety of key sites or infrastructure such as ports and airports, as it happens in Abu Dhabi. According to [5], the company which manages the city airport, decided to implement UAVs employment in their operative solutions. In many events concerning people gathering such as sports or public events, UAVs were used to provide real time data to security teams in order to catch in advance any possible hazard. Red Cross also thought to employ drones to identify injuries within the crowd, dispatching immediate medical help. In the end, when UAVs market will be more mature, they could also be implemented by private citizen to perform autonomous sentinel duty. These functions require different characteristics to be optimal performed. Stationary surveying requires hover capabilities while long distance monitoring requires flying with high endurance and long range.

Another area in which UAVs could bring significant advantages is the E-commerce and delivery sector. Since UAVs can avoid city traffic (which is keep growing in our society), they can assure faster delivery services. Moreover, they can increase the access of remote communities to the retailers around them (i.e. linking mountain villages with the closest pharmacies). Obviously, these functions have to be considered value-adding services which both customers and businesses are willing to pay for. The main application of transports provided by UAVs could be e-commerce packages delivery, medicines transport, spare parts transports and same-day food delivery. Delivering parcels with drones would be an extremely valuable solution for e-commerce, since this type of shipment would be faster, costless and would not require human actions. Both Amazon and Google have already introduced this kind of solution within their lines of business [6], [7]. Amazon developed a programme called Amazon Prime Air to automate last-mile delivery packages using small drones. Google developed a sort of hybrid UAV, Project Wing, useful to carry out last-Km delivery tasks as well. Delivering spare parts by means of UAVs could also be a good solution to increase the efficiency of maintenance interventions and improving the way companies handle and organise their warehouses. Medical logistics is a key area which UAVs could contribute to improve with two main functions: drugs transport and acting like flying defibrillators. Delivering medical supplies in a remote rural area is the most likely application for drones in transport industries, because the need is high and the risk is low. UAVs, unlike cars or motorcycles, are not subject to traffic delays, so injured people can be reached much faster. Moreover, pharmacies are not open at every time, and UAVs could answer to the demand of medicines even when there are no pharmacies open nearby. Clearly the technology of drones is not yet mature enough to effectively act like flying defibrillators. UAVs could also perform food delivering services. The most needed application would regard food distributions in emergency situations or in remote villages. Obviously, the transportation industry has to deal with external factors which can limit the availability of delivering services. The main barriers are the accessibility of the destinations (fundamental to allow the drone to land and to deliver the package) and the proximity to the sender (sender and final target need to be within an acceptable range). The technology solutions which could be able to increase the flying durability and range of UAVs and their ability to land in harsh terrains would certainly drive growth of UAVs employment in the transport and delivery industry.

Table 1.1 summarizes the main missions required by each industry. Then, a recap of the main factors influencing the efficiency of UAVs in completing the proposed tasks is made.

Table 1.1 *Industry analysis summary*

INDUSTRY	MAIN MISSIONS
Agriculture	• Surveying • Precise Spraying
Infrastructure	• Surveying • Inspections • Active intervention
Security and Delivery	• Surveying • Transport

Table 1.1 makes a summary of the main operations that UAVs can perform or could perform in industrial environments. Depending on the specific industry, the operations are different but require common features to be effectively performed. These shared characteristics are the following: range, endurance, payload transport capability, hovering, manoeuvrability, taking-off and landing capability. Even if improving the range or the endurance of the flight could be an advantage, it wouldn't give to drones the possibility of increasing their number of allowed applications. The hovering, taking-off and landing capabilities depend on the category of drone employed; it is possible to make these operations more efficient, but drones are already able

to perform them. Instead, increasing the payload transport capability and the manoeuvrability of UAVs could significantly enhance the fields of application of drones. The industry analysis showed that a significant improvement of the manoeuvrability and payload transport capacity of drones can permit them to both perform more complicate tasks in infrastructure environment and to operate in urban areas. Even a smaller improvement of these characteristics could still lead them to complete already performed missions in a more effective and precise way. For instance, the agriculture industry does not have high performances requirements but could benefit in terms of time and expenses by an improvement in the manoeuvrability of the UAVs. Reminding that flying qualities are "a set of properties that describe the ease and the effectiveness with which an aircraft responds to command inputs in function of the designed mission" [9], their analysis can improve the most required characteristics by industrial applications, enhancing the applicability scenarios of UAVs. This industry analysis also showed a big number of different characteristics drones should possess in order to be effective in each different situation. Naturally, there is a multitude of different UAVs, but a first distinction can be made between two main categories: the fixed wing drones and the multirotor ones. Each category has specific characteristics and applications which make it particularly adequate for certain missions and less appropriate for other ones. In the second chapter of this thesis, it is evaluated how those two families relate to the operative functions required by the environments defined with the industry analysis. In this sense, the industry analysis allowed to decide which category of drone was better to focus on the prosecution of the thesis.

After the analysis of the main industries requiring the employment of UAVs, the focus can be put on the external factors related to UAVs market. In Figure 1.9, the external factors influencing the employment and diffusion of drones are illustrated. Both the image and the description are detailed in the report by McKinsey [2].

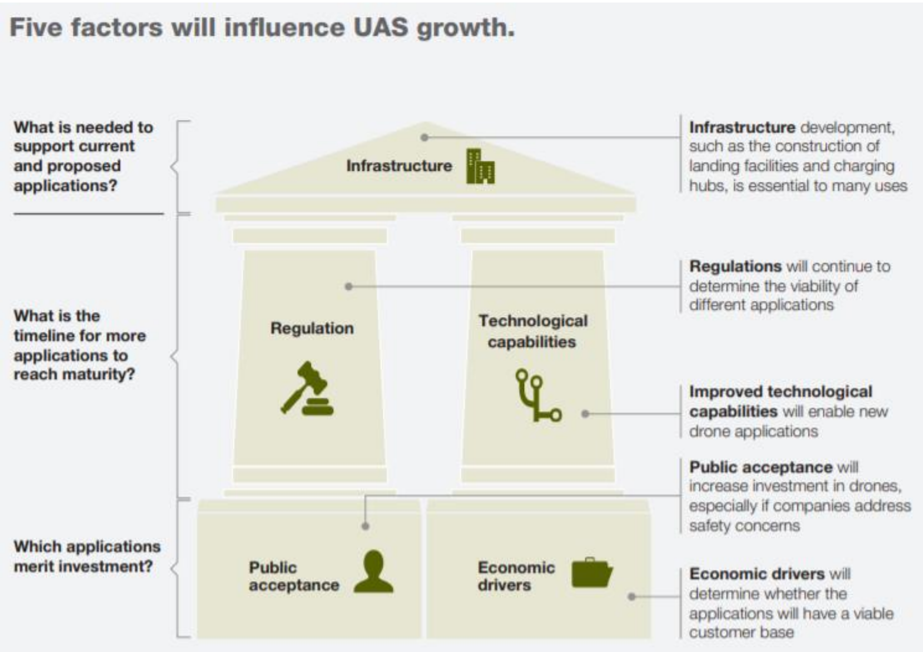

Figure 1.9 *External factors influencing UAVs market growth [2]*

The main questions which help us to identify if the economic environment is ready to deal with UAVs are reported in the left column of Figure 1.9. If no positive answers are given to those questions, then investing in UAV-based solutions is not safe enough from an economic point of view and their advantages are not fully exploited. A description of the highlighted external factors is now presented.

Technology capabilities. The functioning of drones relies on several sophisticated technologies such as autonomous flying, battery performance, detect-and-avoid technologies, integrated Air Traffic Management systems and location technologies besides GPS. Since many of these technologies are still under development, until significant improvements in the mentioned areas are reached, many of the most innovative UAVs applications will remain at a concept stage, particularly those related to drone services for delivery and transport solutions.

Regulation. Most countries are now facing with regulatory issues related to drones, as they deal with an innovation that has implications for public safety. The United States, for instance, have introduced a Drone Advisory Committee which includes regulators and industry stakeholders tasked with integrating drones into the national airspace. Regulators are charged with thoroughly evaluating the implications of new UAVs applications, including potential safety issues, before they reach the market. That means the regulatory process and timeline development will ultimately determine when many UAVs applications will become available on the market [2].

Infrastructure. Most current UAV applications have modest infrastructure requirements. A drone employed for mapping construction sites might simply land on landing spot free from obstacles within the working site and recharge its battery using the same power source other devices do. Naturally, as UAVs sophistication increases, the landing facilities and the recharge stations will have to evolve too, as well as all the other infrastructures related to UAVs employment, in order to keep up with the progress of the UAVs technology. At this stage of UAVs development, these issues are not a big concern yet, but their importance will grow up accordingly with the development of UAVs. Moreover, robust Unmanned Traffic Management (UTM) systems are essential to enable safe low-altitude operations within the national airspace. The beacons and other infrastructure are not yet in place for such systems and every UAVs application also requires counter-UAV solutions to detect and safely disable unauthorized aerial vehicles in the airspace. Then, in order to imagine a future employment of UAVs to transport people and goods within our cities, there are many infrastructure sites which need to be implemented. Vertiports to manage cargo and human transport operations, service centres where aerial vehicles can be inspected and repaired, distribution hubs to receive and load cargo and the most important one: charging stations to recharge batteries.

Public Acceptance and Economic drivers: As it always occurs for disruptive technologies, they need a wide cooperation across both public and private sectors in order to penetrate the market. This means that governments could apply incentives to those companies who decide to use drones within their activities and big private companies could put into the government disposability their ability to gather, collect and analyse great amount of data. One central topic regarding drones diffusion is the ability to handle a big quantity of data. Even though UAVs can bring big advantages to the market just operating within the line of sight, it is easy to understand that the biggest advantages would come from the implementation of autonomous driving concepts. The autonomous piloting, for both drones and cars, relies on the capability of managing data, since they are essential to evaluate precisely the position of each drone of the fleet and to perform air-traffic-management tasks, which are essential to guarantee a safe applicability of this technology on large scale. Figure 1.10 represents the value chain generated by the application of UAVs, underling the main points of the milestones which need to be kept into account to evaluate the impact of drones towards our society: Aircraft hardware, Operations and Services.

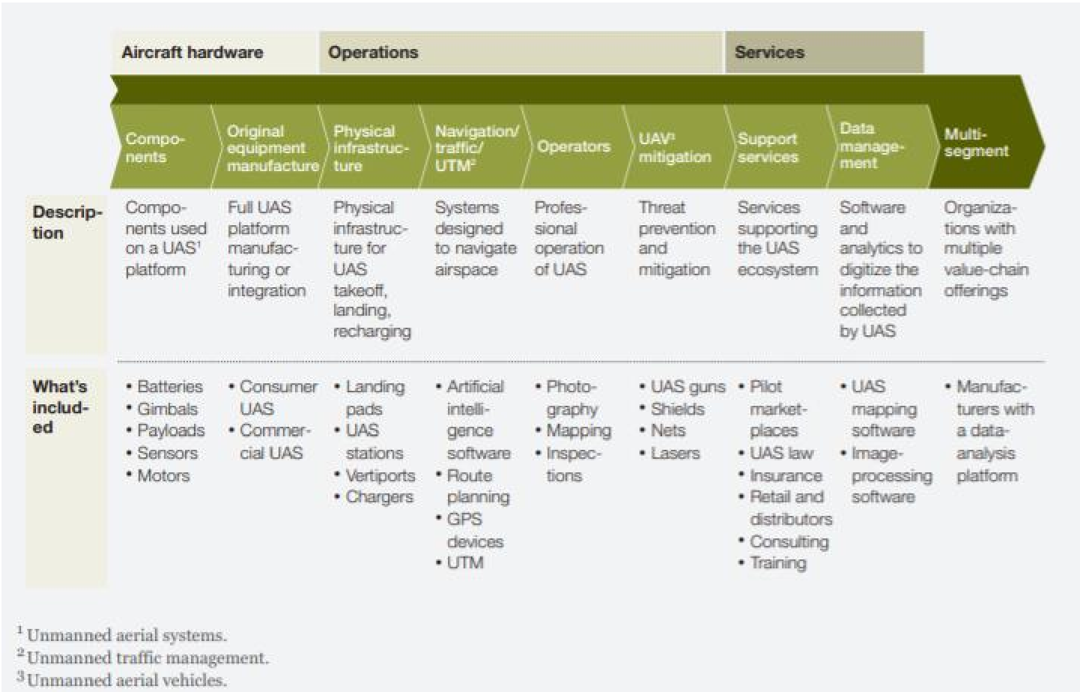

Figure 1.10 *UAVs Value Chain [2]*

Assessing all the factors and parts, which are involved in the employment of drones and in their market diffusion, gives the possibility of dimensioning the market related to the diffusion of these technologies. Obviously, the money moved by the employment of the drones are not just related to their engineering development and production, but they are also referred to the services that drones provide and to the aftermarket functions which need to be carried out. The relation [20], developed by The Boston Consulting Group, sizes the dimension of the UAVs market, giving a precise estimation of the money moved by each economic function related to the UAVs design, production and service employment.

Design, sales and marketing. The amount of money moved by project activities and by the activities of selling and publicize specific UAVs.

Assembly and production. Specific workforce has to be trained and hired, dedicated construction sites have to be built or adapted to the production of drones and all the tools they are going to exert.

Value-added-services. A wide set of services will be generated to exploit the UAVs technology and they will bring to the market the biggest part of the money stream. (i.e. both Amazon and Uber could drastically change their business models by transporting respectively goods and people by means of dedicated UAVs). Another crucial revenue stream could come from the big amount of data that shipments and transport with UAVs are able to generate.

Piloting, operations and maintenance. In order to exploit all the functions drones can provide our society with, a huge amount of people will have to be hired in order to fulfil all the tasks required by each business segment activated by UAVs.
Insurance. Insurance companies have to figure out a complete new policy to regulate the UAVs and assess both the proper class of risk and the responsible parts for each type of application and operative scenario UAVs will be used for.

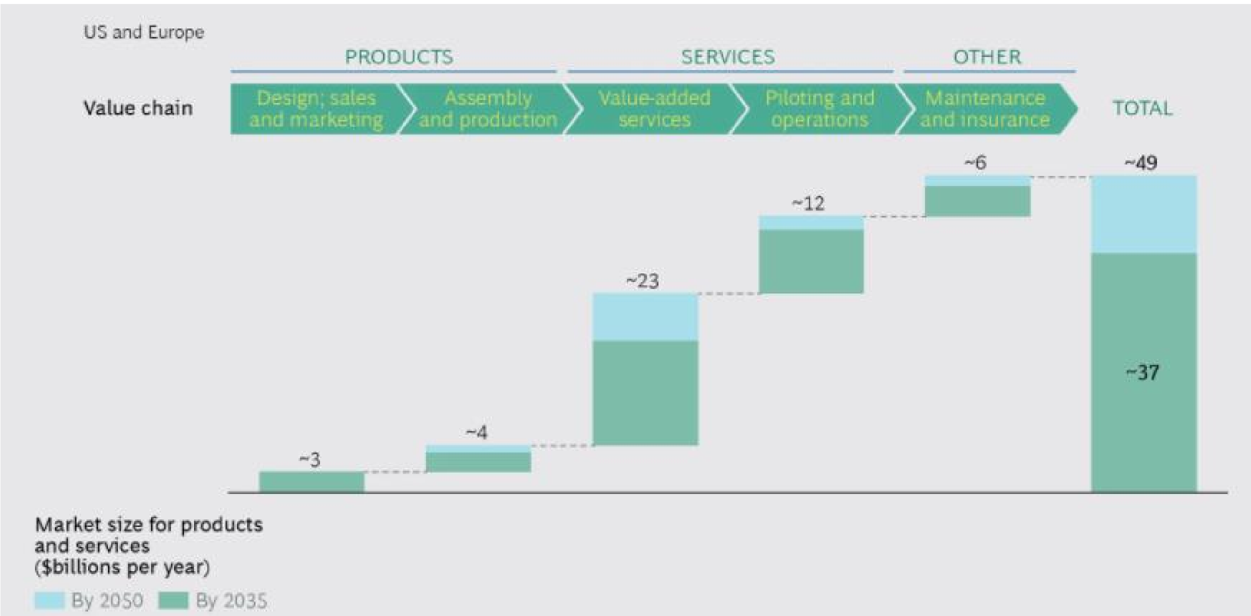

Figure 1.11 *UAVs market size, production and services [20]*

In Figure 1.11, the market size which will be reached within 2035 and 2050 is shown [20]. Accordingly to the illustration, the biggest part of the total flow activable by UAVs will be interested in the next 15 years, and in the following 15 years the evolution of the Value-added services will take place, which need a higher maturity of the close environment in order to be fully appreciated.

Since the main external factors influencing UAVs development and diffusion have been illustrated, but some barriers to prevent Companies and Governments by adopting UAVs technology have been reported in [5]. The first barrier regards the safety of the operations with drones. Particularly, is fundamental the possibility of super-visioning drones, identifying pilots and developing an air traffic management system for UAVs to prevent collisions with other flying vehicles. Moreover, in order to prevent an uncontrolled fall from the air to the ground, UAVs need to possess auto-fail functions. When drones fly over certain types of sites, they collect vast amounts of data, sometimes including confidential or sensitive information about private property or private behaviour information. In order to allow a wider diffusion of UAV-based services, is fundamental to regulate their employment according with the privacy policy developed by the European Union to protect private data. Another important barrier is about the availability of coverage provided by insurance companies. The laws on UAV operators are still evolving, and insurance will become part of the complex regulatory framework. It is expected that insurance will be one of the main actors influencing risk management frameworks for UAVs technologies, in order to provide coverage for risks of physical losses or liabilities during and after drone operations. As the market expands, drone users will need more composite and high-value risk exposure insurance [5].

In conclusion, the main factors impacting the development and diffusion of the UAVs have been analysed. Particulary, a method aimed at improving the flying qualities of UAVs has been proposed and the main industrial environment missions for UAVs have been defined. These considerations are the basis for the prosecution of this work. In fact, the second chapter is used to compare the two main categories of UAV present on the market: fixed wing UAVs and multirotor UAVs will be compared in chapter two. Their characteristics will be compared to figure out which category can bring the highest value to the market, completing the biggest number of functions which were appointed in the previous industry analysis. Once the category of UAV will be selected, in chapter 3 its aerodynamic properties by means of its aerodynamic derivatives and eigenvalues will be studied. Following the methodology presented in [18] and [19], a parametric analysis will be performed to evaluate how the design variations can influence the properties of the UAV, particularly in terms of stability and flying qualities. To conclude this work, in chapter 4 two operative situations will be considered, related to the employment of one specific UAV. By exploiting the previously mentioned parametric analysis, two different strategies will be proposed to improve the flying qualities of the UAV with respect to the operative environment proposed.

This thesis has been developed in collaboration with MAVTech s.r.l., a company that contributes to the development and diffusion of UAVs by completing two main functions: developing its own UAVs and providing to other companies consultancy services and support for the implementation of drones within their business activities. MAVTech also provided the drone which is the object of the parametric analysis and the design optimization mentioned before.

Chapter 2
UAVs – General characteristics and overview

The purpose of this chapter is an overview of fixed and rotary wing UAVs and to focus on a specific analysis of the flying qualities for one of these categories. As described in the introduction, the main objective of this thesis is to provide a method to improve the performance of a drone. Since the missions assigned to UAVs depend on market requests, the main industries demanding the employment of UAV based services are analysed. In this way, the properties and functions most required by our industry environment are defined. It is possible to identify a category of UAVs which, due to its unique properties, is the most adequate one to complete as many missions as possible. Obviously, the bigger is the number of missions and tasks a drone can carry out, the bigger is the interest of the market in its development and employment.
There are two main different categories of UAVs: the fixed wing ones and the multirotor ones. In this chapter, the main features of both categories are analysed, and their advantages and disadvantages are compared. Assessing the properties required by the main missions defined during the introduction, it is possible to identify the specific category of drones which best fits our needs. In the end of this chapter is reported a list with a small description of the main equipment needed by UAVs to perform the most common missions. This is useful to understand why UAVs are complex systems which need several elements to work properly.

2.1 Fixed Wing Vs Multirotor UAVs

In the beginning, a brief description of the design and the technical characteristics of both the categories of UAVs are reported to understand the advantages and disadvantages of the two different categories of drones.

A fixed wing UAV has almost the same design of traditional aircrafts, desptite obvious differences in terms of dimensions. The lift needed to guarantee their vertical equilibrium is naturally generated by the wing while the can be generated in several ways (i.e. for the UAV shown in Figure 2.1, the thrust is generated by means of a dedicated propeller). The dynamic control of these UAVs is usually obtained by exploting the aerodynamic control surfaces which are also characteristics of standard aircrafts. Usually, the weight of these UAVs tends to be as low as possible, so that they can be propelled with low levels of consumption.

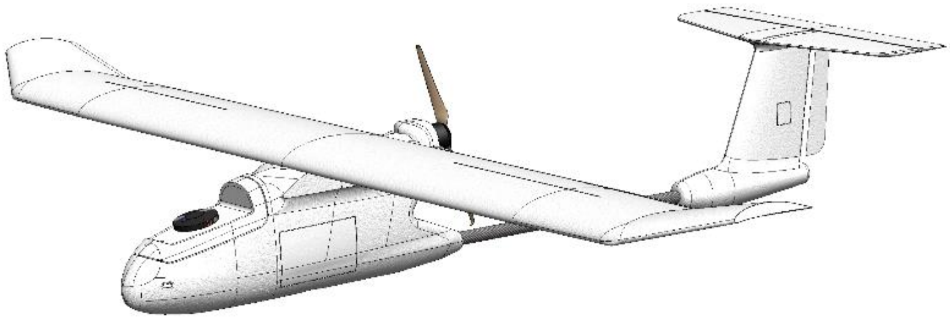

Figure 2.1 *AGRI 1900 developed by MAVTech [30]*

The main advantages of the fixed wing UAVs are:

- Significant flying range. This feature depends basically on the speed of flight and on the durability of its batteries. Since the power produced is only needed to move the drone forward while the lift is generated by its wing, the life of the batteries is usually quite long and allows fixed wing UAV to perform long flights [27], [28], [29]. This aspect makes fixed wing UAVs a perfect fit to perform missions which require great flight endurance or to travel big distances. This characteristic is particularly useful when performing long surveying missions.
- Disturbances resistance. Fixed wing UAVs have great stability in terms of wind and turbulence resistance. This feature becomes very important for those UAVs which are constantly employed in areas with usual harsh environmental conditions [26], [27], [29].
- Safe recover from power losses. Due to their aerodynamic characteristics, fixed wing drones can safely recover from power losses failure. In case of a sudden failure of the propulsion system, the drone loses its capability of accelerating forward but its wing still generates the lift which guarantees the vertical equilibrium of the drone. Therefore, in case of power supply failure, the UAV can glide and land reporting as less damages as possible [27], [29].
- Trajectory accuracy. Fixed wing drones are extremely precise in following specific trajectories, even when dealing with external disturbances. For this reason, they are usually used to perform applications which require to follow a precise path, as it happens for the monitoring of pipeline, railways and powerlines [29].

Instead, the main disadvantages of fixed wing UAVs are:

- Large take off and landing distances. As it happens for the traditional airplanes, UAVs need to reach a specific velocity before being able to take-off. Therefore, a certain distance is required to accelerate the UAV from the null velocity to the target one. Accordingly, a similar distance is required during the landing phase in order to decelerate the drone and stop its motion. These characteristics represent one of the biggest limit to the diffusion of fixed wing drones [27], [28], [29].
- Impossibility to hover. Fixed wing UAVs, due to the mechanism used to generate lift, are not able to perform hover flight. This turns out to be a significant limit for their applicability, since there are many tasks which require either constant monitoring of specific target or the capability to fly at very low speed [27], [28], [29].

On the other hand, a multirotr UAVs are unmanned aerial vheicles which base their functioning on the characteristics of helicopters. As for the helicopters, both the generation of lift and the propulsion of the vehicle is addressed to the rotors. Multirotor drones exploit the action of a certain number of rotors to both generate lift, ensuring their vertical equilibrium, and to let the drone moving forward-backward and right-left. The maneuverability of multirotor UAVs is reached by regulating the speed of each rotor. The variation of the flight altitude is achieved by varying simultaneously the velocity of each rotor while the forward-backward and right-left motion is obtained by increasing or decreasing the velocity of specific rotors [24], [26]. Another crucial difference between helicopters and multirotor UAVs is the lack of the tail rotor, whose goal is to compensate the reaction torque generated by the main rotor. UAVs do not generate any reaction torque because their rotors are divided in couples which are contro-rotating. Two rotors have a clockwise rotation and the other two have a counter clockwise rotation. In this way, each couple compensate the reaction torque generated by the other one. Figure 2.2 shows in a very simple way how the rotation speed of each rotor can be regulated to control the attitude of the drone and to induce a translation in the desired direction.

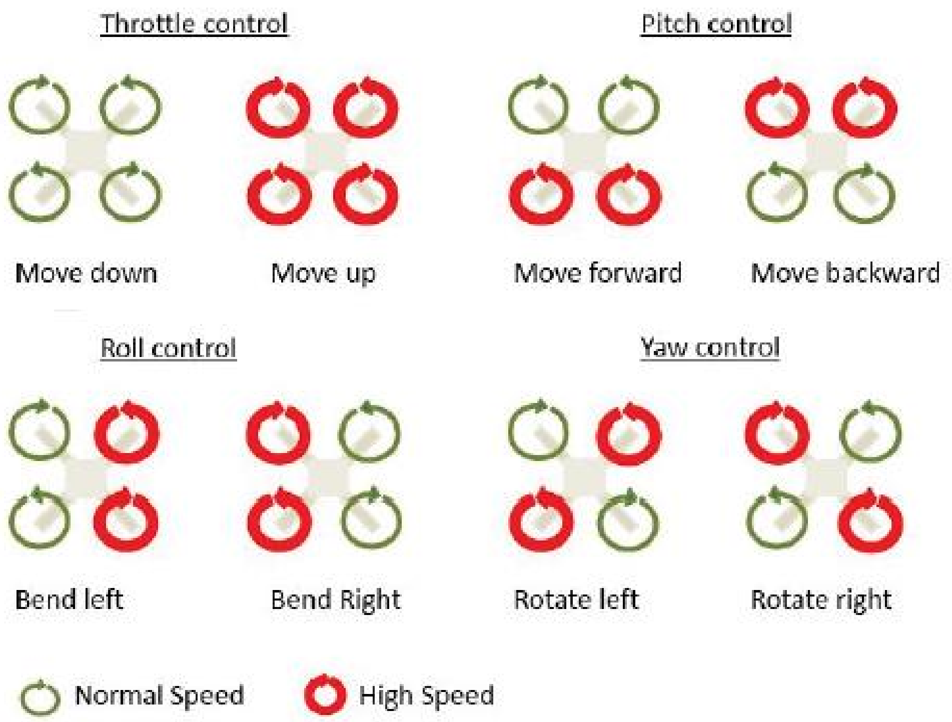

Figure 2.2 *Multirotor Attitude Regulation [24].*

Usually multirotor drones are realized with four rotors but there are also configurations with six or eight rotors, a comparison of the different categories of multirotor is reported in the following pages.

The main advantages of the multirotor configuration UAVs are:

- High Manoeuvrability. This feature comes from the high precision of the maneuver that can be achieved by controlling the UAV with a differential regulation of the angular

speed of the rotors. In this way, multirotor drones can perform manoeuvers up and around objects for easy inspection, mapping and modelling [27], [28], [29].
- Hover flight and vertical take-off and landing. These two operative characteristics have two main advantages. The hover flight is very useful when it comes to surveillance mission (for example when it is needed to control a specific construction site or for security purposes) or for eventual drone employment to perform maintenance activities (which require them to stay hold in a fixed position). The possibility of performing vertical take-off and vertical landing allows the pilot not to be concerned about the characteristics of the ground where he wants to operate with the drone. It is quite easy to understand that this can be a big advantage in terms of applicability and employability [27], [28], [29].
- Ease of use. A multirotor drone is quite easy to handle and pilot by means of a dedicated joystick which easily allows to regulate the speed of each rotor [27], [28], [29].
- Higher Payload capability: Due to their design, multirotor design are able to carry a heavier payload than fixed-wing UAVs [26], [27], [28], [29].

The main disadvantages of multirotor UAVs are:
- Short range. Rotors require a big amount of power in order to provide enough thrust to make the UAV move forward and to balance its weight. Addressing the function of balancing the weight of the whole UAV to the rotors increases the amount of power requested. Instead, fixed wing UAVs only require power to accelerate the UAV forward. Assuming to have a fixed battery capacity, the flight autonomy which is provided to the multirotor UAVs is minor than the one provided to fixed wing drones. This means multioror UAVs are not aimed at travelling long distances or performing long missions [27], [28], [29].
- Disturbances resistance. Multirotor UAVs are deeply sensible to wind and other atmospheric perturbances. An explanation can be found in the fact that the blades usually do not have high mechanical poperties and for this reason their structure is vulnerable to external disturbances [26], [29].
- High price: Multirotor UAVs are characterized by higher prices than fixed wing ones. One simple reason for this aspect is due to the presence of the rotors, which have a high mechanical complexity and are the biggest source of costs. Obviously, higher is the number of rotors, more expensive is the power requested and the cost of the UAV.

Since the goal of this chapter is to identify the configurations of UAVs which could perform the biggest number of missions required by the market, this report of advantages and disadvantages was used to define which category of UAVs has the biggest number of properties required by the most common industrial missions. In chapter 1, five features which are essential to effectively fullfil the most common missions are defined: range, endurance, payload transport capacity, hovering, manoeuvrability, taking-off and landing capacity. In order to account other non-mission related factors, this list is completed by adding additional features. This whole set is used to define whether fixed wing or multirotor UAVs are better to fullfil the mentioned required properties. The results of the previous analysis are summarized by means of Table 2.1. By matching these results with the list of missions required by each industry showed in Table 1.1, is possible to identify which UAV category can be effectively employed in the highest number of industrial environments.

***Table 2.1** Features of UAV categories*

FEATURE	BEST UAV CATEGORY
Manoeuvrability	Multirotor
Range	Fixed Wing
Endurance	Fixed Wing
External disturbances resistance	Fixed Wing
Payload capacity	Multirotor
Take off/Landing easiness	Multirotor
Recover from Power loss	Multirotor
Hover flight	Multirotor
Size/portability	Multirotor
Price	Fixed Wing

Since the properties reported in Table 2.1 are the key requirements to effectively perform certain missions, the definition of the UAV category more appropriate to carry out specific mission is now possible. Table 1.1 shows the main missions required by each reference industry. Since the clearest advantage of fixed-wing UAVs is the possibility to fly long ranges with high endurance, this category of UAVs is the best choice when it is requested to perform surveying mission over long distances. This situation occurs for example when drones need to monitor wide plantations or railways, pipelines and powerlines. For effectively performing these missions, fixed wing UAVs are clearly the best choice. For short-range surveying, fixed wing drones are still better than the multirotor ones but their convenience becomes less evident as the mapping area decreases. Conversely, when UAVs are employed to fly in small spaces, with low velocity or in hover condition, the advantages of the multirotor drones are unavoidable. Their higher manoeuvrability allows them to follow paths and fly trajectories which would be impossible to follow for fixed wing UAVs. This is the case of inspections-tasks in the infrastructure industry. The hover flight is also essential to perform static monitoring or to carry out spraying-missions in the agriculture industry. Moreover, the possibility of performing vertical take-off and landing makes multirotor drones easier to employ regardless of the external environment. This analysis, summarized in Table 2.2, suggests that multirotor UAVs can be exploited for a bigger number of missions and therefore are of big interest for the market. Moreover, also by considering possible future developments of UAVs technology, a further reason to put our focus on the multirotor drones can be found. Their most relevant weak point is that they are not able to fly both long ranges and big amount of time. This problem could be solved by adopting more efficient and effective types of battery, or by making the power supply itself more efficient by reducing power loss due to parasitic effects. Instead, the deficit of manoeuvrability and hover flight of fixed wing UAVs is strictly connected with their design and it is not possible to be changed. These considerations suggest that the issues of the multirotor drones are easier to be solved than the ones of the fixed wing UAVs. This is a further reason to focus the prosecution of this thesis on multirotor UAVs.

Table 2.2 *Mission - UAV Category Match*

APPLICATION	BEST UAV CATEGORY
Plantation mapping and surveying	Fixed Wing /Multirotor
Precise Spraying	Multirotor
Pipelines, railways and powerlines surveying	Fixed Wing
Construction/Engineering sites monitoring	Fixed Wing /Multirotor
Construction/Engineering sites inspections	Multirotor
Active interventions	Multirotor
Target point monitoring	Multirotor
Harsh environment operations	Multirotor
Urban environment operations	Multirotor

Multirotor UAVs can be further distinguished by the number of the rotors. According to [31], the most common and simple realization of multirotor UAVs is the quadrotor. With respect to configurations with a greater number of rotors, quadrotors are faster, easier to manouver, simpler to build and of course cheaper. Their downsides are related to the absence of backup motors and to the impossibility of carrying heavy payloads. Conversely, a configuration with more rotors provide the UAV with more available power (higher range and endurance), the possibiity to fly higher and with more satisfactory levels of stability and safety of the flight. Since the operative scenario designed by MAVTech does not require either to transport heavy payloads or to fly in sensitive environments where safety is an absolut priority, we decided to select as test case for the simulative part of this thesis a quadcopter, the Q4E, shown in Figure 2.3. It is the last quadcopter developed by MAVTech, with the goal of having a solid, simple, flexible and portable flying platform. Its autopilot is the Pixhawk 2, with incredible characteristics in terms of power and reilability, with different configuration opportunites. The propulsive system is the efficient DJI E800. The battery is insert in the middle of the frame, so that an optimal balance of the loads is obtained. The most common applications of the Q4E are photogrammetry operations with multispectral cameras or search and rescue missions [30].

One possible way to maximize the industrial applicability of drones is combining the advantages of both categories in one single drone. For this reason, hybrid UAV solutions have been realized. Even though the main focus of the thesis regards multirotor drones, is useful to report a brief description of hybrid solutions as well. An interesting hybrid UAV solution is based on the concept of tiltrotors. This hybrid UAV takes-off vertically using rotors like thrusters and, once the target altitude is reached, it tilts the rotors of ninety degrees to produce horizontal thrust and push the drone forward. In this phase the lift to guarantee vertical equilibrium is generated by means of the wings. This design is characterized by high complexity and risk, due to the tilt phase of the rotors. For this reason, more intuitive and simple design have been developed by substituting the tiltrotors with fixed rotors instead. They have the function of generating thrust during take-off and hover conditions while the propulsion in forward flight is originated by dedicated thrusters. This last solution has lower energetic efficiency due to a bigger total wight but has lower mechanical complexity and minor risks too [24].

Figure 2.3 *Q4E by MAVTech s.r.l [30]*

2.2 Multirotor UAVs equipment

After this parenthesis regarding the characteristics of hybrid UAV solutions, the main equipment characteristics of multirotor drones are reported. These are the main components which allow these UAVs to fly and to carry out successfully their missions. The main components of their equipment are the following: Flight Controller, Propellers, Batteries, Motors, ESC, RC Receiver & Transmitter and Payload [26].

The flight controller has the key task to compute the state vector characteristic of the UAV, in terms of attitude, velocity and position and provide this information to the pilot. The flight controller is also able to set different flight modes, depending on the characteristics of the mission and the phase of the flight. Particularly, the following flight modes are distinguished: Manual, Stabilize, Alt hold, Loiter, Auto and Return To Launch (RTL). Moreover, this system is also able to adequate the flight of the UAV to deal with particular and difficult external circumstances, setting some specific flight modes: Low battery mode, Loss of radio-link mode, Loss of GPS signal and Geo-fencing.

It is also possible to distinguish between two main families of flight controllers, the open-source ones and the commercial ones. The open-source ones are cheaper, more editable and more easily adaptable but also more complex and less secure than the commercial ones [26].

The propellers have the fundamental task to allow the motion of the UAV, generating adequate lift and providing the requested horizontal velocity. There are different kind of propellers, depending on the material they are built with, the number of the blades, their shape and the value of their key design parameter. Usually, each rotor is formed by two blades. The propellers can be also distinguished between rigid ones and the folding ones. The main parameters which determine the characteristics of the blades are their radius, their chord and the pitch law variation (there are blades with both fixed and variable pitch). In the end, the blades can be built with different materials, the most common are plastic, wood and carbon fibre. Obviously, the choice of the material has a great impact on the effectiveness of the blade, increasing or decreasing their mechanical properties and durability [26].

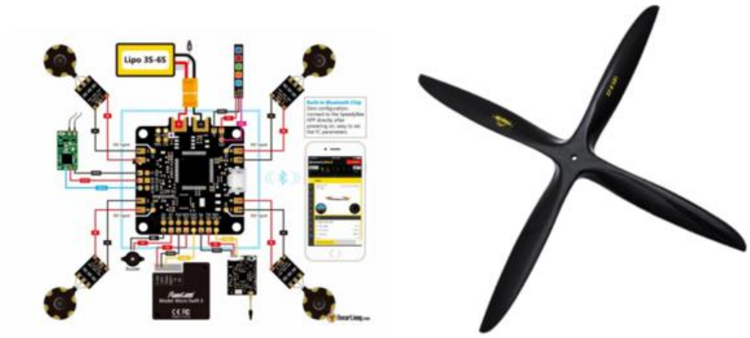

Figure 2.4 *Flight Controller and Propeller*

DC Motors get their power from the batteries and are used to give to the propellers the possibility to rotate, winning the opposition of aerodynamic resistance which acts like a resisting torque over the propeller. Obviously, there are different kind of DC Motors: Brushless, In-Runner and Out-Runner. The main parameters which are used to specify the functioning of the motors are the Voltage, the maximum continuous power and current, the two coefficients of Thrust vs Current and Thrust vs Power, the internal resistance and the weight.
For the brushless DC motor, a very important tool to relate with is the electronic speed controller. It has the key function to change the RPM of each rotor and it happens to be useful in different operative situations. An efficient link between the DC motor and the Electronic Speed Controller is essential to give to the drones a good level of flying qualities [26].
The batteries which are usually implemented, are the Lithium-ion Polymer ones, which bring significant advantages. They do not have the need of a metal case, therefore are lighter and more powerful. They have high peak of discharge current and a very low auto-discharge one, they do not have memory effect and quite high cycle limits with about 500 discharge/charge cycles. A key feature is the way used to charge LiPo batteries, which can actually be charged just with a proper device. There are two different programs which keeps constant current and variable voltage when the program is started, and the other way around when it is about to end. Is also very important to balance the LiPo during the procedure, avoiding overcharge or discharge to much a single cell. Another important aspect to mind during the charge procedure is to store them in a fireproof safety bag or container, to protect the battery against fire or gas spill [26].

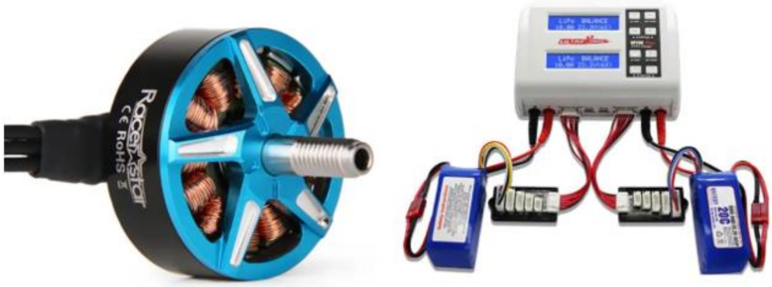

Figure 2.5 *DC Motor and charging batteries*

It is also important to consider the characteristics of both the RC receiver and the RC transmitter. The RC receiver is naturally on board of the vehicle and it has to receive signals from the transmitter. Then, it is put in contact with the flight controller, to which it has to send signals, and with the payload. It is equipped with a SBUS, a serial protocol to manage data and verify their adequacy. It is also equipped with antennas located far from sources of electromagnetic noise (power cables, switching supplier, ESC, etc) and placed with an angular deflection of 90 degrees, so that a maximum efficiency is ensured.
The RC transmitter is used by the pilot to send the desired commands to the aircraft, in order to perform primary commands sticks are used, instead the secondary commands are performed through switches and buttons. The most used transmission bands are at 40 MHz, which is abandoned and at high possibility of disturbance, and the one between 2.4 GHz and 5.8 GH. The power used to transmit signals is 100 mW and the range of communication is up to 2 Km [26].

Figure 2.6 *RC receiver and transmitter*

In the end the payload is considered. It is the most important part of our drone, because the reason why there is the need of the UAV in the first place, is to exploit the payload itself. Looking to future applications, there will be the possbility to implement an active payload, which can perform simple activities exploiting specific tools, such as 3D printing for example (in-loco maintenance activities). But at the current status of technology the payload our drones are able to carry are basically various types of camera. Depending on the kind of mission, and the quality level of the results one wants to get, different types of cameras can be adopted. A brief summary of the main kinds is made: Action cam, Compact camera, Professional camera, Gimbal camera (with rotation around two or three axis), infrared camera and thermal camera. The last two types of cameras happen to be particularly useful to perform the following activities: pipeline inspections, buildings energy efficiency analysis, detection of water stress, power plants surveys, search and rescue applications over night as well. The multispectral camera is used for precision agriculture and forestry. The hyperspectral camera can be used for precision agriculture and forestry, vegetation mapping, terrain use classification and roof inspections[26].

Figure 2.7 *Gimbal camera, Thermal camera, Multispectral camera, [26]*

Chapter 3
Flying Qualities evaluation

The purpose of this chapter is evaluating how the flying qualities and the stability of the Q4E can be modified by changing the design of the drone. To complete this analysis, it is essential to study the characteristics of the natural modes of the Q4E, therefore its eigenvalues and aerodynamic derivatives need to be calculated. This chapter begins with the explanation of the model used to calculate the eigenvalues of quadrotors UAVs and it documents which information they can provide regarding the stability of the natural modes. The meaning and the formulation of each aerodynamic derivative is also reported. Then, the aerodynamic derivatives and the eigenvalues of the Q4E on-design conditions are evaluated. At this point, it is possible to evaluate its flying qualities in terms of stability conditions. In Chapter 1 is reported how the works [11] and [17] stated the inadequacy of standard aircrafts criteria to evaluate the flying qualities of UAVs. For this reason, a simpler strategy, which evaluates the flying qualities of the Q4E depending on the stability characteristics of its natural modes, is followed. Therefore, the flying qualities of each mode are studied independently, and a distinct level is assigned to them. Particularly, the main focus is on studying how the flying qualities can be improved by means of a different design configuration of the drone. To complete this evaluation, we decided to apply the procedure described in Chapter 1 and adopted by [18] and [19]. Some of the Q4E design parameters are selected and the impact of their variation on the evolution of both the aerodynamic derivatives and the eigenvalues is calculated. The goal of this chapter is not recommending specific design variations, but only to map how the possible variations considered can influence the development of the Q4E flying qualities. The obtained results are used in chapter 4 to develop the optimization strategies required to improve the flying qualities of the Q4E with respect to the specific mission it is demanded to perform.

3.1 Summary of the evaluation of eigenvalues and natural modes

No reference model is already available to accurately study the eigenvalues and the natural modes of quadrotor UAVs, and the same can be said regarding their aerodynamic derivatives. In this thesis, the stability of the Q4E is studied by applying the same theoretical model used to study helicopters. In order to make this model as realistic as possible, some punctual corrections to the value of certain aerodynamic derivatives are implemented in order to better represent the dynamic behaviour of a quadrotor UAV, which is clearly different from the one of helicopters (a first evident difference is the lack of tail rotor which causes sensible differences in all the derivatives computed with respect to the yaw angular velocity). According to [25], In order to define the equations characteristics of the helicopter dynamics, it is important to observe that the rotor is an almost stationary dynamic system, which adapts its behaviour to the external command with an instantaneous transition. For this reason, the dynamics of the helicopter can be well approximated with the dynamic response of the fuselage and its degrees of freedom are also representative of the states of the helicopter. The approximation of the rotor as an almost-stationary system allows to apply the small perturbation theory to the equilibrium equations of the UAV. This procedure led us to describe the dynamics and the motion of a helicopter (UAV in this case) with the following state space formulation:

$$\{\dot{x}\} = [A]\{x\} + [B]\{u\} \tag{3.1}$$

By solving this system of equations, it is possible to get all the information needed to describe the dynamic behaviour of the UAV but, previously, it is essential to introduce each variable and two reference frames. This formulation represents a system of nine differential equations with nine different unknowns which are the components of the state vector $\{x\}$. The first reference frame is the North, East, Down Frame (NED). It is based on the surface of the geoid below the centre of gravity of the UAV. The vertical axis z_v is directed along the local gravity accelerator vector. x_v and y_v identify a plane perpendicular to the direction of the gravity acceleration vector and x_v is oriented to the North while y_v points towards the East (in this way a right-handed frame is obtained). This reference frame can be considered a fixed frame with respect to the quadrotors. The second reference is the body reference one. Its origin corresponds to the centre of gravity of the UAV, x_b and z_b lie in the UAV plane of symmetry with x_b parallel to the fuselage reference line and pointing to the forward direction and $z_b$oriented from the upper to lower surface of the blade. y_b axis is oriented to generate a right-handed oriented reference frame. For quadrotor UAVs this reference frame generates a principal axes of Inertia system (which means that the centrifugal moments of inertia I_{xz} and I_{yz} are null). Coming back to the definition of the state vector $\{x\}$, it is composed by three linear velocity components along the body axes (u, v, w), three angular velocity components around the body axes (p, q, r) and three Eulero's angles that identify the attitude of the quadrotor (φ, θ, ψ). u is the linear velocity referred to the x axis, v is the linear velocity referred to y axis and w is the linear velocity referred to z axis. p is the angular velocity of the UAV around the x axis, q is the angular velocity of the UAV around the y axis and w is the angular velocity of the UAV around the z axis. φ is the roll angle and identifies the UAV rotation around the x axis. Its value is null when the y and z axes of the body frame are aligned with the correspondent ones of the NED frame. θ is the pitch angle and identifies the UAV rotation around the y axis. Its value is null when the x and z axes of the body frame are aligned with the correspondent ones of the NED frame. ψ is the yaw angle and identifies the UAV rotation around the z axis. Its value is null when the x and y axes of the body frame are aligned with the correspondent ones of the NED frame. A visualization of both the reference systems and the variables is provided by Figure 3.1.

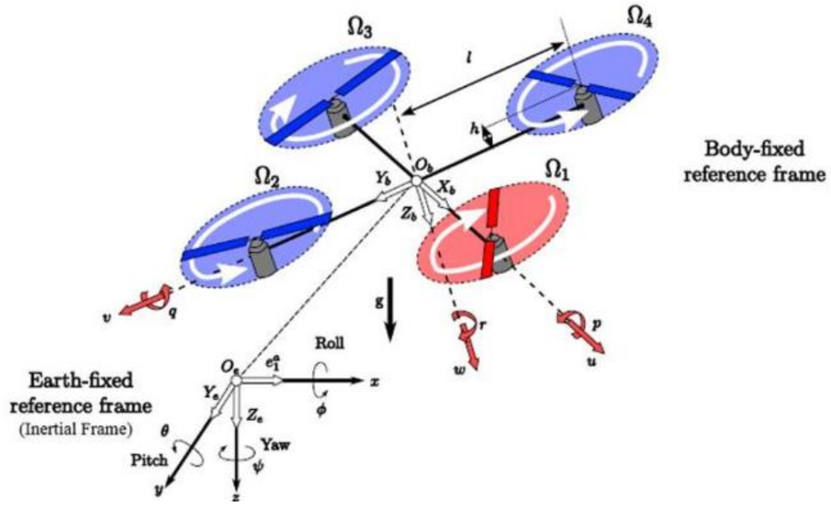

Figure 3.1 *Quadrotor reference system [31]*

Once defined the components of the vector $\{x\}$, the remaining elements of the state space formulation can be presented:

- $[A]$ is the state matrix and it contains the aerodynamic derivatives of the considered helicopter/UAV; its complete formulation is provided in the following part of this chapter.
- $\{u\}$ is the vector of the commands.
- $[B]$ is the control matrix. Since the commands of a helicopter are completely different from the ones of an UAV, it is pointless to apply the same formulation also to study the UAV dynamics.

Therefore, to study the dynamic stability of the Q4E, the following formulation is used:

$$\{\dot{x}\} = [A]\{x\} \tag{3.2}$$

The Helicopter motion can be considered to comprise linear combination of different natural modes [13] and it is essential to analyse the state matrix A to define them. Since the subject of the research is to study and improve the flying qualities of the Q4E in hover condition, the longitudinal plane and the latero-directional one can be analysed separately. Therefore, the previous equation has to be solved two times, one for each independent plane. The hypothesis of uncoupled planes is valid because the natural modes are well separated in hover conditions but, when the forward velocity of the UAV is different from zero, the mutual interactions between the natural modes of the two planes cannot be neglected anymore [25]. The motion of the longitudinal plane is described by u, w, q and θ. The motion of the UAV in the latero-directional plane is described by v, p, r, φ and ψ . Before explaining how this formulation can provide the characteristics of the natural modes of the UAV, the expression of the state-space formulation for the uncoupled planes and the structure of the state matrices are reported. The components of the state matrices are the aerodynamic derivatives of the considered UAV.

$$\{\dot{x}_{long}\} = [A_{long}]\{x_{long}\} \tag{3.3}$$

$$x_{long} = \{x_1\ x_2\ x_3\ x_4\}' = \{u\ w\ q\ \theta\}' \tag{3.4}$$

$$[A_{long}] = \begin{bmatrix} X_u & X_w & X_q & -mg \\ Z_u & Z_w & Z_q & 0 \\ M_u & M_w & M_q & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{3.5}$$

$$\{\dot{x}_{lat}\} = [A_{lat}]\{x_{lat}\} \tag{3.6}$$

$$x_{lat} = \{x_1\ x_2\ x_3\ x_4\ x_5\}' = \{v\ p\ r\ \varphi\ \psi\}' \tag{3.7}$$

$$[A_{lat}] = \begin{bmatrix} Y_v & Y_p & Y_r & mg & 0 \\ L_v & L_p & L_r & 0 & 0 \\ N_v & N_p & N_r & 0 & 0 \\ 0 & \frac{1}{\Omega} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{\Omega} & 0 & 0 \end{bmatrix} \tag{3.8}$$

The procedure to determine the characteristics of the natural modes of the UAV is here described. Helicopter motion can be considered to comprise linear combination of natural modes. Uncoupling the two planes, seven natural modes are obtained in hover condition. They are described as linearly independent and, if a single mode is excited precisely, the motion will remain in that mode only [13]. The characteristics in terms of temporal evolution, stability and amplification of each mode are provided by the eigenvalues of the state matrices, which are calculated by solving the following equations:

$$\det[A_{long} - \lambda_{long} I] = 0 \tag{3.9}$$

$$\det[A_{lat} - \lambda_{lat} I] = 0 \tag{3.10}$$

where $[I]$ is the identity matrix, the eigenvalues are the components of the two vectors λ_{long} and λ_{lat}. They are considered unknowns and their value can be only determined by solving equations 3.9 and 3.10. The expressions of the two vectors are the following:

$$\lambda_{long} = \{\lambda_p\ \lambda_{ph}\ \lambda_{ph}\ \lambda_H\}' \tag{3.11}$$

$$\lambda_{lat} = \{\lambda_r\ \lambda_{dr}\ \lambda_{dr}\ \lambda_h\ \lambda_s\}' \tag{3.12}$$

Each eigenvalue is associated to a natural mode and has the following expression:

$$\lambda_i = a + ib \tag{3.13}$$

The time evolution of the natural modes can be aperiodic or oscillatory depending on the characteristics of its associated eigenvalues. If a natural mode is oscillatory, it is associated to a conjugate complex pair of eigenvalues. Instead, if it is aperiodic, it is associated to just one single eigenvalue with null imaginary part. Moreover, the numeric entity of each eigenvalue gives important information regarding the stability and amplification of each mode. The stability of the natural mode depends on the sign of the real part of its associated eigenvalue; a mode is stable if the real part of its eigenvalue is negative. The more negative it is, the bigger is the stability margin of the considered natural mode. Accordingly, natural modes are unstable if the real part of their associated eigenvalues is positive and, when its positivity increases, the instability of the modes increases as well. Considering the imaginary part of the eigenvalue, it induces an aperiodic behaviour of the natural mode when it is equal to zero. If the imaginary part is different from zero, the time response of the natural mode is oscillatory, with a level of amplification which depends on the value of the parameter b. The greater its value, the more amplificated is the time response of the associated mode. The information regarding both the stability and the amplification of each mode can be easily visualized by means of the Root Locus (looking to Figure 3.1 as example). It is a diagram reporting on the x axis the value of the real part of the eigenvalues and on the y axis the value of the imaginary one. By looking at the root locus, it is possible to immediately collect a big amount of information regarding the dynamics of the UAV. In this thesis, the root loci of both the longitudinal plane and the latero-directional one are analysed separately. The characteristics of the natural modes of the helicopter/multirotor UAV dynamics are here described.

For the longitudinal plane, the eigenvalues are two real numbers and one conjugate complex pair. Therefore, three independent modes are distinguished: the Pitch mode, the Phugoid mode and the Heave mode.

- Pitch mode: it is represented by the first eigenvalue within the λ vector, it usually has an aperiodic time response and it mainly depends on the state variable q and θ. $\lambda_p \approx M_q$ in hover condition.
- Phugoid mode: it is represented by the conjugate complex pair in the position second and third of the λ vector. It is a periodic mode, mostly depending on u, q and θ and it is usually unstable in hover conditions.
- Heave mode: it is represented by the fourth eigenvalue of the λ vector, it is usually aperiodic, and it depends mainly on w, hence it is quite sensible to variations of vertical position. $\lambda_H \approx Z_w$ in hover condition.

For the latero-directional plane instead, the eigenvalues are three real numbers and one conjugate complex pair. In this case, four independent natural modes are obtained: the Roll mode, the Dutch Roll mode, the Heading mode and the Spiral mode.

- Roll mode: it is associated to the first eigenvalue of the vector λ, it is an aperiodic mode which depends mostly on the angular velocity p, in hover its effect is related to the dihedral effect; $\lambda_r \approx L_p$ in hover condition.
- Dutch Roll mode: it is represented by the conjugate complex pairs in the second and third position of the λ vector. It is a periodic mode and it is mainly influenced by v, φ and ψ.
- Heading mode: it is associated to the fourth eigenvalue of the vector λ and it is related to the azimuth angle ψ. Since the dynamics of the quadrotor does not change with the variation of this angle, this eigenvalue is always zero.
- Spiral mode: It is identified by the last eigenvalue of the vector λ, in hovering it depends on r and ψ and it can be calculated with the yaw damping derivative. It is an aperiodic mode. Due to the lack of tail rotor, the dynamics of the spiral mode significant differences between helicopters and multirotor UAVs. Therefore, $\lambda_s = \mathrm{N}_r$ is considered in hover conditions.

The eigenvalues analysis has central relevance in this thesis because, as reported by [32], the flying qualities of the helicopters are strongly influenced by the stability of its natural modes. Since the dynamics of the Q4E is studied by applying a helicopter model, assumption is made that the flying qualities of the Q4E are influenced by the stability of its natural modes as well.

Once the characteristics of both modes and eigenvalues were described, the complete formulation of the two systems of equations (one for the longitudinal plane and one for the latero-directional one) that are solved to calculate the state vector of the UAV is reported. A description of the parameters involved is also reported. This description begins with the expression of the linear system representing the dynamics of multirotor UAVs with respect to the longitudinal plane.

$$\{\dot{x}_{long}\} = [A_{long}]\{x_{long}\} \tag{3.14}$$

$$x_{long} = \{x_1\ x_2\ x_3\ x_4\}' = \{u\ w\ q\ \theta\}' \tag{3.15}$$

$$\begin{cases} \dot{x}_1 = \dot{u} = \dfrac{1}{m}\dfrac{\partial X}{\partial u}x_1 + \dfrac{1}{m}\dfrac{\partial X}{\partial w}x_2 + \dfrac{1}{m}\dfrac{\partial X}{\partial q}x_3 - gx_4 \\ \dot{x}_2 = \dot{w} = \dfrac{1}{m}\dfrac{\partial Z}{\partial u}x_1 + \dfrac{1}{m}\dfrac{\partial Z}{\partial w}x_2 + \dfrac{1}{m}\dfrac{\partial Z}{\partial q}x_3 \\ \dot{x}_3 = \dot{q} = \dfrac{1}{I_{yy}}\dfrac{\partial M}{\partial u}x_1 + \dfrac{1}{I_{yy}}\dfrac{\partial M}{\partial w}x_2 + \dfrac{1}{I_{yy}}\dfrac{\partial M}{\partial q}x_3 \\ \dot{x}_4 = \dot{\theta} = x_3 \end{cases} \tag{3.16}$$

Where X is the force acting with respect to the x_b axis, Z is the force acting with respect to the z_b axis of the UAV and M is the pitch momentum acting around the y axis of the UAV. m is the mass of the system, I_{yy} is its momentum of inertia with respect to the axis y_b. g is the gravitational constant. The same procedure is followed for the latero-directional plane.

$$\{\dot{x}_{lat}\} = [A_{lat}]\{x_{lat}\} \tag{3.17}$$

$$x_{lat} = \{x_1\, x_2\, x_3\, x_4\, x_5\}' = \{v\, p\, r\, \varphi\, \psi\}' \tag{3.18}$$

$$\begin{cases} \dot{x}_1 = \dot{v} = \dfrac{1}{m}\dfrac{\partial Y}{\partial v}x_1 + \dfrac{1}{m}\dfrac{\partial Y}{\partial p}x_2 + \dfrac{1}{m}\dfrac{\partial Y}{\partial r}x_3 + gx_4 \\ \dot{x}_2 = \dot{p} = \dfrac{1}{I_{xx}}\dfrac{\partial L}{\partial v}x_1 + \dfrac{1}{m}\dfrac{\partial L}{\partial p}x_2 + \dfrac{1}{m}\dfrac{\partial L}{\partial r}x_3 \\ \dot{x}_3 = \dot{q} = \dfrac{1}{I_{zz}}\dfrac{\partial N}{\partial v}x_1 + \dfrac{1}{I_{zz}}\dfrac{\partial N}{\partial p}x_2 + \dfrac{1}{I_{zz}}\dfrac{\partial N}{\partial r}x_3 \\ \dot{x}_4 = \dot{\varphi} = \dfrac{p}{\Omega} \\ \dot{x}_5 = \dot{\psi} = \dfrac{r}{\Omega} \end{cases} \tag{3.19}$$

Y is the force acting with respect to the y_b axis of the UAV, L is the roll momentum acting around the x_b axis and N is the yaw momentum acting around the z_b axis. I_{xx} is its momentum of inertia with respect to the x_b axis and I_{zz} is its momentum of inertia with respect to the z_b axis.

At this point, the aerodynamic derivatives can be introduced. Their meaning and also the formulations used to compute their value, which obviously depends on the entity of the design parameters of the UAV, are reported. The following formulations are originally thought to study the helicopters dynamics, but they can be also applied to study multirotor UAVs one. The meaning of every mentioned parameter and coefficient is also explained. The expression of the aerodynamic derivatives is taken from [13], while the explanation of their meaning can be found in [25] and [32]. Each aerodynamic derivative contains the derivation of a force or momentum with respect to a kinematic quantity. They express how the variation of the specific kinematic quantity influences the value of the considered force or momentum.

X_u is one of the so called “velocity derivatives” and in hover condition it is basically due to the tilt of the rotors to react to external perturbations of the velocity u.

$$\frac{\partial X}{\partial u} = -\rho A_b(\Omega R)^2 \frac{\partial \left({C_H}/{\sigma}\right)}{\partial \alpha_{is}} \frac{\partial \alpha_{is}}{\partial \mu} \frac{\partial \mu}{\partial \dot{x}} \tag{3.20}$$

ρ is the air density, $A_b$is the area of the blade, Ω is the rotation speed of the rotors, R is the radius of the blades. As far as the other coefficients are concerned, this is their expression:

$$\frac{\partial \left({C_H}/{\sigma}\right)}{\partial \alpha_{is}} = 1.5\frac{C_T}{\sigma}\left(1 - \frac{a}{18}\frac{\vartheta_{0,75}}{\frac{C_T}{\sigma}}\right) \tag{3.21}$$

where C_T is the thrust coefficient of the rotor, σ is the rotor solidity, $\vartheta_{0,75}$ is the pitch of the blade at the 75% of the chord and a is the angular slope of the $C_L - \alpha$ curve. C_H is the non-dimensional version of the H force, which is the resultant of the horizontal forces acting on the rotor and perpendicular to the rotor shaft. α_{is} is an approximate value of the longitudinal flapping angle assumed by the blades with respect to the rotor shaft and, particularly, it is the first harmonic coefficient used to approximate its formulation (a complete explanation and derivation of the last two parameters proposed can be found in [13]).

$$C_T = \frac{mg}{\rho A_b (\Omega R)^2} \tag{3.22}$$

$$\sigma = \frac{A_b}{\pi R^2} \tag{3.23}$$

$$\frac{\partial \alpha_{is}}{\partial \mu} = 4\vartheta_{0,75} - 2\lambda_i \tag{3.24}$$

λ_i is the inflow ratio with respect to the swashplate of the rotor and it is modelled as uniform.

$$\lambda_i = \frac{\sigma a}{16}\left(\sqrt{1 + \vartheta_{0,75}\frac{64}{3\sigma a}} - 1\right) \tag{3.25}$$

μ is the advancement ratio and has the following expression:

$$\mu = \frac{\dot{x}}{\Omega R} \tag{3.26}$$

$$\frac{\partial \mu}{\partial \dot{x}} = \frac{1}{\Omega R} \tag{3.27}$$

X_q reflects the effect of the thrust acting on the rotors in a direction which is not perfectly perpendicular to them and it represents the reaction the X force has towards a disturbance in terms of pitch angular velocity.

$$\frac{\partial X}{\partial q} = -\rho A_b (\Omega R)^2 \frac{\partial \left({}^{C_H}/_{\sigma} \right)}{\partial \alpha_{is}} \frac{\partial \alpha_{is}}{\partial q} \tag{3.28}$$

$$\frac{\partial \alpha_{is}}{\partial q} = -\frac{16}{\gamma \Omega \left(1 - \frac{e}{\Omega}\right)^2} \tag{3.29}$$

Where e is the hinge offset and γ is the Lock number.

$$\gamma = \frac{\rho A_b C_m R^4}{I_b} \tag{3.30}$$

$$I_b = \frac{m_b R^3}{3}\left(1 - \frac{e}{R}\right)^3 \tag{3.31}$$

Where C_m is the medium chord of the blade and I_b is the inertia momentum of the blade with respect to the flapping hinge and m_b is the mass of the blade.

Z_w is the heave damping derivative and it represents the effects induced by the transitory phase of vertical accelerations on the dynamics of the UAV.

$$\frac{\partial Z}{\partial w} = -\rho A_b (\Omega R) \frac{\partial \left({C_T}/{\sigma} \right)}{\partial \lambda'} \tag{3.32}$$

$$\frac{\partial \left({C_T}/{\sigma} \right)}{\partial \lambda'} = \frac{1}{\frac{8}{a} + \sqrt{\frac{\sigma^2}{2C_T}}} \tag{3.33}$$

Where λ' is the inflow ratio calculated with respect to the tip path plane.

M_u is the speed static stability derivative, and it plays an essential role to evaluate the static stability of the drone in the longitudinal plane. When the speed of the drone increases, the rotors tend to tilt back, generating a decreasing of speed. For this reason, in order to provide the UAV with a stable behaviour, its sign needs to be positive.

$$\frac{\partial M}{\partial u} = \frac{\partial M}{\partial \alpha_{is}} \frac{\partial \alpha_{is}}{\partial \mu} \frac{\partial \mu}{\partial \dot{x}} - \frac{\partial X}{\partial \dot{x}} h_m \tag{3.34}$$

Where h_m is the vertical offset of the rotor.

$$\frac{\partial M}{\partial \alpha_{is}} = \frac{3e\rho A_b a R (\Omega R)^2}{4R\gamma} \tag{3.35}$$

$$\frac{\partial X}{\partial \dot{x}} = -\rho A_b (\Omega R)^2 \frac{\partial \left({C_H}/{\sigma} \right)}{\partial \alpha_{is}} \frac{\partial \alpha_{is}}{\partial \mu} \frac{\partial \mu}{\partial \dot{x}} \tag{3.36}$$

M_w is the incidence static stability derivative. It represents how our drone reacts to disturbances in terms of angle of attack. When a disturbance in terms of incidence occurs, in order to have a stable static behaviour, drones need to react by generating a momentum which opposes itself to the first variation. Therefore, this derivative is stable when is negative.

$$\frac{\partial M}{\partial w} = \frac{\partial Z}{\partial w} l_m \tag{3.37}$$

Where l_m is diagonal wheelbase of the drone.

M_q is a damping derivative which reflects the short-term oscillating response of UAVs and it is particularly important to evaluate the characteristics of the Pitch mode.

$$\frac{\partial M}{\partial q} = \frac{\partial M}{\partial \alpha_{is}} \frac{\partial \alpha_{is}}{\partial q} - \frac{\partial X}{\partial q} h_m \tag{3.38}$$

For a quadrotor UAV in hover condition is used to have $X_w = 0$, Z_u = 0 and Z_q = 0, [33].

To explain why X_w is null in hover, it is easy to understand that, if an external disturbance induces a vertical movement of the drone, the thrust generated by each rotor does not change either its module or its direction, therefore the horizontal force X does not feel any change. The same reasoning can be made for Z_u. But this time, is the vertical force Z which is not impacted by a variation of the position of the UAV with respect to the x axis. A disturbance in terms of pitch velocity induces a disturbance in terms of vertical force which is small enough to be not considered.

Y_v is one of the so called "velocity derivatives" and in hover condition it is basically due to the tilt of the rotors to react to external perturbations of the velocity v.

$$\frac{\partial Y}{\partial v} = -\rho A_b (\Omega R)^2 \frac{\partial \left({C_H}/{\sigma}\right)}{\partial \alpha_{is}} \frac{\partial \alpha_{is}}{\partial \mu} \frac{\partial \mu}{\partial \dot{x}} \tag{3.39}$$

Y_p reflects the effect of the thrust acting on the rotors in a direction which is not perfectly perpendicular to them and it represents the reaction of Y towards a disorder in terms of roll angular velocity.

$$\frac{\partial Y}{\partial p} = -\rho A_b (\Omega R)^2 \frac{\partial \left({C_H}/{\sigma}\right)}{\partial \alpha_{is}} \frac{\partial \alpha_{is}}{\partial q} \tag{3.40}$$

L_v is one of the most important derivatives of the latero-directional plane and is called dihedral effect. It represents the influence lateral velocity has towards the generation of a Roll momentum around the x axis of the UAV. A negative value is stabilizing for this derivative.

$$\frac{\partial L}{\partial v} = -\frac{\partial M}{\partial u} = -\frac{\partial M}{\partial \alpha_{is}} \frac{\partial \alpha_{is}}{\partial \mu} \frac{\partial \mu}{\partial \dot{x}} - \frac{\partial X}{\partial \dot{x}} h_m \tag{3.41}$$

L_p is a damping derivative reflecting short-term oscillating response of our UAV and it is particularly important to evaluate the dynamic characteristics of the Roll mode.

$$\frac{\partial L}{\partial p} = \frac{\partial L}{\partial b_{is}} \frac{\partial b_{is}}{\partial p} + \frac{\partial Y}{\partial p} h_m \tag{3.42}$$

$$\frac{\partial L}{\partial b_{is}} = \frac{3e\rho A_b a R (\Omega R)^2}{4R\gamma} \tag{3.43}$$

$$\frac{\partial b_{is}}{\partial p} = -\frac{16}{\gamma \Omega \left(1 - \frac{e}{\Omega}\right)^2} \tag{3.44}$$

Where b_{is} is an approximate value of the lateral flapping angle the blades assume with respect to the rotor shaft and particularly, it is the first harmonic coefficient used to approximate its formulation.

N_r is the yaw damping derivative and in traditional helicopters its effect mainly depends on the presence of the tail rotor. For this reason, this formulation is not entirely precise to reflect the static characteristics of a multirotor UAV in terms of yaw response.

$$\frac{\partial N}{\partial r} = -\rho A_b (\Omega R)^2 \frac{C_Q}{\sigma} \tag{3.45}$$

$$\frac{C_Q}{\sigma} = \sqrt{\frac{\sigma}{2}} \left(\frac{C_T}{\sigma}\right)^{\frac{3}{2}} + \frac{C_d}{8} \tag{3.46}$$

Where C_d is the blade chord at the 75% of its length and C_Q is the torque coefficient of the rotor.

$$C_Q = \frac{Q}{\rho A_b R(\Omega R)^2} \tag{3.47}$$

Where Q is the torque acting on the rotor.

In Hover condition for a quadrotor UAV is common to have Y_r = 0, L_r = 0, N_v = 0 and N_p = 0, [33].

It is quite simple to understand why Y_r is null. A disturbance in terms of yaw velocity causes a rotation of the UAV around the z axis, but this rotation does not tilt the rotor and no variation of the lateral force Y is induced. Accordingly, a yaw ration does not cause a variation in terms of roll moment, therefore L_r is null. For the same reasons, the yaw momentum N is not affected by external disturbances in terms of both v and p. Particularly, N_v is mainly influenced by the presence of the tail rotor and also for helicopters tends to be really close to the null value in hover condition. Since Quadrotors do not have the tail rotor, the contribution of N_v becomes negligible.

The theorical model just described, is now applied to the Q4E, with the final goal of defining its characteristics in terms of stability and flying qualities.

3.2 Numerical Application – Q4E on design

In this section the analysis introduced in the previous pages is applied to the specific case considered, and the stability of the Q4E with respect to both the longitudinal plane and the latero-directional one is assessed. The first step of the calculation is reporting the design parameters of the Q4E shown in Figure 2.3.

Table 3.1 *Q4E on design parameters*

Drone weight	1900 g
Blade weight	8 g
Rotor weight	76.8 g
On-design take-off weight	3350 g
Inertia momentum around y axis	41.61 g*m^2
Inertia momentum around x axis	39.67 g*m^2
Inertia momentum around z axis	74.7 g*m^2
Radius of the blades	165.1 mm

Surface of the blades	3740 mm^2
Flight speed on design	0 m/s
Wheelbase distance	590 mm
Vertical offset of the rotor	0.30 mm
Rotor speed on design	5000<Ω<5500 RPM

The first step of the analysis is reporting the numeric value of the aerodynamic derivatives and evaluating their stability. After that, the eigenvalues proper of each plane will be calculated and the stability characteristics of its modes will be assessed. A necessary step is to introduce the following design coefficients and derivatives

Table 3.2 *Design coefficients*

$\frac{\partial C_H/\sigma}{\partial \alpha_{is}}$	$1.9042\ rad^{-1}$
$\frac{\partial \alpha_{is}}{\partial \mu}$	$0.8066\ rad$
$\frac{\partial \alpha_{is}}{\partial q}$	$-0.0057\ s$
$\frac{\partial C_T/\sigma}{\partial \lambda'}$	0.5803
$\frac{\partial M}{\partial \alpha_{is}}$	$0.7297\ \ (Kg * m^2)/(rad * s^2)$
$\frac{\partial L}{\partial b_{is}}$	$0.7297 (Kg * m^2)/(rad * s^2)$
$\frac{\partial b_{is}}{\partial p}$	$-0.0057\ s$
$\frac{C_Q}{\sigma}$	0.3238
μ	0
$\frac{\partial \mu}{\partial \dot{x}}$	$0.011\ s/m$
γ	5.1212
σ	0.0873
C_T	0.1163
λ_i	0.0677

After the evaluation of these coefficients, it is possible to calculate each derivative which is part of the two state matrixes.

Longitudinal Plane

***Table 3.3** Longitudinal plane aerodynamic derivatives on-design*

$\boldsymbol{X_u}$	$-1.1975\ Kg/s$
$\boldsymbol{X_q}$	$0.7659\ (m * Kg)/(rad * s)$
$\boldsymbol{Z_w}$	$-0.4525\ Kg/s$
$\boldsymbol{M_u}$	$0.0260\ (m * Kg)/s$
$\boldsymbol{M_w}$	$-0.1335\,(m * Kg)/s$
$\boldsymbol{M_q}$	$-0.0271\,(m^2 * Kg)/(rad * s)$
$\boldsymbol{X_u}$, $\boldsymbol{Z_u}$, $\boldsymbol{Z_q}$	0

Now, looking at the stability derivatives involved in the longitudinal plane, it is possible to evaluate the static stability of the Q4E.

***Table 3.4** Longitudinal plane static stability summary*

	$\boldsymbol{M_u}$	$\boldsymbol{M_w}$
Stability sign	+	-
Actual sign	+	-
Result	Stable	Stable

As far as the longitudinal plane is concerned, the two main derivatives which influence the static stability of the Q4E are M_u and $M_{w,}$ which are called speed and incidence static stability derivatives. The fact that M_u is positive means that in case of a perturbation in horizontal speed, the UAV will react with a nose down moment, which will decrease the velocity itself. The minus sign of the incidence static stability means that if the UAV is subject to a decrease of the angle of attack, it reacts with a nose down moment which works against the first variation. This specific behaviour is critical to assure the static stability of our drone in the longitudinal plane [32]. Looking at their numerical value, the speed stability derivative is really close to the null value, which means that little external disturbances could induce its value to become negative, compromising the stability of the drone. The stability margin of M_w is consistent instead. Regardless of their on-design value, It's obviously important to study how its stability changes with respect to design parameters variation.

Once the state matrix for the longitudinal plane is built, it is possible to calculate the eigenvalues to study the stability characteristics of each natural mode. The stability and amplification of each natural mode can be easily and quickly visualized by means of the Root Locus.

***Table 3.5** Longitudinal plane eigenvalues on design*

λ_p	-2.2163 + 0.0000i
λ_{ph}	0.6034 + 1.5495i
λ_{ph}	0.6034 - 1.5495i
λ_h	-0.1351 + 0.0000i

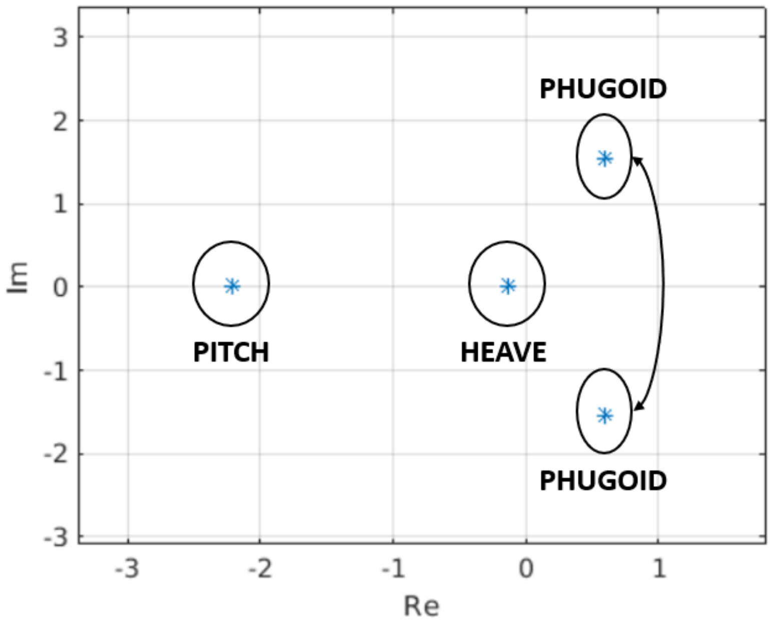

***Figure 3.2** Root locus longitudinal plane on-design*

From this first analysis emerges that on design conditions the longitudinal plane has two stable modes: The Pitch one and the Heave one. Instead, the Phugoid mode is unstable.

Latero-directional Plane

Table 3.6 *Latero-directional plane aerodynamic derivatives on-design*

$\boldsymbol{Y_v}$	$-1.1975\ Kg/s$
$\boldsymbol{Y_p}$	$-0.7659\ (m * Kg)/(rad * s)$
$\boldsymbol{L_v}$	$-0.0260\ (m * Kg)/s$
$\boldsymbol{L_p}$	$-0.0271\ (m^2 * Kg)/(rad * s)$
$\boldsymbol{N_r}$	$7.5551\ (m^2 * Kg)/(rad * s)$
$\boldsymbol{Y_r}, \boldsymbol{N_v}, \boldsymbol{N_p}$	0

By looking at the sign of the aerodynamic derivatives introduced before, it is possible to evaluate the static stability of the Q4E with respect to the latero-directional plane.

Table 3.7 *Latero-directional plane static stability summary*

	$\boldsymbol{L_v}$	$\boldsymbol{N_r}$
Stability sign	-	-
Actual sign	-	+
Result	Stable	Unstable

As far as the latero-directional plane is concerned, the two main derivatives which need to be evaluated are L_v and N_r, which are also known as the dihedral effect and the yaw damping derivative. The first derivative determines a response in terms of roll angle to a lateral velocity disturbance, and the negative sign means that the UAV reacts opposing the roll moment to the speed variation, assuming a stable behaviour. Coming to the second derivative, it is supposed to be a damping derivative, therefore negative [32]. Since it is positive, it means that it reacts to a perturbation in angular velocity around the z-axis with a growing moment around the same-one. Analysing a normal helicopter, the main effects behind the value of this derivative are related to the tail rotor, which is clearly not present in UAVs. Due to the lack of tail rotor, the formulation used to calculate N_r is not totally accurate and its value is only indicative of the real behaviour of the Spiral mode. Anyway, from experimental flights with the Q4E, the Spiral mode was proven to be clearly unstable. Therefore, the value obtained for N_r may be not extremely accurate but is fore sure a good representation of the unstable behaviour assumed by the Spiral mode.

Applying the same procedure followed for analysing the longitudinal plane, the eigenvalues characteristics of the latero-directional dynamics of the Q4E can be calculated. Thus, the stability of each natural mode can be studied.

Table 3.8 *Latero-directional plane eigenvalues on-design*

λ_r	-0.9550 + 0.0000i
λ_{dr}	-0.0431 + 0.1020i
λ_{dr}	-0.0431 - 0.1020i
λ_H	0.0000 + 0.0000i
λ_s	7.5551 + 0.0000i

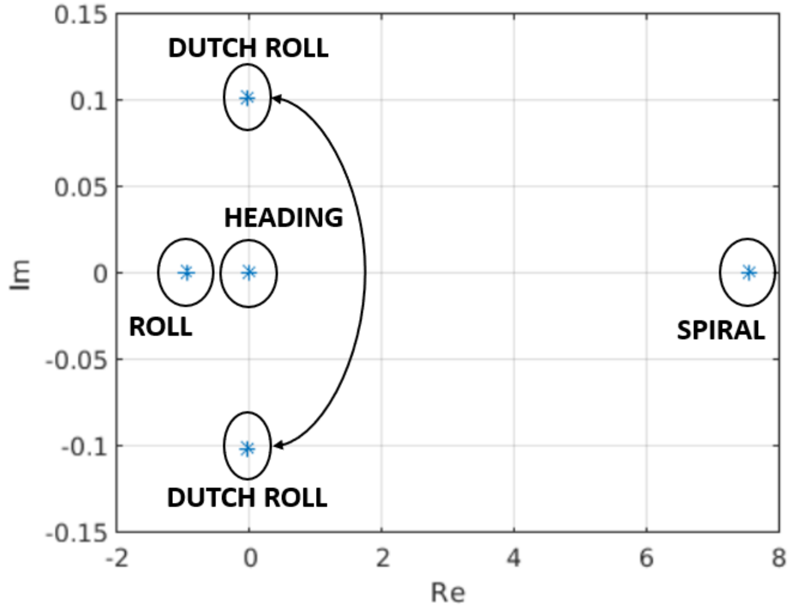

Figure 3.3 *Root locus latero-directional plane on-design*

As far as the latero-directional plane is concerned, two modes are actually stable: the Roll one and the Dutch Roll one. The Heading mode is neutral. The last natural mode, the Spiral one, is largely positive and therefore unstable.

By calculating the eigenvalues of the Q4E on-design conditions, it is possible to assign a level of flying qualities to the natural modes of the Q4E. Three different levels of flying qualities are assigned with reference to the standard identified by the modified Cooper Harper rating scale [14]. A level 1, which [14] identifies as an "excellent and highly desirable" way of flying is assigned to the natural modes of the UAV when they are largely stable. A level 2, which in [14] is identified as a "good with negligible deficiencies" way of flying is assigned when the real part of the eigenvalues is really close to the null value (either when the real part is slightly positive or slightly negative). A level 3, which in [14] is identified as a "fair with unpleasant deficiencies" way of flying is assigned when the real parts of one or more eigenvalues is clearly negative, inducing the associated natural mode to be unstable. In this analysis, the assigned levels of flying qualities are addressed to the specific natural mode of the UAV. By looking first to the longitudinal plane, the flying qualities of both the Heave mode and the Pitch one are associated to level 1 because they have a significant stability margin. The Phugoid mode instead obtains a Level 3 of flying qualities due to the large positivity of the real parts of its associated eigenvalues. Regarding the latero-directional plane, the Roll mode is clearly stable and consequently associated to Flying qualities of level 1. The eigenvalues of the Dutch Roll mode have slightly negative real parts, therefore its flying qualities can be assigned to level 1 or level 2, a precise distinction is impossible to made. Finally, λ_s has a deeply positive real part and the flying qualities of the Spiral mode are undoubtedly assigned to Level 3. The boundaries between the different levels of flying qualities are not defined with respect to the on-design conditions. In order to define the borders between one level and the other, the evolution of the eigenvalues as a function of the aerodynamic derivatives is studied. In this way, it is possible to identify an interval of variation of the eigenvalues and, depending on the development of their stability margin, a level of flying qualities is assigned.

3.3 Flying Qualities parametric analysis

The final goal of the following parametric analysis is to understand how the design of the Q4E can be changed to improve its flying qualities. Firstly, before discussing the design variations, the procedure followed to evaluate the flying qualities is presented. As proven by [1] and [17], adapting standard criteria to evaluate the flying qualities of UAV does not produce satisfactory results. Moreover, as stated by [32], the flying qualities of helicopters and UAVs are deeply impacted by the stability of their natural modes. For these two reasons, the flying qualities of the Q4E are evaluated relying on the stability of its natural modes. Generally, the bigger is the stability margin of each mode, the better are the flying qualities of the UAV. Therefore, a level of flying qualities is assigned to each natural mode of the UAV. Then, the judgement regarding the level of flying qualities is linked to both the eigenvalues and the aerodynamic derivatives. Particularly, the judgement of the flying qualities related to a specific mode is assigned depending on the value assumed by certain aerodynamic derivatives. By looking to the values assumed by a specific aerodynamic derivative, our framework lets define the level of the flying qualities associated to a specific mode. The first step of this analysis is to assign a specific level of flying qualities to the values assumed by certain aerodynamic derivatives which have the predominant influence on the natural modes of the Q4E. Firstly, a list of the aerodynamic derivatives taken as reference to evaluate the stability of each mode is reported. As it was previously illustrated, as far as the longitudinal plane is concerned, the characteristics of the pitch mode are basically related to the derivative M_q and the ones of the heave mode depend mainly on Z_w. The Phugoid mode is not specifically influenced by a single derivative and its characteristics are consequently studied by means of the derivatives M_q and M_v, which are the ones most influencing its dynamics. Discussing now the latero-directional plane dynamics, the Heading mode is always null in hover, the Spiral mode is associated to N_r and the Roll one to L_p. It is impossible to determine one single aerodynamic derivative influencing the Dutch roll mode and its characteristics are analysed with respect to the derivatives L_p and L_v. In the following lines the procedure used to assign a level of flying qualities to a specific range of values of the aerodynamic derivatives is described. According to [18], the evaluation of the flying qualities is intended as a study of how much “the behaviour and the controllability of the UAV is adequate for completing the mission without any complications". The first step of this analysis is to induce each aerodynamic derivative to vary around its design value. Then, for each value assumed by the aerodynamic derivative, the eigenvalues of the Q4E are calculated again, and the main focus is put on the eigenvalues which were affected by the variation of that specific derivative. In this method, the assignment of flying quality levels depends just on the stability of its mode, hence on the sign of the real part of the associated eigenvalues. The evolution of the real parts of the interested eigenvalues is plotted against the variation of the selected aerodynamic derivative in order to study the variation of the static margin associated to each mode. Obviously, an increase of the static margin improves the level of quality of the flight. Following this procedure, a certain number of intervals were identified, and a level of flying qualities was assigned to each of them. Following this procedure, it is possible to study how the stability of all the natural modes is influenced by the variation of specific aerodynamic derivatives. In details, these are the results of the analysis.

The analysis starts by assessing the flying qualities related to the Heave mode by means of the derivative Z_w. Its nominal value is -0.4495 and it is varied between -1.5 and 0.5. A first observation is that only the Heave mode is influenced by the variation of Z_w. The flying quality levels are expressed with the criterion previously explained; the level 1 is obtained when Z_w is minor than -0.15, the level 2 is assigned for values of Z_w between -0.15 and 0.15, level 3 is reached when Z_w is greater than 0.15. Reference is made to Figure 3.4. The variation of the derivative M_q is now considered and the information it provides about the stability of the Pitch mode (which strictly depends on this derivative) and of the Phugoid one can be derived. The nominal value of M_q is -0.0273 and it is varied between -0.15 and 0.07. According with the traditional behaviour of helicopters and UAVs in hover condition, the phugoid mode is unstable for all the variation interval of M_q considered. For this reason, in the interval proposed there are no conditions where a level 1 of flying qualities can be assigned to the Phugoid mode. Level three is assigned for M_q greater than -0.08, a level 2 is assigned for values of M_q between -0.15 and -0.08. Instead, as shown in Figure 3.5, the Pitch mode always has a stability margin greater than zero and its flying qualities are always of level 1. The variation interval was not extended further because the difference with the on-design value would have been too high. Anyway, Figure 3.5 shows that the real part of λ_{ph} is slowly decreasing, approaching the null value and thus the stable condition. Anyway, this situation would occur for value of M_q which are very far from the on-design conditions and therefore are not of our interest. Finally, the variation of M_u and its influence over the flying qualities of the longitudinal plane natural modes can be considered by means of Figure 3.6. Firstly, it is important to notice that, for values of M_u minor than zero, the Phugoid mode and the Pitch one are combined in a unique stable oscillatory mode. The evolution of the real part of the eigenvalues associated to the Phugoid mode is quite slow in all the interval considered, despite for a small range of values around the null value of M_u. In this layer the flying qualities of the Phugoid mode are assigned to level 2, instead, level 1 is assigned in association to negative values of the considered derivative and level 3 is assigned in correspondence to positive values of M_u. It is insightful to notice that M_u is stable in static condition when it is greater than zero, but this condition induce the Phugoid mode to be unstable, compromising the flying qualities of the Q4E. Unfortunately, In the prosecution of this chapter is shown that no design parameter can induce M_u or M_q to vary so much that the Phugoid mode becomes stable, therefore its flying qualities are always assigned to a level 3. The instability of the Phugoid mode is a situation common to every helicopter and UAV in hover condition, this natural mode tends to become stable when the vehicle acquire a horizontal velocity different from zero.

A brief explanation of how the Figures 3.5-3.8 have to be read is given. The black vertical lines define the intervals associated to each level of flying qualities. The numbers inside the circles represent the flying qualities levels assigned to each interval identified by the vertical lines. In Figure 3.5 and 3.6, since the Pitch mode is always stable, the vertical lines identify the intervals of the different flying quality levels assigned to the Phugoid mode. Blue colour is used for the flying qualities of the Pitch mode and red colour is used for the ones of the Phugoid mode.

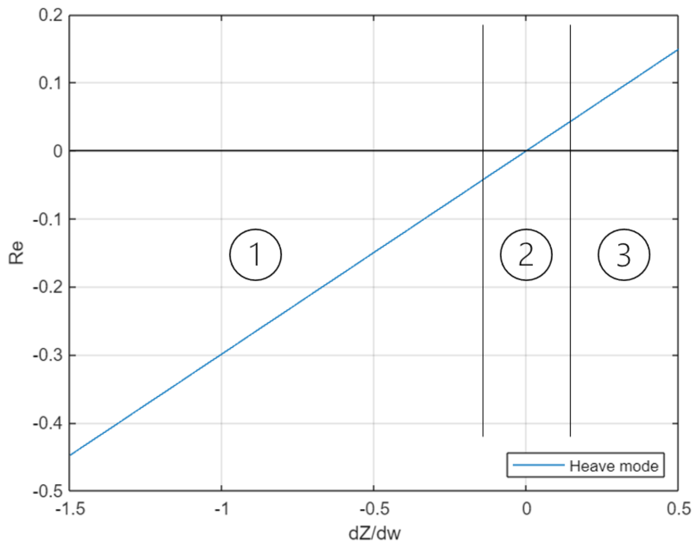

Figure 3.4 *Influence of dZ/dw on the Heave mode stability*

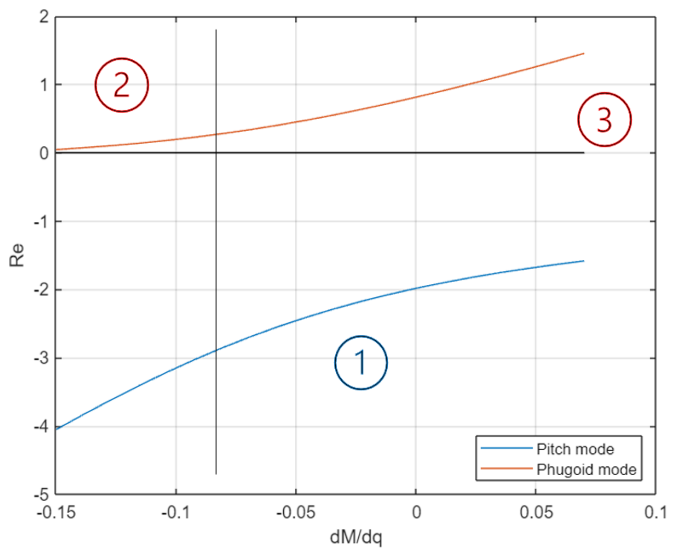

Figure 3.5 *Influence of dM/dq on longitudinal plane natural modes*

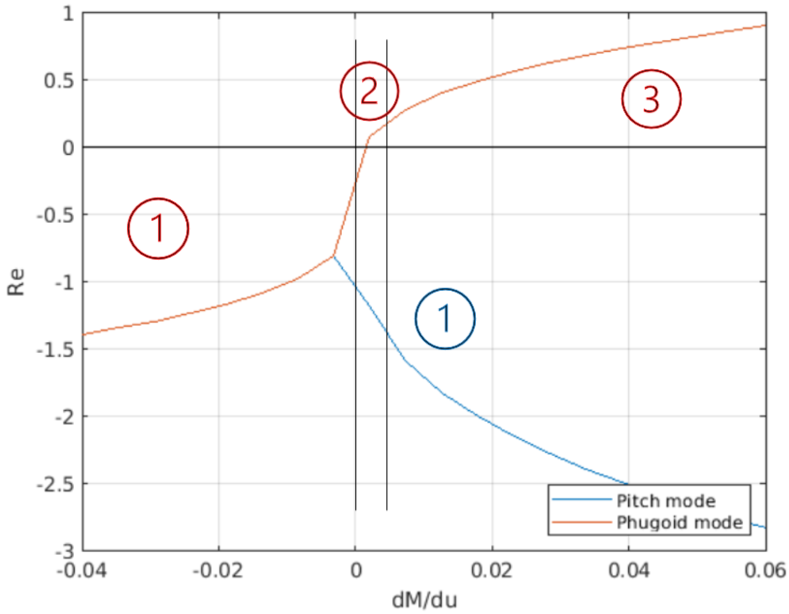

Figure 3.6 *Influence of dM/du on longitudinal plane natural modes*

The latero-directional plane is now considered. The characteristics of the spiral mode are associated to the derivative N_r which has an on-design value equal 7.551 and it is therefore clearly unstable. No variation interval is needed to assign a level 3 to the flying qualities of the Spiral mode. The flying qualities of the Roll mode are mainly influenced by L_p. Its nominal value is -0.0273 and, as illustrated in Figure 3.7, its variation is considered between -0.060 and 0.04, influencing the stability of the Roll mode and the Dutch roll one. Starting with the characteristics of the Roll mode, the real part of λ_r is negative for a big portion of the variation interval and the increases suddenly becoming positive. Level 1 on flying qualities is assigned before 0.019 , level 2 between 0.019 and 0.021 , level 3 for values of L_p greater than 0.021. The behaviour of the Dutch roll mode is more complicated. For values of L_p between -0.04 and -0.002 the structure of the eigenvalues is the usual one: λ_2 and λ_3 are a conjugate complex pair and λ_1 has null imaginary part. Instead, when L_p is either minor than -0.04 or greater than -0.002 all the three modes have non-periodic behaviour with null imaginary part. Level 1 of flying qualities is assigned to the Dutch roll mode when L_p is between -0.05 and -0.028 because all the eigenvalues clearly have neative real part. Level 2 is assigned when L_p either is minor than -0.05 or is between -0.028 and -0.007, in these intervals at least one eigenvalue has real part extremely close to the null value. When L_p is greater than -0.007 level 3 is assigned.

The derivative L_v is now considered. Its nominal value is -0.0260 and it is varied between -0.060 and 0.4. Before discussing the level of flying qualities assigned to each interval, it is useful to describe the evolution of the three modes. For values of L_v minor than -0.018 the shape of the eigenvalues is the usual one: λ_2 and λ_3 are a conjugate complex pair and λ_1 has null imaginary part. For L_v greater than -0.018 but minor than 0.08 the three eigenvalues all have null imaginary part. For L_v greater than 0.08 λ_1 and λ_2 form a conjugate complex pair while λ_3 has null imaginary part and a non-periodic behaviour. The values assumed by L_v are used to evaluate the flying qualities of the Dutch Roll mode. Level 1 is assigned when L_v is between -0.028 and -0.012 because all the eigenvalues have clearly negative real parts. Level 2 is assigned for two different intervals where at least one eigenvalue is really close to the null value: between -0.045 and -0.028 and between -0.012 and 0.017. In the end, level three is assigned when L_v is either minor than -0.045 or bigger than 0.017, In these intervals at least one real part of the three considered eigenvalues is clearly negative and their associated mode is unstable. Reference is made to Figure 3.8.

Blue colour is used for the flying qualities of the Roll mode and red colour is used for the ones of the Dutch Roll mode. In Figure 3.7 the three vertical lines on the left are referred to the Dutch Roll mode, the two on the right to the Roll one. In Figure 3.8 all the vertical lines are used to identify the flying qualities levels of the Dutch Roll mode.

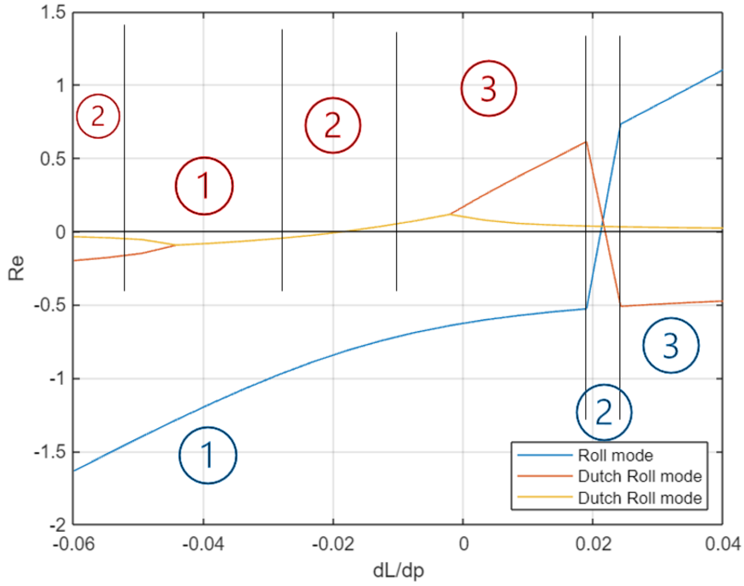

Figure 3.7 *Influence of dL/dp on latero-directional plane natural modes*

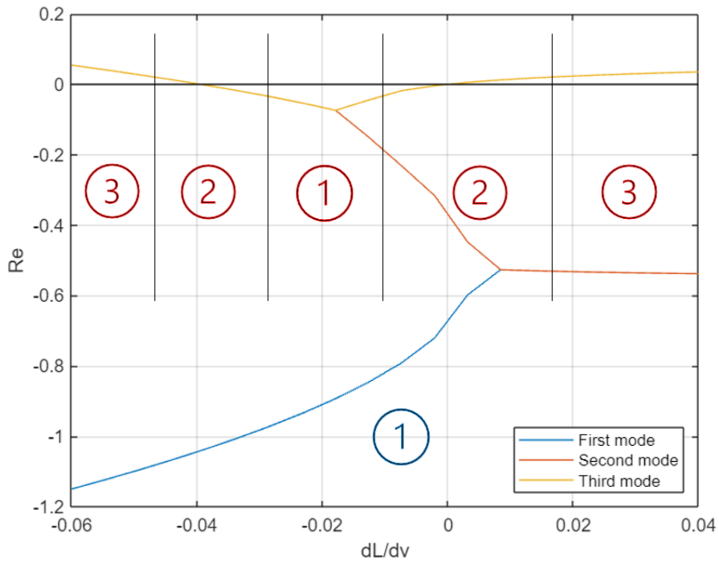

Figure 3.8 *Influence of dL/dv on latero directional plane natural modes*

The evaluation of the flying qualities levels is to be considered valid only for the values assumed by the derivatives in the intervals above declared. The analysis was not extend to a bigger interval because it would have induced the derivatives to assume values too far from the conditions on-design.

Table 3.9 *Flying qualities levels summary*

Natural Mode	Level 1	Level 2	Level 3
Heave	$Z_w < -0.15$	$-0.15 < Z_w < 0.15$	$Z_w > 0.15$
Phugoid	/	$M_q < -0.08$	$M_q > -0.08$
Phugoid	$M_u < -0.005$	$-0.005 < M_u < 0.005$	$M_u > 0.005$
Pitch	$-0.15 < M_q < 0.007$	/	/
Roll	$L_p < 0.019$	$0.019 < L_p < 0.21$	$L_p > 0.21$
Dutch Roll	$-0.028 < L_v < -0.012$	$-0.045 < L_v < -0.028$ $-0.012 < L_v < 0.017$	$L_v < -0.045$ $L_v > 0.017$
Dutch Roll	$-0.05 < L_p < -0.028$	$L_p < -0.05$ $-0.028 < L_p < 0.07$	$L_p > 0.07$
Spiral	$N_r < -0.5$	$-0.5 < N_r < 0.5$	$N_r > 0.5$

This analysis is used in the prosecution of the chapter to evaluate the development of flying qualities induced by the variation of design parameters. The characteristics of the parametric analysis and the analysis developed to figure out the evolution of the flying qualities of the Q4E are presented in the following pages.

Since procedure shown by [18] and [19] is followed in order to improve the stability of the Q4E, this parametric analysis is essential to completely map the effect that the variation of the design parameters has towards the flying qualities of the drone. Once a complete understanding of the effects of these variations is obtained, it is possible to customize a specific strategy oriented to improve specific performances of the UAV regarding the assigned missions. Between all the design parameters, there are some which are characteristic of the drone and can only be selected during the first design phase. Other design parameters can be changed depending on the specific mission and sometimes the mission itself requires a change in the design of the UAV (i.e. different missions with different payload implies different total weight of the UAV).

The target parameters which are varied are the mass of the UAV, the radius of its blades, the angular velocity of the rotors and the vertical offset of the rotors.

- Mass variation: there are several different reasons to change the mass of the whole UAV and almost every different mission needs a specific mass configuration. Mass variations can be addressed to a variation of the Payload, to a different type of battery or power source or to the selection of different type of materials. In fact, the mass variation can be seen both as a design solution and as a solution forced by external factors.

- Blade radius variation: the length of the blade radius is a property of the rotor. Usually, this parameter is selected at the beginning of the project, to assess which dimension is a better fit for the considered UAV. A Drone can be designed to fly with two or three nominal value of the blade radius but it is impossible to decide, depending on the requirements of the mission, which is the better radius to assign to the blade.

- Rotors speed variation: the speed of the rotors is defined on-design and then it can be changed within a certain range of limitation. Moreover, a variation of the rotor speed is requested also in the transitory phases of the landing and the take-off.

- Vertical offset variation: this value is not a design parameter, and it can be critically changed depending on the characteristic of the payload. The heavier is the payload, the lower will be the position of the centre of gravity of the system.

In order to evaluate how the variation of the proposed design parameters impacted the flying qualities of the Q4E, the evolution of the natural modes is analysed by means of the aerodynamic derivatives and the eigenvalues. For each varied design parameter, the evolution of the main aerodynamic derivatives and of the eigenvalues is analysed and plotted by means of the root loci. Particularly, the analysis summarized in Table 3.9 is used to assign a flying quality level to each mode depending on the evolution of the principal aerodynamic derivative as a function of the design parameter. Moreover, the evolution of the natural modes is summarized by the root locui and is exploited to get an overview regarding the global evolution of the flying qualities of the Q4E. This parametric analysis starts by considering the effects of the mass variation.

3.3.1 Mass variation

- Design parameter: m = 3.35 Kg
- Parameter Variation: 2.35 ÷ 4.35 Kg
- Design Coefficients affected: I_b, C_T, $\frac{dC_H/\sigma}{d\alpha_{is}}$, $\frac{dC_T}{dL}$, $\frac{C_Q}{\sigma}$
- Aerodynamic Derivatives affected: X_u , X_q, Z_w, M_w, M_q, Y_v, Y_p, L_p, N_r

Eleven values of the mass parameter within the interval mentioned above are considered and, for each of them, the new values of both the aerodynamic derivatives and the eigenvalues are calculated. These new values are analysed to assess how the mass can be changed to improve the flying qualities of the Q4E, stabilizing its natural modes. In Table 3.10, the interval of variation of the aerodynamic derivatives induced by the mass variation is reported along with the evolution of their margin of stability.

***Table 3.10** Effect of the mass variation on the aerodynamic derivatives*

	Interval of variation	**Margin of Stability**
m	2.35 ÷ 4.35	
X_u	-0.8288 ÷ -1.5831	
X_q	0.5300 ÷ 1.0125	
Z_w	-0.4504 ÷ -0.4488	
M_q	-0.0200 ÷ -0.0345	
M_w	-0.1329 ÷ -0.1324	decrease
Y_v	-0.8288 ÷ -1.5831	
Y_p	-0.5300 ÷ -1.0125	
L_p	-0.0200 ÷ -0.0345	
N_r	4.4939 ÷ 11.2171	decrease

In Table 3.11, the flying quality levels assigned to each natural mode are classified depending on the value assumed by its related aerodynamic derivatives.

***Table 3.11** Aerodynamic derivatives influence on natural modes, mass variation*

Natural Mode	**Flying quality level**
Heave	Z_w – Level 1
Pitch	M_q – Level 1
Phugoid	M_q – Level 3 M_u – on-design conditions Level 3
Roll	L_p – Level 1
Dutch Roll	L_v – Level 1 – constant on-design condition L_p – From level 1 to level 2

Spiral	N_r – Level 3

The only aerodynamic derivative whose variation range can induce significant changes in the FQ level assigned to the associated mode is L_p. In Figure 3.9, 3.12 and 3.17 the horizontal black lines identify, according with Table 3.9, the interval of the considered aerodynamic derivative for which a specific flying quality level is assigned. The intersection between the coloured lines and the horizontal black ones identifies the value of the design parameter which determines the change of the flying quality level assigned to the considered natural mode.

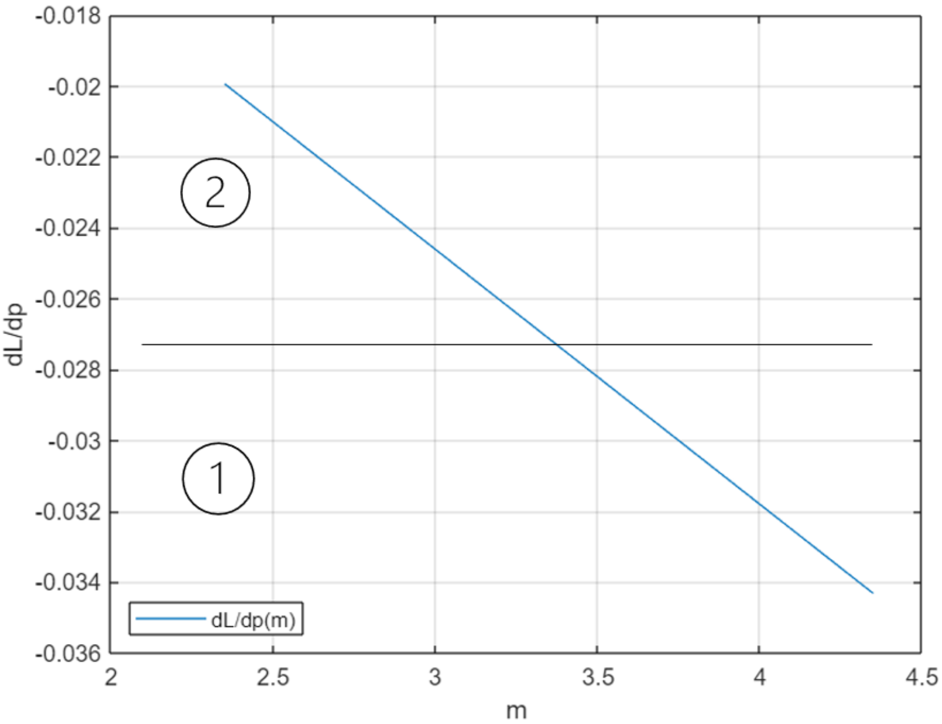

Figure 3.9 *Influence of mass variation on dL/dp*

As it is shown by Table 3.11, the variation of Z_w determines level 1 flying qualities of the Heave mode for the whole considered interval. All the variation interval of M_q induces the Phugoid mode to have flying qualities of level 3 and the Pitch mode to have flying qualities of level 1. M_u is not affected by the mass variation and its value is constant in providing the phugoid mode with level 1 of flying qualities. The Roll mode is stable in level 1 of flying qualities due to the variation of L_p. The evolution of the Dutch Roll mode is more complicated. As stated before, L_p and L_v are considered as the main factors influencing the Dutch Roll mode. The mass variation does not affect L_v and this derivative induced level 1 flying qualities for the considered mode on-design conditions. Analysing the variation of L_p, it generates flying qualities of level 1 for $m < 3{,}45$ and flying qualities of level 2 when the mass exceeds this threshold. Discussing the flying qualities of the spiral mode by means of the derivative N_r, it is easy to understand that the spiral mode is always largely unstable end therefore its flying qualities are assigned to level 3. It is worthy to observe that the lowest considered mass values can actually determine a significant reduction of the instability margin of the spiral mode by notably decreasing the positive value of N_r.

At this point, a complete evaluation of the flying qualities of the Q4E can be obtained by analysing how the eigenvalues vary in response of the mass variation.

The numerical entity assumed by the four eigenvalues of the longitudinal plane as a function of the eleven values of the mass parameter is reported in Table 3.12.

Table 3.12 *Mass variation influence on longitudinal plane eigenvalues*

	λ_p	λ_{ph}	λ_{ph}	λ_H
m_1	-2.1464 + 0.0000i	0.6586 + 1.5561i	0.6586 - 1.5561i	-0.1929 + 0.0000i
m_2	-2.1603 + 0.0000i	0.6473 + 1.5549i	0.6473 - 1.5549i	-0.1777 + 0.0000i
m_3	-2.1742 + 0.0000i	0.6361 + 1.5537i	0.6361 - 1.5537i	-0.1647 + 0.0000i
m_4	-2.1881 + 0.0000i	0.6251 + 1.5524i	0.6251 - 1.5524i	-0.1535 + 0.0000i
m_5	-2.2022 + 0.0000i	0.6142 + 1.5510i	0.6142 - 1.5510i	-0.1437 + 0.0000i
m_6	-2.2163 + 0.0000i	0.6034 + 1.5495i	0.6034 - 1.5495i	-0.1351 + 0.0000i
m_7	-2.2306 + 0.0000i	0.5928 + 1.5479i	0.5928 - 1.5479i	-0.1274 + 0.0000i
m_8	-2.2449 + 0.0000i	0.5823 + 1.5462i	0.5823 - 1.5462i	-0.1206 + 0.0000i
m_9	-2.2594 + 0.0000i	0.5718 + 1.5444i	0.5718 - 1.5444i	-0.1144 + 0.0000i
m_{10}	-2.2741 + 0.0000i	0.5615 + 1.5426i	0.5615 - 1.5426i	-0.1089 + 0.0000i
m_{11}	-2.2888 + 0.0000i	0.5513 + 1.5406i	0.5513 - 1.5406i	-0.1038 + 0.0000i

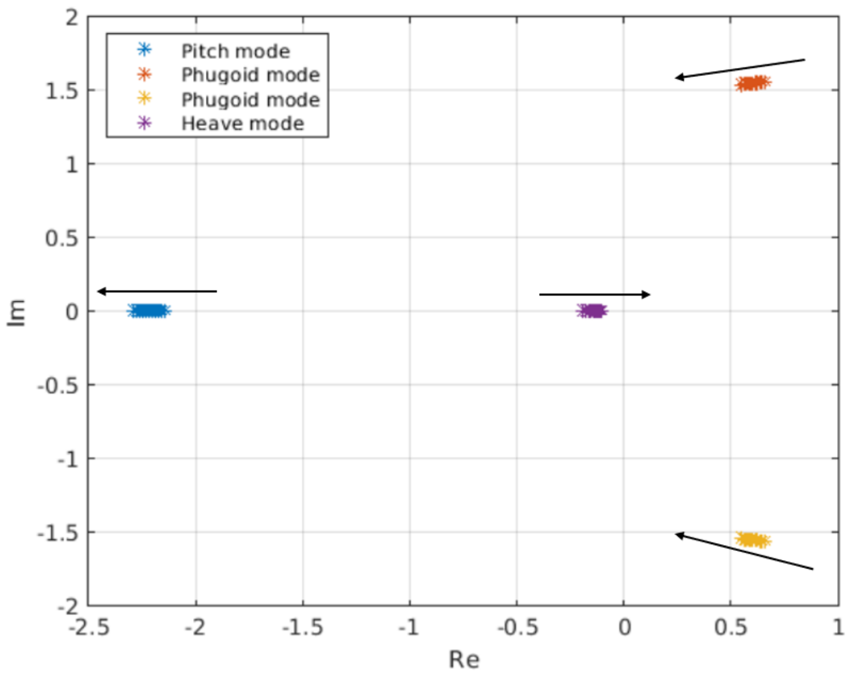

Figure 3.10 *Influence of mass variation on longitudinal plane natural modes*

The numerical entity assumed by the five eigenvalues of the latero-directional plane as a function of the eleven values of the mass parameter are reported in Table 3.13.

Table 3.13 Mass variation influence on latero-directional plane eigenvalues

	λ_r	λ_{dr}	λ_{dr}	λ_h	λ_s
m_1	-0.8345 + 0.0000i	-0.0091 + 0.1181i	-0.0091 - 0.1181i	0.0000 + 0.0000i	4.4666 + 0.0000i
m_2	-0.8576 + 0.0000i	-0.0166 + 0.1157i	-0.0166 - 0.1157i	0.0000 + 0.0000i	5.0400 + 0.0000i
m_3	-0.8812 + 0.0000i	-0.0238 + 0.1128i	-0.0238 - 0.1128i	0.0000 + 0.0000i	5.6364 + 0.0000i
m_4	-0.9053 + 0.0000i	-0.0306 + 0.1095i	-0.0306 - 0.1095i	0.0000 + 0.0000i	6.2548 + 0.0000i
m_5	-0.9299 + 0.0000i	-0.0370 + 0.1059i	-0.0370 - 0.1059i	0.0000 + 0.0000i	6.8946 + 0.0000i
m_6	-0.9550 + 0.0000i	-0.0431 + 0.1020i	-0.0431 - 0.1020i	0.0000 + 0.0000i	7.5551 + 0.0000i
m_7	-0.9807 + 0.0000i	-0.0489 + 0.0977i	-0.0489 - 0.0977i	0.0000 + 0.0000i	8.2356 + 0.0000i
m_8	-1.0068 + 0.0000i	-0.0544 + 0.0931i	-0.0544 - 0.0931i	0.0000 + 0.0000i	8.9355 + 0.0000i
m_9	-1.0335 + 0.0000i	-0.0596 + 0.0882i	-0.0596 - 0.0882i	0.0000 + 0.0000i	9.6543 + 0.0000i
m_{10}	-1.0607 + 0.0000i	-0.0645 + 0.0829i	-0.0645 - 0.0829i	0.0000 + 0.0000i	10.3916 + 0.0000i
m_{11}	-1.0883 + 0.0000i	-0.0691 + 0.0773i	-0.0691 - 0.0773i	0.0000 + 0.0000i	11.1469 + 0.0000i

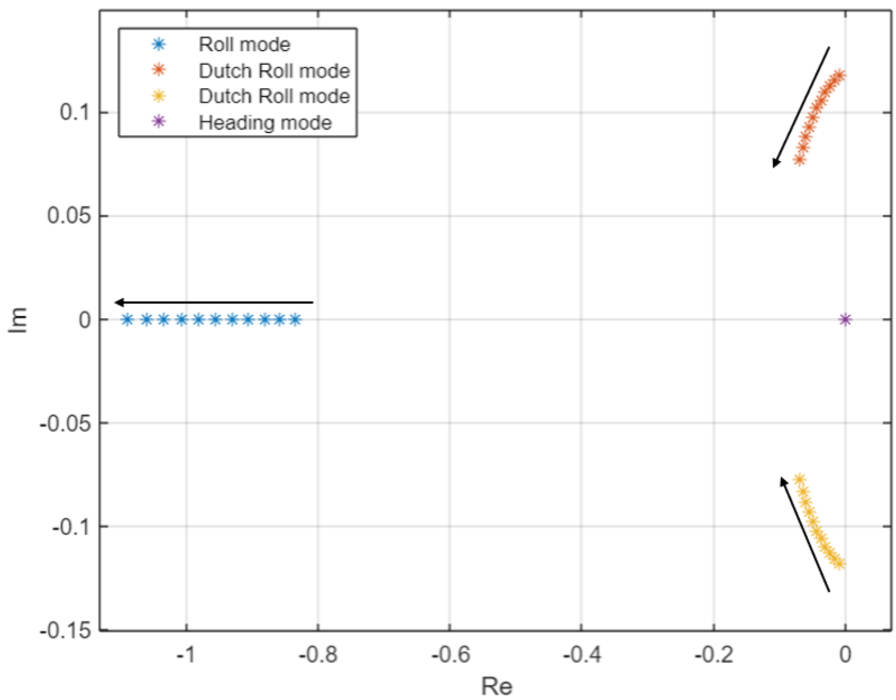

Figure 3.11 Influence of mass variation on latero-directional plane natural modes

Table 3.14 is exploited to see how the mass variation influences each mode, whose variation percentage is calculated with respect to the associated eigenvalues with the formulation presented in equation 3.48.

$$SMV1\%_i = \frac{Re(\lambda_{i-11}) - Re(\lambda_{i-1})}{Re(\lambda_{i-6})} \tag{3.48}$$

Where $\lambda_{i/11}$ and $\lambda_{i/1}$ are the eigenvalues characteristics of the limit values of the mass interval and $\lambda_{i/6}$ is the eigenvalue associated to on-design condition (the vector associated to the mass variation is built making the sixth element equal to the on-design condition.)

Table 3.14 *Mass variation influence on natural modes*

Mode	Stability Margin	$SMV1\%$	Stable
Pitch	increase	+ 6.4%	Yes
Phugoid	decrease	+ 17.8%	No
Heave	decrease	- 66%	Yes
Roll	increase	+ 26%	Yes
Dutch Roll	increase	+ 139%	Yes
Heading	decrease	0	Yes
Spiral	decrease	- 88%	No

The variations reported in this table and their representation on the Root loci are used to obtain a global overview of the effect of the mass variation over the dynamic behaviour and the flying qualities of the Q4E. Considering first the longitudinal plane, the Heave mode is the most influenced one and its eigenvalues approaches the null value when the mass increases, reducing the margin of stability of the Heave mode. Instead, the margin of stability of both the Pitch mode and the Phugoid one slightly increases without sensibly modifying the overall stability of the Q4E. Regarding the Phugoid mode, its oscillatory time response becomes less amplificated when the mass of the drone is decreased. Considering now the evolution of the natural modes associated to the latero-directional plane, the Dutch Roll mode is deeply influenced by the mass variation: its stability is enhanced by high values of mass and is almost compromised for low values of the mass of the Q4E. It is also clear that increasing the mass of the drone induce the oscillatory time response of the Dutch Roll mode to be less amplificated. The margin of stability of the Roll mode is instead always large and its stability is not much affected by changing the value of the mass parameter. Considering now the Spiral mode, it is clearly unstable for all the proposed mass values and, even though its margin of stability increases for smaller mass values, it remains extremely distant from the stability condition. Summarizing how the overall flying qualities and stability of the Q4E is influenced by the mass variation, increasing the mass can be useful to improve the flying qualities of the Phugoid mode (decreasing its instability) but has a negative impact on the Heave mode (which approaches the instability boundary) and on the Spiral mode (which becomes even more unstable). Conversely, reducing the mass of the Q4E can improve the flying qualities related to the Spiral mode, reducing its margin of instability, but at the same time it induces a less stable behaviour of the Phugoid mode (which becomes even more unstable) and the Dutch Roll mode (which approaches the instability condition). Discussing about the mass variation, it is important to underline that flying with different mass properties can be imposed by the characteristics of the mission, requiring for example a different payload. Therefore, the mass parameter is not chosen specifically to improve the flying qualities of the UAVs, but it is often imposed by external condition. Moreover, heavier is the drone, bigger is the power supply it needs to fly and more complicated becomes the equipment it needs. For this reason, it is impossible to select too high mass values. The mass parameter is usually imposed by external factors and mission requirements. Hence, the other design parameters can be changed in order to mitigate the negative effects induced by the mass variation on the UAV flying qualities.

3.3.2 Blade radius variation

- Design Value: R = 0.1651 m
- Parameter Variation: 0.1150 ÷ 0.2150 m
- Design Coefficients affected: σ, A_b, C_T, σ, A_b, C_T, $\frac{dC_H/\sigma}{d\alpha_{is}}$, $\frac{d\alpha_{is}}{d\mu}$, $\frac{dC_T}{dL}$, $\frac{dM}{d\alpha_{is}}$, $\frac{d\mu}{dx}$, $\frac{dL}{db_{is}}$, $\frac{dC_Q}{d\sigma}$, $\frac{d\alpha_{is}}{dp}$
- Aerodynamic Derivatives affected: X_u, X_q, Z_w, M_u, M_q, Y_v, Y_p, L_v, L_p, N_r

Eleven values of the blade radius within the interval mentioned above are considered and, for each of them, the new values of both the aerodynamic derivatives and the eigenvalues are calculated. These results are analysed to assess how the blade radius can be changed to improve the flying qualities of the Q4E, stabilizing its natural modes. In Table 3.15, the interval of variation of the aerodynamic derivatives induced by the blade radius variation is reported along with the evolution of their margin of stability. The only aerodynamic derivatives whose variation range can induce significant changes in the FQ level assigned to the associated mode are L_p and L_v. Hence, their evolution is plotted in Figure 3.12 to get a better understanding of how they are influenced by the blade radius variation.

Table 3.15 *Effect of the blade radius variation on the aerodynamic derivatives*

	Interval of variation	Margin of Stability
R	0.1150 ÷ 0.2150	
X_u	-1.1874 ÷ -1.1621	
X_q	0.5422 ÷ 0.9542	
Y_v	-1.1874 ÷ -1.1621	
Z_w	-0.2060 ÷ -0.6982	
M_u	0.0234 ÷ 0.0288	increase
M_q	-0.0180 ÷ -0.0362	
M_w	-0.0608 ÷ -0.2060	increase
Y_p	-0.5422 ÷ -0.9542	
L_p	-0.0180 ÷ -0.0362	
L_v	-0.0234 ÷-0.0288	increase
N_r	6.2484 ÷ 8.7116	decrease

In Table 3.16 the flying quality levels assigned to each natural mode are classified depending on the value assumed by the related aerodynamic derivatives.

Table 3.16 *Aerodynamic derivatives influence on natural modes, blade radius variation*

Natural Mode	Flying quality level
Heave	Z_w – Level 1
Pitch	M_q – Level 1
Phugoid	M_q – Level 3 M_u – Level 3
Roll	L_p – Level 1
Dutch Roll	L_v – From level 1 to level 2 L_p – From level 2 to level 1
Spiral	N_r – Level 3

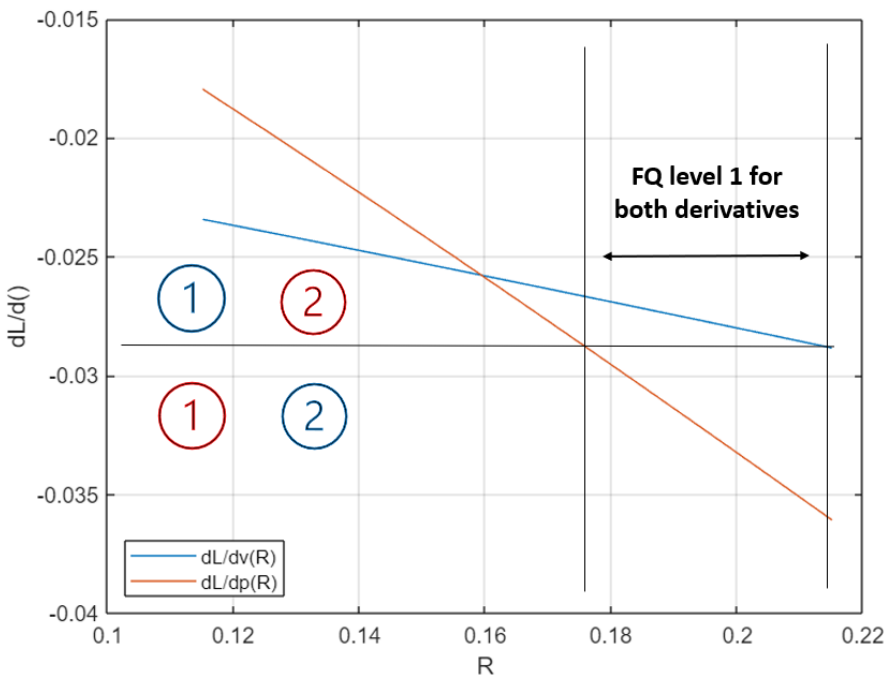

Figure 3.12 *Influence of blade radius variation on dL/dp and dL/dv*

For the considered variation interval of the blade radius the following results in terms of flying qualities are obtained: The induced variation of Z_w is associated for the whole interval to a level 1 of flying quality, indeed the Heave mode is always clearly stable. Z_w induces the Heave mode to approach level 2 of flying qualities when the blade radius is at the lower boundary of the considered interval, but this condition is too far from the on-design ones and therefore it is not an applicable configuration for the Q4E. The values assumed by both M_u and M_q are always associated to a level 3 of flying qualities with respect to the Phugoid mode. Instead, the Pitch mode constantly obtain flying qualities of level 1 in association to the variation interval of M_q. The Roll mode has flying qualities of level 1 due to the values assumed by L_p. The stability of the Roll mode is compromised for values of L_p close to 0.02, which is extremely distant from the interval induced by the variation of the blade radius. As expected, the variation of the flying qualities of the Dutch Roll mode is more complicated to be studied, due to the mutual influence of both L_p and L_v. As reported in Table 3.9, the value -0.0288 is the boundary between level 1 and level 2 for both the derivatives but with an opposite direction. For the considered variation interval. In Figure 3.12, it is possible to see that the Dutch Roll mode obtains flying qualities of level 1 from both derivatives when the radius blade is between 0.175 and 0.212. Since $\lambda_s = N_r$ in hover condition, its values is clearly positive and therefore λ_s is undoubtedly unstable, with a level 3 of flying qualities. From this analysis it emerges that the best flying qualities for the latero-directional plane are obtained when the blade radius is between 0.17 m and 0.2 m.

At this point, a complete evaluation of the flying qualities of the Q4E is obtained by analysing how the eigenvalues vary in response of the blade radius variation. The numerical entity assumed by the four eigenvalues associated to the longitudinal plane as a function of the eleven values of the blade radius parameter is reported in Table 3.17.

Table 3.17 *Blade radius variation influence on longitudinal plane eigenvalues*

	λ_p	λ_{ph}	λ_{ph}	λ_H
R_1	-2.0579 + 0.0000i	0.6372 + 1.5093i	0.6372 - 1.5093i	-0.0619 + 0.0000i
R_2	-2.0883 + 0.0000i	0.6314 + 1.5182i	0.6314 - 1.5182i	-0.0728 + 0.0000i
R_3	-2.1190 + 0.0000i	0.6257 + 1.5270i	0.6257 - 1.5270i	-0.0846 + 0.0000i
R_4	-2.1500 + 0.0000i	0.6200 + 1.5356i	0.6200 - 1.5356i	-0.0973 + 0.0000i
R_5	-2.1813 + 0.0000i	0.6143 + 1.5439i	0.6143 - 1.5439i	-0.1108 + 0.0000i
R_6	-2.2129 + 0.0000i	0.6087 + 1.5520i	0.6087 - 1.5520i	-0.1252 + 0.0000i
R_7	-2.2447 + 0.0000i	0.6031 + 1.5599i	0.6031 - 1.5599i	-0.1404 + 0.0000i
R_8	-2.2768 + 0.0000i	0.5976 + 1.5676i	0.5976 - 1.5676i	-0.1565 + 0.0000i
R_9	-2.3091 + 0.0000i	0.5921 + 1.5750i	0.5921 - 1.5750i	-0.1734 + 0.0000i
R_{10}	-2.3416 + 0.0000i	0.5868 + 1.5822i	0.5868 - 1.5822i	-0.1911 + 0.0000i
R_{11}	-2.3743 + 0.0000i	0.5814 + 1.5892i	0.5814 - 1.5892i	-0.2096 + 0.0000i

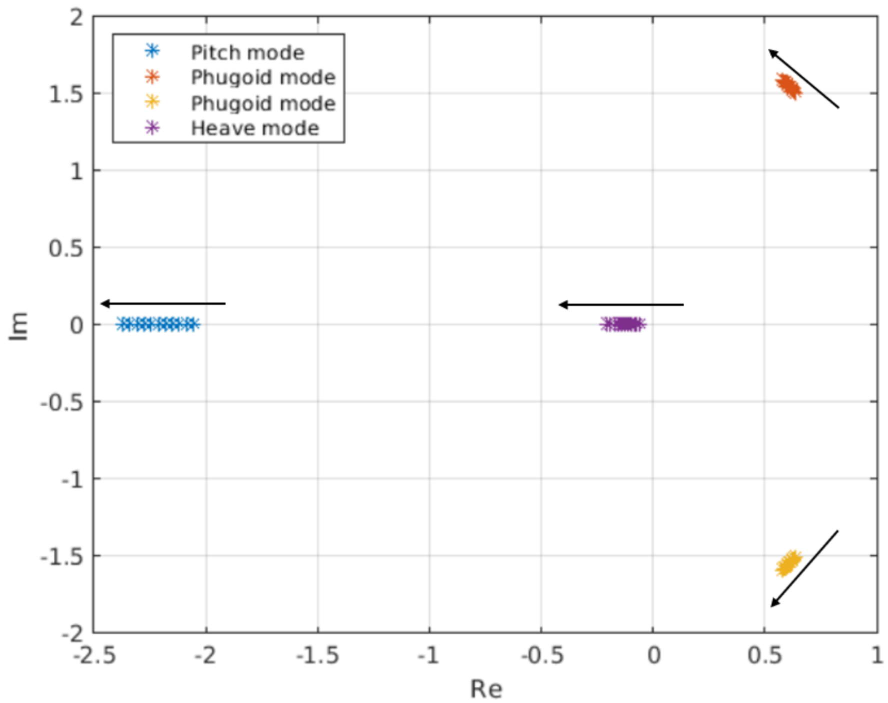

Figure 3.13 *Influence of blade radius variation on longitudinal plane natural modes*

The numerical entity assumed by the five eigenvalues associated to the latero-directional plane as a function of the eleven values of the blade radius is reported in Table 3.18.

Table 3.18 *Blade radius variation influence on latero-directional plane eigenvalues*

	λ_r	λ_{dr}	λ_{dr}	λ_h	λ_s
R_1	-0.7491 + 0.0000i	-0.0362 + 0.1131i	-0.0362 - 0.1131i	0.0000 + 0.0000i	6.2484 + 0.0000i
R_2	-0.7901 + 0.0000i	-0.0383 + 0.1104i	-0.0383 - 0.1104i	0.0000 + 0.0000i	6.5197 + 0.0000i
R_3	-0.8321 + 0.0000i	-0.0400 + 0.1080i	-0.0400 - 0.1080i	0.0000 + 0.0000i	6.7823 + 0.0000i
R_4	-0.8752 + 0.0000i	-0.0413 + 0.1057i	-0.0413 - 0.1057i	0.0000 + 0.0000i	7.0376 + 0.0000i
R_5	-0.9190 + 0.0000i	-0.0423 + 0.1036i	-0.0423 - 0.1036i	0.0000 + 0.0000i	7.2868 + 0.0000i
R_6	-0.9637 + 0.0000i	-0.0431 + 0.1017i	-0.0431 - 0.1017i	0.0000 + 0.0000i	7.5311 + 0.0000i
R_7	-1.0090 + 0.0000i	-0.0436 + 0.1000i	-0.0436 - 0.1000i	0.0000 + 0.0000i	7.7714 + 0.0000i
R_8	-1.0549 + 0.0000i	-0.0438 + 0.0984i	-0.0438 - 0.0984i	0.0000 + 0.0000i	8.0088 + 0.0000i
R_9	-1.1014 + 0.0000i	-0.0439 + 0.0970i	-0.0439 - 0.0970i	0.0000 + 0.0000i	8.2440 + 0.0000i
R_{10}	-1.1483 + 0.0000i	-0.0438 + 0.0958i	-0.0438 - 0.0958i	0.0000 + 0.0000i	8.4780 + 0.0000i
R_{11}	-1.1957 + 0.0000i	-0.0435 + 0.0947i	-0.0435 - 0.0947i	0.0000 + 0.0000i	8.7116 + 0.0000i

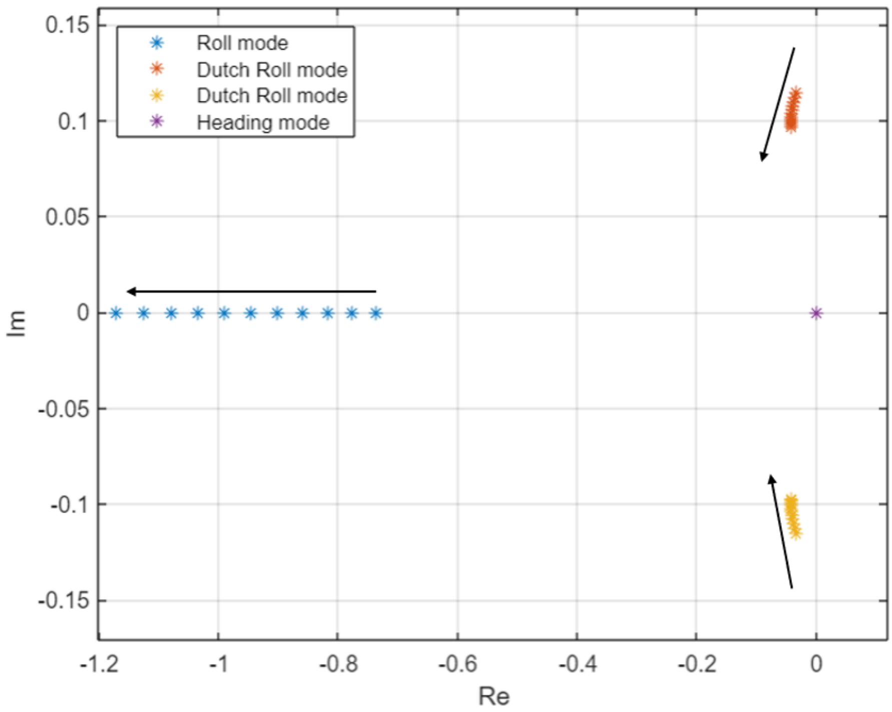

Figure 3.14 *Influence of blade radius variation on latero-directional plane natural modes*

Table 3.19 is exploited to see how the blade radius variation influences each mode. (3.48) is applied considering the values assumed by the eigenvalues as a function of the blade radius variation.

Table 3.19 *Blade radius variation influence on natural modes*

Mode	**Stability Margin**	$SMV1\%$	**Stable**
Pitch	Increase	+ 14%	Yes
Phugoid	Increase	+ 9.2%	No
Heave	Increase	+ 118%	Yes
Roll	Increase	+ 46%	Yes
Dutch Roll	Increase	+ 18%	Yes
Heading	stable	0	Yes
Spiral	decrease	- 33%	No

The variations reported in these tables and their representation on the root loci are used to obtain a global overview of the effect of the blade radius variation over the dynamics of the Q4E.

The variations reported in this table and their representation on the Root loci are used to obtain a global overview of the effect of the blade radius variation over the dynamic behaviour and the flying qualities of the Q4E. Starting with the analysis of the longitudinal plane, all the natural modes increase their margin of stability when the blade radius is increased. This effect can be seen particularly for the Heave mode which becomes also very close to the instability point when the blade radius decreases its values significantly below the on-design conditions. The

Phugoid mode remains unstable for all the variation interval considered and its oscillatory time response becomes more amplificated when the blade radius increases. No significant changes in the stability of the Pitch mode occur. As far as the latero-directional plane is concerned, no natural mode experiences a significant change of its stability properties. The Roll mode is always safely stable and its stability improves when the blade radius increases. The same happens to the Dutch Roll mode with the difference that it approaches the unstable conditions when the blade radius gets close to the lower limit of the interval. The oscillatory behaviour of this mode is amplificated by decreasing the blade radius. In the end, the instability of the Spiral mode decreases for small values of the blade radius. Summarizing how the overall flying qualities and stability of the Q4E is influenced by the blade radius variation, increasing the blade radius improves the flying qualities of all the natural modes despite the Spiral one. Consequently, increasing the blade radius has a positive effect towards the overall stability of the Q4E and it has only one downside: increasing the instability of an already largely unstable mode. On the contrary, decreasing the blade radius is useful to improve the flying qualities of the Spiral mode but this solution has many critical points. First, even the smallest considered blade radius values cannot lead the Spiral mode to approach the stable condition and its instability margin always remains extremely consistent. At the same time, the flying qualities of both the Dutch Roll mode and the Heave one get worse, with the real part of their associated eigenvalues which approaches the null value.
The Blade radius value is a design requirement ant it is selected in order to make the UAV flying in the best possible way on-design conditions. Moreover, it is impossible to realize a blade with a variable radius so that it can be adapted depending on the requirement of the specific mission. However, it is possible to select a defined and limited number of different blade radius, so that this parameter can be changed and selected with respect to the specific mission. To define the variation interval of this parameter is important to underline that the bigger the blade radius is, the higher is the risk of mutual interactions and interferences between the different rotors. Moreover, usually varying the blade radius implies to vary the rotor speed as well. Keeping it fixed while changing the blade radius can generate a value of lift which is not adapt to the designed flying conditions.

3.3.3 Rotors speed variation

- Design Value: Ω = 549.00 rad/s
- Parameter Variation: 523 ÷ 575 rad/s
- Design Coefficients affected: C_T, $\frac{dC_T}{dL}$, $\frac{dM}{d\alpha_{is}}$, $\frac{d\mu}{dx}$, $\frac{dL}{db_{is}}$, $\frac{db_{is}}{dp}$, $\frac{d\alpha_{is}}{dq}$
- Aerodynamic Derivatives affected: X_u , X_q, Z_w, M_u, M_q, Y_v, Y_p, L_v , L_p, N_r

Eleven values of the rotors speed within the interval mentioned above are considered and, for each of them, the new values of both the aerodynamic derivatives and the eigenvalues are calculated. These results are analysed to assess how the rotor speed can be varied to improve the flying qualities of the Q4E, stabilizing its natural modes. InTable 3.20, the interval of variation of the aerodynamic derivatives induced by the rotor speed variation is reported along with the evolution of their margin of stability.

***Table 3.20** Effect of the rotor speed variation on the aerodynamic derivatives*

	Interval of variation	**Margin of Stability**
Ω	523 ÷ 575	
X_u	-1.2627 ÷ -1.1380	
X_q	0.8075 ÷ 0.7278	
Z_w	-0.4310 ÷ -0.479	
M_u	0.0257 ÷ 0.0263	increase
M_q	-0.0282 ÷ -0.0262	
M_w	-0.1271 ÷ -0.1398	increase
Y_v	-1.2627 ÷ -1.1380	
Y_p	-0.8075 ÷ -0.7278	
L_p	-0.0282 ÷ -0.0262	
L_v	-0.0257 ÷ -0.0263	increase
N_r	7.9211 ÷ 7.2230	increase

In Table 3.21 the flying quality levels assigned to each natural mode are classified depending on the value assumed by its related aerodynamic derivatives.

***Table 3.21** Aerodynamic derivatives influence on natural modes, rotors speed variation*

Natural Mode	**Flying quality level**
Heave	Z_w – Level 1
Pitch	M_q – Level 1
Phugoid	M_q – Level 3 M_u – Level 3
Roll	L_p – Level 1
Dutch Roll	L_v – Level 1 L_p – Level 2
Spiral	N_r – Level 3

For the considered variation interval of the rotors speed the following results in terms of flying qualities are obtained: the Heave mode is not much affected by the rotors speed variation and the value of Z_w constantly results in flying qualities of level 1. The Phugoid mode is always associated to flying qualities of level 3 because the variation of both M_q and M_u induces constantly a positive real part of the associated eigenvalues. The Roll mode, evaluated by means of L_p, is always stable and obtains flying qualities of level 1 for all the considered interval of Ω. The evaluation of the flying qualities of the Dutch roll mode is more complicated and it has to account the variation of both L_v and L_p . L_v induces flying qualities of level 1 and L_p induces flying qualities of level 2, low values of Ω increase the negativity of its real part. N_r is largely positive and therefore induces flying qualities associated to the Spiral mode of level 3. After this analysis, it is clear that minor is the value of Ω, the better are the flying qualities of the UAV, foremost in association to the Dutch Roll mode. At this point, a complete evaluation of the flying qualities of the Q4E is obtained by analysing how the eigenvalues vary in response of the rotors speed variation.

The numerical entity assumed by the four eigenvalues associated to the longitudinal plane as a function of the eleven values of the rotors speed is reported in Table 3.22.

Table 3.22 *Rotors speed variation influence on longitudinal plane eigenvalues*

	λ_p	λ_{ph}	λ_{ph}	λ_H
Ω_1	-2.2272 + 0.0000i	0.5865 + 1.5411i	0.5865 - 1.5411i	-0.1287 + 0.0000i
Ω_2	-2.2249 + 0.0000i	0.5900 + 1.5428i	0.5900 - 1.5428i	-0.1299 + 0.0000i
Ω_3	-2.2226 + 0.0000i	0.5934 + 1.5445i	0.5934 - 1.5445i	-0.1312 + 0.0000i
Ω_4	-2.2204 + 0.0000i	0.5968 + 1.5462i	0.5968 - 1.5462i	-0.1325 + 0.0000i
Ω_5	-2.2183 + 0.0000i	0.6002 + 1.5478i	0.6002 - 1.5478i	-0.1338 + 0.0000i
Ω_6	-2.2163 + 0.0000i	0.6034 + 1.5495i	0.6034 - 1.5495i	-0.1351 + 0.0000i
Ω_7	-2.2143 + 0.0000i	0.6067 + 1.5511i	0.6067 - 1.5511i	-0.1363 + 0.0000i
Ω_8	-2.2125 + 0.0000i	0.6098 + 1.5528i	0.6098 - 1.5528i	-0.1376 + 0.0000i
Ω_9	-2.2106 + 0.0000i	0.6130 + 1.5544i	0.6130 - 1.5544i	-0.1389 + 0.0000i
Ω_{10}	-2.2089 + 0.0000i	0.6161 + 1.5560i	0.6161 - 1.5560i	-0.1402 + 0.0000i
Ω_{11}	-2.2072 + 0.0000i	0.6191 + 1.5576i	0.6191 - 1.5576i	-0.1415 + 0.0000i

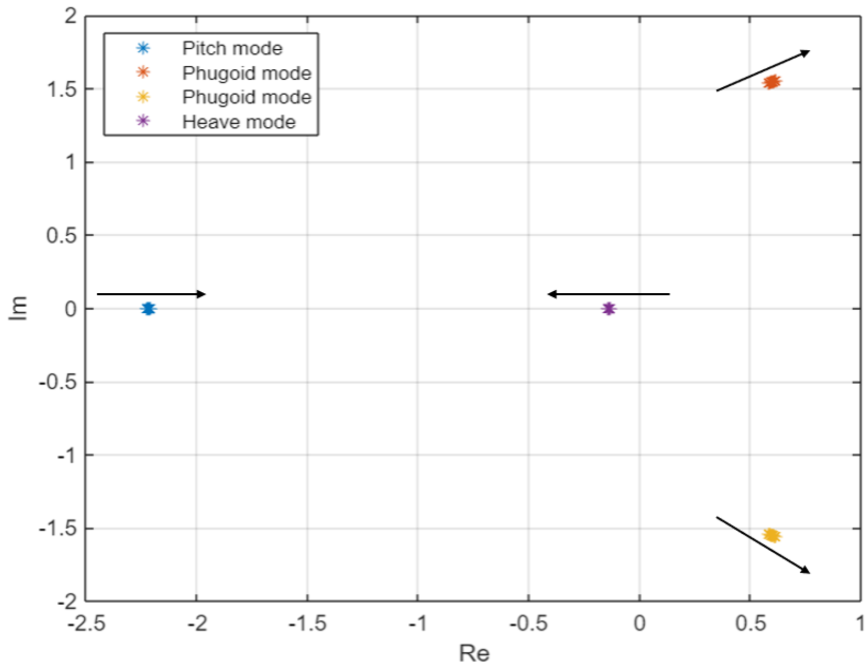

Figure 3.15 *Influence of rotors speed variation on longitudinal plane natural modes*

The numerical entity assumed by the five eigenvalues of the latero-directional plane as a function of the eleven values of the rotors speed is reported in Table 3.23.

***Table 3.23** Rotors speed variation influence on latero-directional plane eigenvalues*

	λ_r	λ_{dr}	λ_{dr}	λ_h	λ_s
Ω_1	-0.9866 + 0.0000i	-0.0504 + 0.0989i	-0.0504 - 0.0989i	0.0000 + 0.0000i	7.9211 + 0.0000i
Ω_2	-0.9800 + 0.0000i	-0.0489 + 0.0996i	-0.0489 - 0.0996i	0.0000 + 0.0000i	7.8450 + 0.0000i
Ω_3	-0.9736 + 0.0000i	-0.0474 + 0.1002i	-0.0474 - 0.1002i	0.0000 + 0.0000i	7.7703 + 0.0000i
Ω_4	-0.9673 + 0.0000i	-0.0459 + 0.1008i	-0.0459 - 0.1008i	0.0000 + 0.0000i	7.6972 + 0.0000i
Ω_5	-0.9611 + 0.0000i	-0.0445 + 0.1014i	-0.0445 - 0.1014i	0.0000 + 0.0000i	7.6254 + 0.0000i
Ω_6	-0.9550 + 0.0000i	-0.0431 + 0.1020i	-0.0431 - 0.1020i	0.0000 + 0.0000i	7.5551 + 0.0000i
Ω_7	-0.9491 + 0.0000i	-0.0418 + 0.1025i	-0.0418 - 0.1025i	0.0000 + 0.0000i	7.4861 + 0.0000i
Ω_8	-0.9432 + 0.0000i	-0.0405 + 0.1030i	-0.0405 - 0.1030i	0.0000 + 0.0000i	7.4184 + 0.0000i
Ω_9	-0.9375 + 0.0000i	-0.0392 + 0.1034i	-0.0392 - 0.1034i	0.0000 + 0.0000i	7.3521 + 0.0000i
Ω_{10}	-0.9319 + 0.0000i	-0.0379 + 0.1038i	-0.0379 - 0.1038i	0.0000 + 0.0000i	7.2869 + 0.0000i
Ω_{11}	-0.9263 + 0.0000i	-0.0367 + 0.1042i	-0.0367 - 0.1042i	0.0000 + 0.0000i	7.2230 + 0.0000i

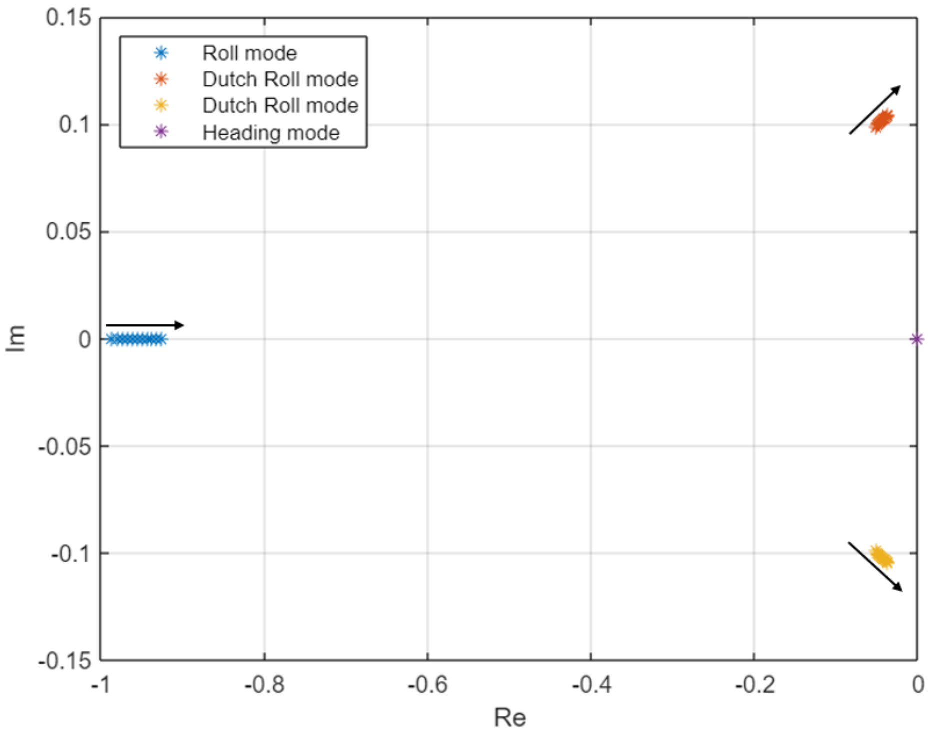

***Figure 3.16** Influence of rotors speed variation on latero-directional plane natural modes*

Table 3.24 is exploited to see how the blade radius variation influences each mode. Equation (3.48) is applied considering the values assumed by the eigenvalues as a function of the rotors speed variation.

Table 3.24 *Rotors speed variation influence on natural modes*

Mode	Stability Margin	$SMV1\%$	Stable
Pitch	decrease	- 0.9%	Yes
Phugoid	decrease	- 5,4%	No
Heave	decrease	- 9.5%	Yes
Roll	decrease	- 6.3%	Yes
Dutch Roll	decrease	- 32%	Yes
Heading	stable	0	Yes
Spiral	increase	+ 9.2%	No

The variations reported in this table and their representation on the root loci are used to obtain a global overview of the effect of the rotors speed variation over the dynamic behaviour and the flying qualities of the Q4E. In the first point, the rotors speed variation does not have a significant influence on the stability margin of the natural modes either of the longitudinal plane or the latero-directional one. The most affected mode is the Dutch Roll one, which decreases its margin of stability for high values of the rotors speed. Moreover, the oscillatory time response of both the Dutch Roll mode and the Phugoid one is amplified when the speed of the rotors increases. Basically, increasing the rotors speed can only improve the flying qualities of the Spiral mode, which slightly decreases its instability, and at the same time induces the stability of the Dutch Roll mode, which approaches the instability conditions worsening its flying qualities. Instead, decreasing the speed of the rotors can have a positive but small effect over the stability of every mode, with the only downside of making the Spiral mode even more unstable.

The on-design value of the rotor speed is just an indicative value, and in operative conditions the speed of the rotors can vary within the interval proposed, depending on external factors such as the flight height. Obviously, there are also transitory phases during the flight (take-off, landing) in which the speed of the rotors is forced to change. As previously reported, the variation of the rotors speed is deeply linked with the variation of the blade radius and often one variation is not possible without implying consequences on the other one. It is also worth to report that increasing the speed of the rotors can generate several problems related to a higher vibration level and materials with better mechanical properties are needed.

3.3.4 Rotors vertical offset variation

- Design Value: h_m = 0.030 m
- Parameter Variation: 0.020 ÷ 0.060 m
- Aerodynamic Derivatives affected: M_u, M_q, L_v and L_p

Eleven values of the vertical offset of the rotors within the interval mentioned above are considered and, for each of them, the new values of both the aerodynamic derivatives and the eigenvalues are calculated. These results are analysed to assess how the vertical offset of the rotor can be variated to improve the flying qualities of the Q4E, stabilizing its natural modes. In Table 3.25, the interval of variation of the aerodynamic derivatives induced by the h_m variation is reported along with the evolution of their margin of stability.

Table 3.25 *Effect of the rotors vertical offset variation on the aerodynamic derivatives*

	Interval of variation	**Margin of Stability**
h_m	0.020 ÷ 0.060	
M_u	0.0195 ÷ 0.0455	increase
M_q	-0.0196 ÷ -0.0504	
L_p	-0.0196 ÷ -0.0504	
L_v	-0.0195 ÷ -0.0455	increase

Table 3.26 *Aerodynamic derivatives influence on natural modes, rotors vertical offset variation*

Natural Mode	**Flying quality level**
Heave	Z_w – Level 1
Pitch	M_q – Level 1
Phugoid	M_q – Level 3 M_u – Level 3
Roll	L_p – Level 1
Dutch Roll	L_v – Level 1 L_p – Level 2
Spiral	N_r – Level 3

The only aerodynamic derivative whose variation range can induce significant changes in the FQ level assigned to the associated mode are L_p and L_v, therefore their evolution is plotted in Figure 3.17 to get a better understanding of how they are influenced by the variation of the vertical offset of the rotors.

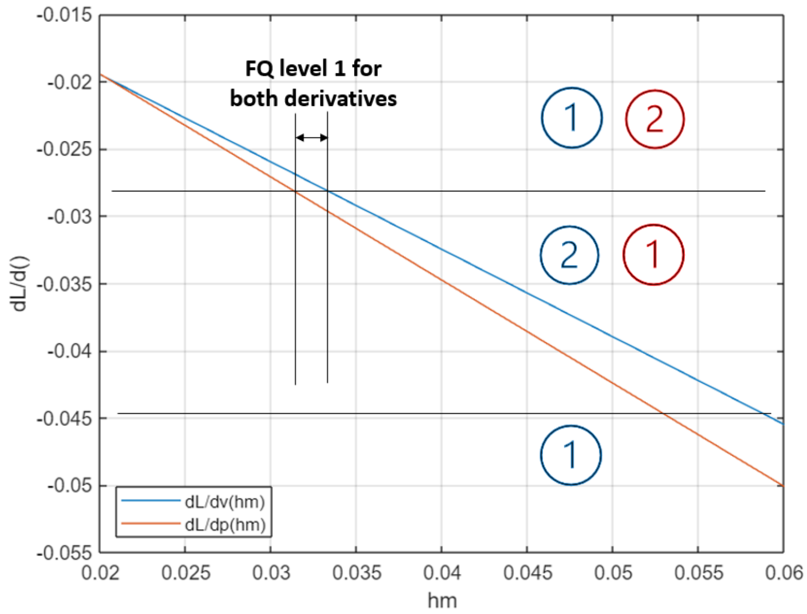

Figure 3.17 *Influence of rotors vertical offeset on dL/dp and dL/dv*

For the considered variation interval of the rotors speed the following results in terms of flying qualities are obtained: The Heave mode always gets flying qualities of level 1 since Z_w is not influenced by the variation of the vertical offset of the rotors. The values assumed by M_q induce a level 1 of flying qualities regarding the Pitch mode and flying qualities of the Phugoid mode of level 3 due to its constant instability. Accordingly, Phugoid mode obtains always flying qualities of level 3 also in association to the derivative M_u, whose variation is significant in terms of module but with no influence in improving the flying qualities of the Q4E. The flying qualities of the Roll modes are always assigned to Level 1 due to the variation of L_p. The evaluation of the flying qualities of the Dutch Roll mode depends on the value assumed by both L_p and L_v. With the previous graph a range of h_m correspondent to level 1 of flying qualities in association to both L_p and L_v is identified. Therefore, selecting a value of vertical offset of the rotors close to 0.034 m is the best solution to improve the flying qualities of the Dutch Roll mode in association to both the considered derivatives.

At this point, a complete evaluation of the flying qualities of the Q4E is obtained by analysing how the eigenvalues vary in response of the rotors speed variation. The numerical entity assumed by the four eigenvalues associated to the longitudinal plane as a function of the eleven values of the vertical offset parameter is reported in Table 3.27.

Table 3.27 *Rotors vertical offset variation influence on longitudinal plane eigenvalues*

	λ_p	λ_{ph}	λ_{ph}	λ_H
h_{m1}	-1.9741 + 0.0000i	0.5744 + 1.4135i	0.5744 - 1.4135i	-0.1351 + 0.0000i
h_{m2}	-2.0745 + 0.0000i	0.5878 + 1.4715i	0.5878 - 1.4715i	-0.1351 + 0.0000i
h_{m3}	-2.1701 + 0.0000i	0.5987 + 1.5246i	0.5987 - 1.5246i	-0.1351 + 0.0000i
h_{m4}	-2.2617 + 0.0000i	0.6077 + 1.5735i	0.6077 - 1.5735i	-0.1351 + 0.0000i
h_{m5}	-2.3500 + 0.0000i	0.6151 + 1.6189i	0.6151 - 1.6189i	-0.1351 + 0.0000i

h_{m6}	-2.4355 + 0.0000i	0.6210 + 1.6612i	0.6210 - 1.6612i	-0.1351 + 0.0000i
h_{m7}	-2.5187 + 0.0000i	0.6258 + 1.7009i	0.6258 - 1.7009i	-0.1351 + 0.0000i
h_{m8}	-2.5999 + 0.0000i	0.6296 + 1.7383i	0.6296 - 1.7383i	-0.1351 + 0.0000i
h_{m9}	-2.6793 + 0.0000i	0.6325 + 1.7736i	0.6325 - 1.7736i	-0.1351 + 0.0000i
h_{m10}	-2.7571 + 0.0000i	0.6346 + 1.8069i	0.6346 - 1.8069i	-0.1351 + 0.0000i
h_{m11}	-2.8337 + 0.0000i	0.6360 + 1.8386i	0.6360 - 1.8386i	-0.1351 + 0.0000i

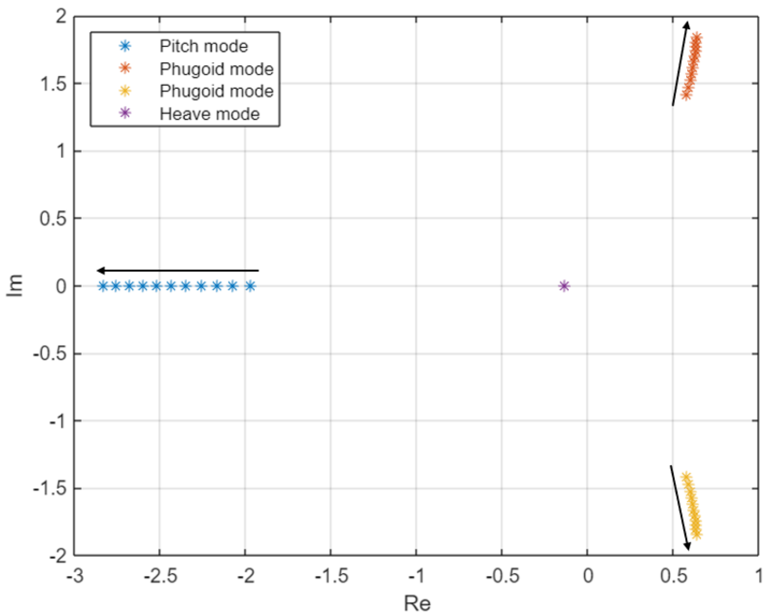

***Figure 3.18** Effect of rotors vertical offset variation on longitudinal plane natural modes*

The numerical entity assumed by the five eigenvalues associated to the latero-directional plane as a function of the eleven values of the vertical offset parameter considered is reported in Table 3.28.

***Table 3.28** Rotors vertical offset variation influence on latero-directional plane eigenvalues*

	λ_r	λ_{dr}	λ_{dr}	λ_h	λ_s
h_{m1}	-0.7819 + 0.0000i	-0.0332 + 0.1006i	-0.0332 - 0.1006i	0.0000 + 0.0000i	7.5551 + 0.0000i
h_{m2}	-0.8502 + 0.0000i	-0.0377 + 0.1014i	-0.0377 - 0.1014i	0.0000 + 0.0000i	7.5551 + 0.0000i
h_{m3}	-0.9198 + 0.0000i	-0.0415 + 0.1019i	-0.0415 - 0.1019i	0.0000 + 0.0000i	7.5551 + 0.0000i
h_{m4}	-0.9905 + 0.0000i	-0.0447 + 0.1020i	-0.0447 - 0.1020i	0.0000 + 0.0000i	7.5551 + 0.0000i
h_{m5}	-1.0621 + 0.0000i	-0.0475 + 0.1021i	-0.0475 - 0.1021i	0.0000 + 0.0000i	7.5551 + 0.0000i
h_{m6}	-1.1345 + 0.0000i	-0.0499 + 0.1020i	-0.0499 - 0.1020i	0.0000 + 0.0000i	7.5551 + 0.0000i
h_{m7}	-1.2075 + 0.0000i	-0.0521 + 0.1019i	-0.0521 - 0.1019i	0.0000 + 0.0000i	7.5551 + 0.0000i
h_{m8}	-1.2809 + 0.0000i	-0.0539 + 0.1017i	-0.0539 - 0.1017i	0.0000 + 0.0000i	7.5551 + 0.0000i
h_{m9}	-1.3548 + 0.0000i	-0.0556 + 0.1015i	-0.0556 - 0.1015i	0.0000 + 0.0000i	7.5551 + 0.0000i
h_{m10}	-1.4291 + 0.0000i	-0.0571 + 0.1013i	-0.0571 - 0.1013i	0.0000 + 0.0000i	7.5551 + 0.0000i
h_{m11}	-1.5036 + 0.0000i	-0.0584 + 0.1011i	-0.0584 - 0.1011i	0.0000 + 0.0000i	7.5551 + 0.0000i

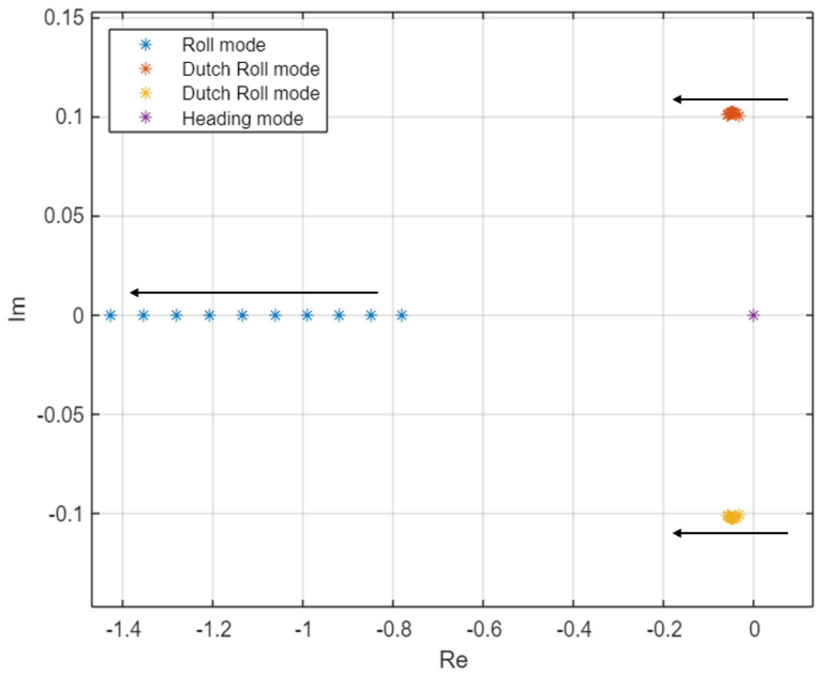

Figure 3.19 *Effect of rotors vertical offset variation on latero-directional plane natural modes*

Table 3.29 is exploited to see how the blade radius variation influences each natural mode. The variation reported is calculated applying the equation (3.48) considering the values assumed by the eigenvalues as a function of the rotors vertical offset variation.

Table 3.29 *Rotors vertical offset variation influence on natural modes*

Mode	Stability Margin	$SMV1\%$	Stable
Pitch	increase	+ 35%	Yes
Phugoid	decrease	- 10%	No
Heave	stable	0	Yes
Roll	increase	+ 64%	Yes
Dutch Roll	increase	+ 50%	Yes
Heading	stable	0	Yes
Spiral	stable	0	No

The variations reported in this table and their representation on the Root loci are used to obtain a global overview of the effect of the vertical offset variation over the dynamic behaviour and the flying qualities of the Q4E. A first consideration is that the Heave mode and the Spiral one are not influenced at all by this design parameter. The Pitch always maintains a consistent stability margin while the Phugoid mode remains unstable without being much affected by the h_m variation in terms of stability. The oscillatory time response of the Phugoid mode becomes more amplificated when the rotors vertical offset is increased. Discussing the stability of the natural modes of the latero-directional plane, both the Roll mode and the Dutch Roll one are significantly influenced by the variation of h_m. Moreover, the oscillatory time response of the Dutch Roll mode is not much affected by the variation of h_m, but it is slightly amplificated when h_m increases. Therefore, increasing the vertical offset of the rotors has the advantage of improving significantly the flying qualities related to the Roll mode, the Dutch Roll and the Pitch ones, with the only downside of slightly decreasing the stability of the Phugoid mode. Conversely, decreasing the vertical offset of the rotors can reduce the instability of the Phugoid mode improving its flying qualities, with the downside of decreasing the stability of the other modes. Particular attention has to be paid towards the Dutch Roll mode because it approaches the instability condition for small values of h_m. The value of this design parameter is just in part a design decision but for the biggest part it is a consecution of the characteristics of the mission for which the Q4E is required. A different value of the rotors vertical offset is found every time the payload is changed. The heavier is the payload, lower goes the position of the centre of gravity of our entire system. Therefore, is important to analyse how the flying qualities of the Q4E are influenced by the possible variations of h_m induced by the eventual different missions.

Table 3.30 is built with the purpose of summarizing the design variations that can be implemented to improve the flying qualities of each natural mode.

Table 3.30 *Parametric analysis summary*

Natural Mode	$\boldsymbol{m}$	$\boldsymbol{R}$	$\boldsymbol{\Omega}$	$\boldsymbol{h_m}$
Pitch	Increase	Increase	Decrease	Increase
Phugoid	Increase	Increase	Decrease	Decrease
Heave	Decrease	Increase	Decrease	/
Roll	Increase	Increase	Decrease	Increase
Dutch Roll	Increase	Increase	Decrease	Increase
Spiral	Decrease	Decrease	Increase	/

The results obtained by the analysis developed in this chapter and summarized in the table above are used in the next chapter to propose two specific strategies to improve the flying qualities of the Q4E with respect to two different missions

Chapter 4
Flying Qualities optimization

In this chapter, two different missions assigned to the Q4E are considered and the improvement of the Q4E flying qualities with respect to the specific operative conditions is studied. Each mission requires a different payload and different batteries, resulting in a specific design configuration, which is characterized by a particular value of total mass and vertical offset of the rotors. These two parameters are the most influenced by a change of payload and batteries. In fact, a different payload obviously results in a variation of the total mass of the UAV and adding mass below the centre of gravity of the system induces a consequent variation of the vertical offset of the rotors. These design changes obviously have a consequence on the flying qualities of the Q4E. The main goal of this chapter is to exploit the parametric analysis developed in chapter 3 to improve the flying qualities of the Q4E in both the operative circumstances proposed. As previously discussed, two out of the four variable design parameters considered are imposed by the mission. The remaining two (the blade radius and the rotors speed) are instead variated so that an improved design configuration can be found. Naturally, the design configuration is considered improved when its associated flying qualities are better than the ones of the original state. The adopted procedure is the following. The first step is studying the characteristics of the Q4E natural modes in the two proposed configurations (accounting only the effect of the changed mass and rotors vertical offset). In this way, is possible to understand which modes are most critical for the dynamic behaviour of the Q4E in the proposed configurations. Once this step is completed, the jointly variation of both the blade radius and the rotors speed can be analysed and exploited to improve the flying qualities of the Q4E. Since the considered variations of mass and rotors vertical offset are almost minimal, their influence on the dynamic behaviour of the Q4E will not be affected in deep. The most impacting downsides of Q4E dynamic behaviour are the ones already defined in chapter 4, or rather the stability of the Spiral mode and of the Phugoid one. Therefore, in the end of the chapter, two different strategies are proposed to improve these two distinct aspects of the Q4E dynamic behaviour.

4.1 Operative configurations

The first operative scenario proposed by MAVTech regards employing the Q4E to perform surveillance missions over crops and plantations, with the goal of identifying the diseases of the vegetation in their incipient phase. To perform this task, the Q4E is equipped with a multispectral camera, the Micasense RedEdge-MX. The second proposed employment of the Q4E is related to a search-and-rescue scenario and includes the presence of a thermal camera, the Flir Duo Pro R. Moreover, the design of the Q4E is further influenced by two different battery packs, the Lipo 6S 5200 mAh and the Lipo 6S 10000 mAh. Depending on the payload and batteries selection, four different design configurations are identified and each one is associated to a different value of weight and vertical offset of the rotors. To perform the optimization analysis, the two configurations with the greatest possible variation in terms of weight and vertical offset of the rotors have been considered. In this way, the variation in terms of flying qualities level can be better appreciated. Two different configurations are here presented.

Configuration A): Micasense RedEdge-MX alimented with battery Lipo 6S 5200 mAh

- UAV Mass = 1900 g
- Payload mass (Micasense RedEdge-MX) = 232 g
- Battery mass (Lipo 6S 5200 mAh) = 755 g
- Total mass = 2877 g
- Vertical offset of the rotors = 0.015 m

Configuration B): FLIR DUO PRO R alimented with battery Lipo 6S 10000 mAh

- UAV mass = 1900 g
- Payload mass (FLIR DUO PRO R) = 325 g
- Battery mass (Lipo 6S 10000 mAh) = 1305 g
- Total mass = 3550 g
- Vertical offset of the rotors = 0.060 m

Figure 4.1 *Multispectral camera(left) and thermal camera(right)*

In order to study the characteristics of the two different proposed configurations, their eigenvalues are calculated. The configuration A is analysed first.

Design parameters

- m = 2.887 g
- h_m = 0.015 m
- R = 0.1651 m
- Ω = 549.00 rad/s.

Table 4.1 proposes the value assumed by the aerodynamic derivatives in relation to the design configuration A of the Q4E.

Table 4.1 *Aerodynamic derivatives configuration A on-design*

X_u	$-1.0240\ Kg/s$
X_q	$0.6635\ (m * Kg)/(rad * s)$
Z_w	$-0.4529\ Kg/s$
M_u	$0.0163\ (m * Kg)/s$
M_w	$-0.1336(m * Kg)/s$
M_q	$-0.0142\ (m^2 * Kg)/(rad * s)$
Y_v	$-1.0240\ Kg/s$
Y_p	$-0.6635\ (m * Kg)/(rad * s)$
L_v	$-0.0163\ (m * Kg)/s$
L_p	$-0.0142\ (m^2 * Kg)/(rad * s)$
N_r	$6.0658\ (m^2 * Kg)/(rad * s)$

Once the aerodynamic derivatives are defined, the eigenvalues are calculated of both the longitudinal plane and of the latero-directional one.

Table 4.2 *Longitudinal plane eigenvalues configuration A on-design*

λ_1	-1.8292 + 0.0000i
λ_2	0.5669 + 1.3354i
λ_3	0.5669 - 1.3354i
λ_4	-0.1574 + 0.0000i

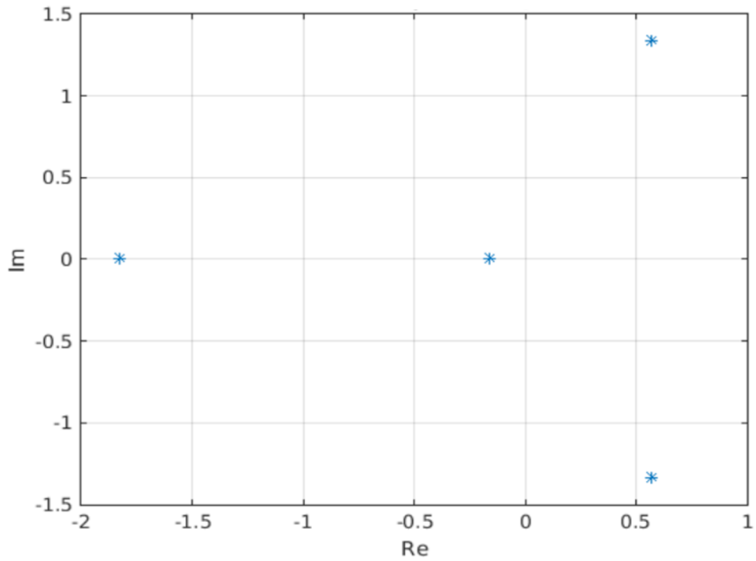

Figure 4.2 *Longitudinal plane root locus configuration A on-design*

Table 4.3 *Latero-directional plane eigenvalues configuration A on design*

λ_1	-0.5637 + 0.0000i
λ_2	-0.0132 + 0.1009i
λ_3	-0.0132 – 0.1009i
λ_4	0.0000 + 0.0000i
λ_5	6.0515 + 0.0000i

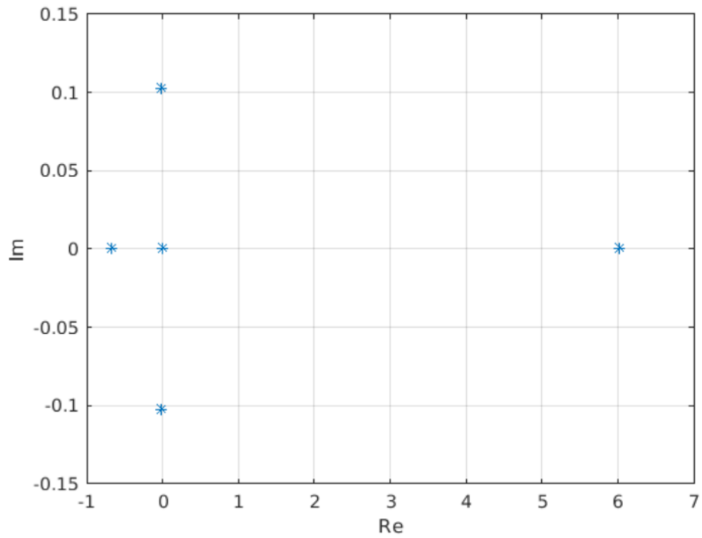

Figure 4.3 *Latero-directional plane root locus configuration A on-design*

The flying qualities of the Q4E in its configuration A are evaluated by analysing the values assumed by the aerodynamic derivatives and by the eigenvalues of this specific configuration. As noticed in the configuration on-design proposed in chapter 3, the most critical natural modes are the Phugoid and the Spiral ones. In fact, their associated eigenvalues have positive real parts, and they are consequently unstable. Anyway, this configuration with reduced mass and rotors vertical offset induces a significant reduction of the instability margin of the Spiral mode while there is no big modification in the behaviour of the Phugoid one. In this configuration, particular attention needs to be paid to the evolution of the Dutch Roll mode. In fact, the value assumed by the derivative L_p is associated to a level 2 of flying qualities for the Dutch Roll mode and the value assumed by L_v is at the boundary between level 1 and level 2. Indeed, the real part of the Dutch Roll eigenvalues approaches the null value, resulting in a significant reduction of the stability margin of the Dutch Roll mode. Hence, the strategies employed to optimize the design of configuration A have to focus not only on the Phugoid and Spiral modes, but also on the Dutch Roll one.

Now the configuration B with the following design parameters can be studied:

- $m =$ 3.530 g
- h_m = 0.060 m
- $R =$ 0.1651 m

- Ω = 549.00 rad/s

Table 4.4 proposes the value assumed by the aerodynamic derivatives in relation to the design configuration B of the Q4E

Table 4.4 *Aerodynamic derivatives configuration B on design*

X_u	$-1.2650\, Kg/s$
X_q	$0.8197\, (m * Kg)/rad * s$
Z_w	$-0.4523\, Kg/s$
M_u	$0.0456\, (m * Kg)/s$
M_w	$-0.1334\, (m * Kg)/s$
M_q	$-0.0534\, (m^2 * Kg)/(rad * s)$
Y_v	$-1.2650\, Kg/s$
Y_p	$-0.8197\, (m * Kg)/(rad * s)$
L_v	$-0.0456\, (m * Kg)/s$
L_p	$-0.0534(m^2 * Kg)/(rad * s)$
N_r	$8.1658\, (m^2 * Kg)/(rad * s)$

Once the aerodynamic derivatives are defined, the analysis proceeds by calculating the eigenvalues of both the longitudinal plane and of the latero-directional one.

Table 4.5 *Longitudinal plane eigenvalues configuration B on design*

λ_p	-2.8730 + 0.0000i
λ_{ph}	0.6151 + 1.8336i
λ_{ph}	0.6151 - 1.8336i
λ_h	-0.1281 + 0.0000i

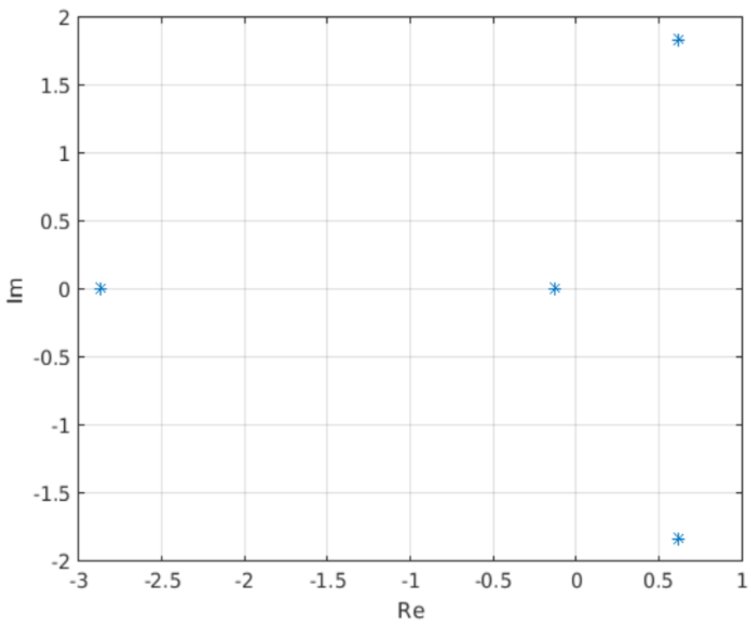

Figure 4.4 *Longitudinal plane root locus configuration B on-design*

Table 4.6 *Latero-directional plane eigenvalues configuration B on-design*

λ_r	-1.5769 + 0.0000i
λ_{dr}	-0.0644 + 0.0942i
λ_{dr}	-0.0644 - 0.0942i
λ_H	0.0000 + 0.0000i
λ_s	8.1658 + 0.0000i

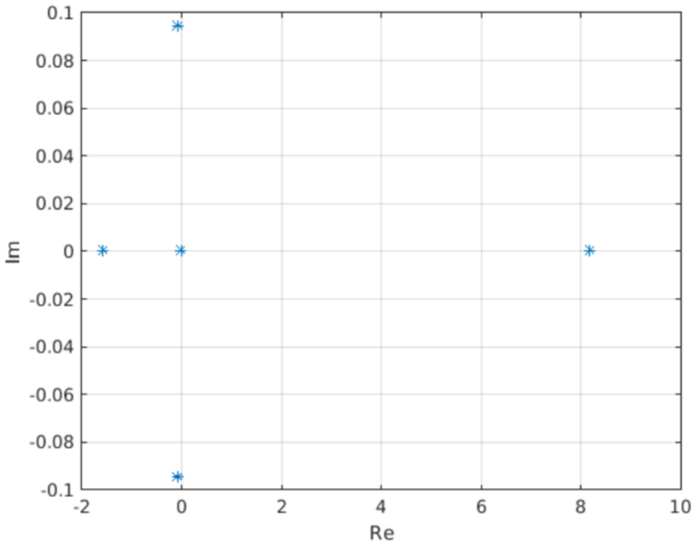

Figure 4.5 *Latero-directional plane root locus configuration B on-design*

The flying qualities of the Q4E in its configuration B) are evaluated by analysing the values assumed by the aerodynamic derivatives and by the eigenvalues of this specific configuration. As noticed in both the configuration on-design proposed in chapter 3, the most critical natural modes are the Phugoid and the Spiral ones. In fact, their associated eigenvalues have positive real parts and they are consequently unstable. The increase of mass and rotors vertical offset induces both the Phugoid mode and the Spiral one to become more unstable. The Phugoid mode has just a slight increase of instability while the variation of the Spiral mode is more consistent. Unlike configuration A, configuration B induces an improvement of the flying qualities related to the Dutch Roll mode. The value assumed by both L_p and L_v are very close to the conditions of level 1 flying qualities and, consequently, the eigenvalues associated to the Dutch Roll mode increase their negativity, hence the stability of the associated natural mode itself.

This analysis underlined that the most incisive way to improve the flying qualities of the Q4E in both configurations is to decrease the instability of the Spiral mode and of the Phugoid one. To do so, the variations of blade radius and rotors speed are needed. These two parameters are varied simultaneously, so that the best possible effect is reached. In order to avoid significant problems in terms of lift generation, when the blade radius is reduced, the rotors speed has to be increased and vice versa. Another important point to consider is that, when improving the stability of those two modes, is essential not to induce the other ones to approach instability conditions

4.2 Optimization strategies

The most critical aspect of the dynamic behaviour of the Q4E which need to be improved have just been identified and the optimization strategies are going to be presented. In chapter 3 a parametric analysis has been adopted to evaluate the effect of some relevant design parameters over the flying qualities of the Q4E. In this chapter, the variations are implemented to improve the flying qualities of the Q4E, with the goal of improving the most critical aspect of Q4E dynamic behaviour. In order to give an overview of the effect of each design parameter on the variation of the flying qualities levels of each natural mode, a modification of the Table 3.30 has been proposed, edited to keep into account only the variation of blade radius and rotors speed. In each cell is indicated the variation required to the design parameter in order to improve the flying qualities of the corresponding natural mode.

Table 4.7 *Parameters variation needed to enhance natural modes stability*

Natural mode	$\boldsymbol{R}$	$\boldsymbol{\Omega}$
Pitch	Increase	Decrease
Phugoid	Increase	Decrease
Heave	Increase	Decrease
Roll	Increase	Decrease
Dutch Roll	Increase	Decrease
Spiral	Decrease	Increase

As previously stated, the most significant problem related to Q4E dynamics is the instability of the Phugoid mode and of the Spiral one. Therefore, two optimization strategies can be addressed, the first one aims at improving the flying qualities of the Phugoid mode, and the second one aims at improving the flying qualities of the Spiral mode.

- Strategy 1) – Phugoid mode stabilization. From the previous table, improving the flying qualities associated to the Phugoid mode is possible by increasing the blade radius and decreasing the rotors speed. These variations have also a positive effect on the flying qualities of the remaining natural modes, despite the Spiral one.

- Strategy 2) – Spiral mode stabilization. According to Table 4.7, improving the flying qualities of the Spiral mode is possible by decreasing the blade radius and increasing the rotors speed. This strategy has the negative side of decreasing the stability margin of the other natural modes. Particular attention has to be paid to the evolution of the Dutch Roll mode. In fact, particularly for configuration A, the Dutch Roll mode is close to the instability condition. Therefore, in this case the variation of R and Ω has to be particularly precise, in order to not induce the Dutch Roll mode to become unstable.

These two optimization strategies are applied to optimize the design of both configurations, and the evolution of their flying qualities is studied as usual by means of the aerodynamic derivatives and of the eigenvalues. The effect of the optimization strategy is also evaluated by a gain coefficient, which balances the variation of the Phugoid mode with respect to the Spiral one. The variation of the "improved" mode is divided for the variation of the "worsened" one, so that a result of the strategy is finally proposed. The Stability Margin Variation (SMV%) and the Strategy Gain (SG) coefficients are computed as follow:

$$SMV2\%_i = \frac{Re\left(\lambda_{i-optimized}\right) - Re(\lambda_{i-standard})}{Re(\lambda_{i-standard})} \tag{4.1}$$

$$SG = \frac{SMV2\%_{Improved\ mode}}{SMV2\%_{Worsened\ mode}} \tag{4.2}$$

Since the optimization strategies are based on the variation of the blade radius and of the rotors speed, it is important to report now the variation range considered for both design parameters. The blade radius can vary between 0.140m and 0.190m. Due to compatibility issues with the motors, the upper boundary of blade radius variation is 0.190m, the motors are not compatible with bigger radius. The lower boundary of variation is obtained by subtracting to the value on-design the same delta between the on-design value and the upper boundary. The variation interval of the rotors speed is between 523 rad/s and 575 rad/s. In the beginning, the application of the strategy 1 to both configurations is presented.

Strategy 1 - configuration A) design parameters

- m = 2.8870 g
- h_m = 0.015 m
- R = 0.1900 m
- Ω = 523 rad/s

Table 4.8 *Longitudinal plane eigenvalues, configuration A strategy 1*

λ_p	-1.8910 + 0.0000i
λ_{ph}	0.5228 + 1.3297i
λ_{ph}	0.5228 - 1.3297i
λ_h	-0.1726 + 0.0000i

Table 4.9 Latero-directional plane eigenvalues, configuration A strategy 1

λ_r	-0.7927 + 0.0000i
λ_{dr}	-0.0364 + 0.0919i
λ_{dr}	-0.0364 - 0.0919i
λ_H	0.0000 + 0.0000i
λ_s	8.4198+ 0.0000i

The effects of the adopted strategy on the dynamic behaviour and flying qualities of the Q4E are summarized in Table 4.10.

Table 4.10 Effect of Strategy 1 on configuration A natural modes

Mode	$SMV2\%$	Flying Qualities level	Stable
Pitch	+ 3.37 %	M_q – Level 1	Yes
Phugoid	+ 7.77 %	M_q , M_q – Level 3	No
Heave	+ 9.7 %	Z_w – Level 1	Yes
Roll	+ 40.6 %	L_p – Level 1	Yes
Dutch Roll	+ 175.8 %	L_v – Level 1, L_p – Level 2	Yes
Heading	0 %	/	Neutral
Spiral	- 39.2 %	N_r – Level 3	No

The application of the first strategy to the configuration A results in SG = 0.20. One significant improvement of this configuration is not strictly related to the final goal of the proposed strategy but to the enhancement of the Dutch Roll mode. In the proposed conditions, the Dutch Roll was really close to the instability level. By applying this strategy, its eigenvalues become more negative and its behaviour definitely more stable.

Strategy 1 - configuration B) design parameters

- m = 3.530 g
- h_m = 0.060 m
- R = 0.1900 m
- Ω = 523 rad/s

***Table 4.11** Longitudinal plane eigenvalues, configuration B strategy 1*

λ_p	-3.0543 + 0.0000i
λ_{ph}	0.5146 + 1.8047i
λ_{ph}	0.5146 - 1.8047i
λ_h	-0.1422 + 0.0000i

***Table 4.12** Latero-directional plane eigenvalues, configuration B strategy 1*

λ_r	-1.8995 + 0.0000i
λ_{dr}	-0.1015 + 0.0325i
λ_{dr}	-0.1015 - 0.0325i
λ_H	0.0000 + 0.0000i
λ_s	11.2085 + 0.0000i

The effects of the adopted strategy on the dynamic behaviour and flying qualities of the Q4E are summarized in Table 4.13

***Table 4.13** Effect of Strategy 1 on configuration B natural modes*

Mode	$SMV2\%$	**Flying Qualities level**	**Stable**
Pitch	+ 6.31 %	M_q – Level 1	Yes
Phugoid	+ 16.3 %	M_q , M_q – Level 3	No
Heave	+ 11.0 %	Z_w – Level 1	Yes
Roll	+ 20.5 %	L_p – Level 1	Yes
Dutch Roll	+ 57.6 %	L_v – Level 2, L_p – Level 1	Yes
Heading	0 %	/	Neutral
Spiral	- 37.1 %	N_r – Level 3	No

The application of the first strategy to the configuration B results in SG = 0.44.

At this point, is possible to see that the evolution of the stability of all the considered natural modes is the same for both the proposed configurations. One first difference is that the variation of blade radius and rotors speed is amplified by highest values of mass and rotors vertical offset, therefore the variation of stability margin of the configuration B modes is bigger than for configuration A. This observation is true for all the mode despite the Spiral one. In this last case the variation induced is about the same for both configurations. The stability of the Phugoid mode is only slightly improved. Actually, the Phugoid mode of helicopters and multirotor use to be unstable in hover condition and stabilizes itself for growing values of the advancement ratio. For this reason, the obtained slight improvement of the Phugoid mode is acceptable for both the configurations. All the natural modes, despite the Spiral one, increase their stability when this specific strategy is adopted. One critical observation is related to the Strategy gain coefficient. In both cases, its value is quite low, which means that the decreasing of flying qualities of the Spiral mode is greater than the improvement of the Phugoid mode ones. Anyway, this evolution is acceptable because the Spiral mode was already largely unstable in the configuration proposed. Decreasing the stability of an already very unstable mode is worthy to reduce the instability of the Phugoid one and to improve the flying qualities of all the other natural modes. One important benefit of this strategy is related to the improvement of the flying qualities of the Dutch Roll mode, which was almost unstable in the configuration A as it was originally proposed.

Finally, the effect of applying the second strategy to both the proposed configurations is here studied. In this case the main target is to improve the flying qualities associated to the Spiral mode.

Strategy 2 - configuration A) design parameters

- m = 2.8870 g
- h_m = 0.015 m
- R = 0.1520 m
- Ω = 555 rad/s

Table 4.14 *Longitudinal plane eigenvalues, configuration A strategy 2*

λ_p	-1.7977 + 0.0000i
λ_{ph}	0.5840 + 1.3337i
λ_{ph}	0.5840 - 1.3337i
λ_h	-0.1456 + 0.0000i

Table 4.15 *Latero-directional plane eigenvalues, configuration A strategy 2*

λ_r	-0.6297 + 0.0000i
λ_{dr}	-0.0075 + 0.1067i
λ_{dr}	-0.0075 - 0.1067i
λ_H	0.0000 + 0.0000i
λ_s	5.0756 + 0.0000i

The effects of the adopted strategy on the dynamic behaviour and flying qualities of the Q4E are summarized in Table 4.16.

***Table 4.16** Effect of Strategy 2 on configuration A natural modes*

Mode	$SMV2\%$	Flying Qualities level	Stable
Pitch	- 1.7 %	M_q – Level 1	Yes
Phugoid	- 3.0 %	M_q , M_q – Level 3	No
Heave	- 7.5 %	Z_w – Level 1	Yes
Roll	- 11.7 %	L_p – Level 1	Yes
Dutch Roll	- 43.2 %	L_v – Level 2, L_p – Level 2	Yes
Heading	0 %	/	Neutral
Spiral	+ 16.1 %	N_r – Level 3	No

The application of the second strategy to the configuration A results in $SG.$ = 5.37. It is important to underline that to apply the second strategy to the configuration A, all the admissible variation interval of the blade radius and of the rotors speed was not exploited. In fact, this strategy has also a deep effect on the stability of the Dutch Roll mode. If the values of blade radius and rotors speed which are the boundaries of the respective intervals are selected, maximizing the improvement of the Spiral mode flying qualities, the dynamic behaviour of the Dutch Roll mode would have become unstable. Naturally, inducing another natural mode to become unstable is not worthy reducing further the instability of an anyway unstable natural mode.

Strategy 2 - configuration B) design parameters

- m = 3.5300 g
- h_m = 0.060 m
- R = 0.140 m
- Ω = 575 rad/s

***Table 4.17** Longitudinal plane eigenvalues, configuration B strategy 2*

λ_p	-2.7080 + 0.0000i
λ_{ph}	0.7132 + 1.8556i
λ_{ph}	0.7132 - 1.8556i
λ_h	-0.1130 + 0.0000i

***Table 4.18** Latero-directional plane eigenvalues, configuration B strategy 2*

λ_r	-1.2689 + 0.0000i
λ_{dr}	-0.0308 + 0.1202i
λ_{dr}	-0.0308 - 0.1202i
λ_H	0.0000 + 0.0000i
λ_s	5.6050 + 0.0000i

The effects of the adopted strategy on the dynamic behaviour and flying qualities of the Q4E are summarized in Table 4.19.

Table 4.19 *Effect of Strategy 2 on configuration B natural modes*

Mode	$SMV2\%$	**Flying Qualities level**	**Stable**
Pitch	- 5.7 %	M_q – Level 1	Yes
Phugoid	- 15.9 %	M_q , M_q – Level 3	No
Heave	- 11.8 %	Z_w – Level 1	Yes
Roll	- 19.5 %	L_p – Level 1	Yes
Dutch Roll	- 52.2 %	L_v – Level 2, L_p – Level 1	Yes
Heading	0 %	/	Neutral
Spiral	+ 37.9 %	N_r – Level 3	No

The application of the second strategy to the configuration B results in SG = 2.38.

At this point, the results of the second strategy are similar for both configurations. Particularly, even though a significant improvement of the Spiral mode flying qualities is reached, its dynamic behaviour remains clearly unstable. The other natural modes are instead negatively affected by the application of this strategy. The variation of the Pitch, Roll and Heave modes are not concerning because their stability margin remains wide and their stability is not compromised. Instead, the instability of the Phugoid mode is unavoidably increased. Nevertheless, as it is underlined by the Strategy Gain coefficient, the improvement of Spiral mode flying qualities is significantly greater than the decrease of the Phugoid mode ones. In the end, also the evolution of the Dutch Roll mode needs to be closely studied. In fact, the decrease of its stability is significant and, as explained for configuration A, it can bring the natural mode to the unstable condition. Fortunately, the starting design of configuration B had a consistent stability margin in association to the Dutch Roll mode. Therefore, the whole interval of variation of blade radius and rotors speed is exploited in order to maximize the improvement of the Spiral mode without compromising the stability of the Dutch Roll one.

Figure 4.6 and 4.7 are reported in order to provide a clear visualization of how the flying qualities of the configuration A are influenced by the application of both strategies.

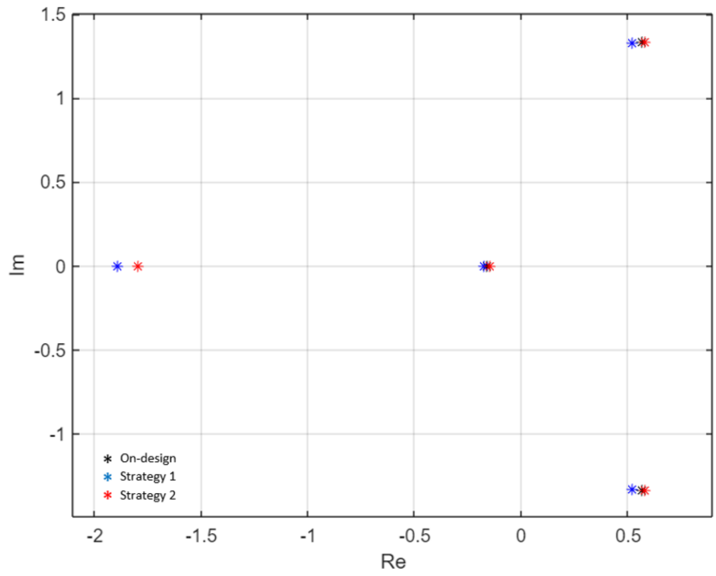

Figure 4.6 *Influence of Strategy 1 and 2 on configuration A, longitudinal plane*

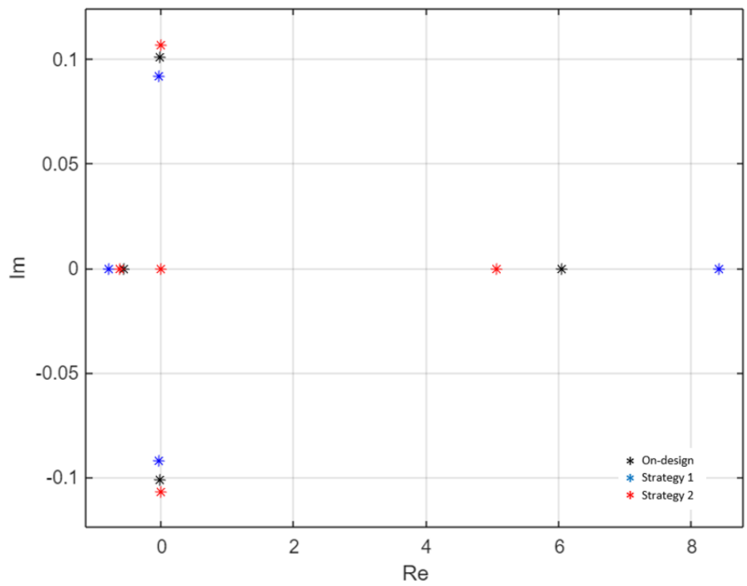

Figure 4.7 *Influence of Strategy 1 and 2 on configuration A, latero-directional plane*

Figure 4.8 and 4.9 are reported in order to provide a clear visualization of how the flying qualities of the configuration B are influenced by the application of both strategies.

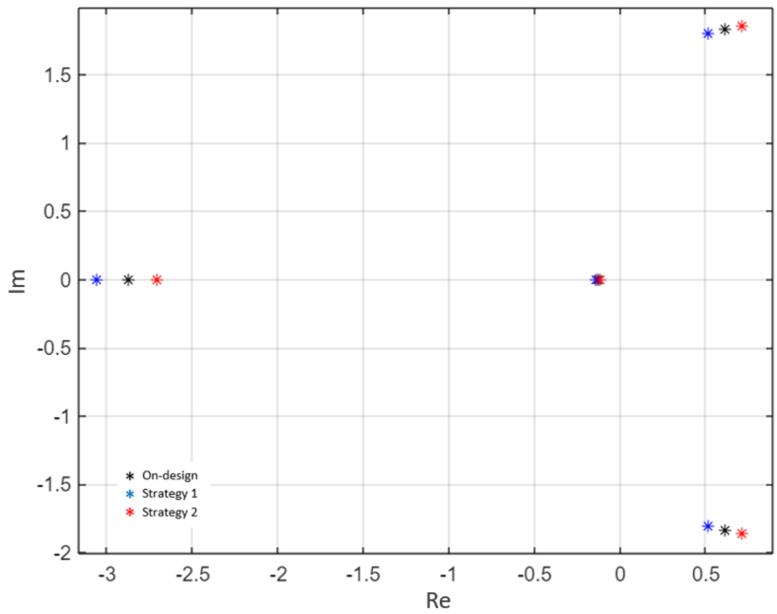

Figure 4.8 *Influence of Strategy 1 and 2 on configuration B, longitudinal plane*

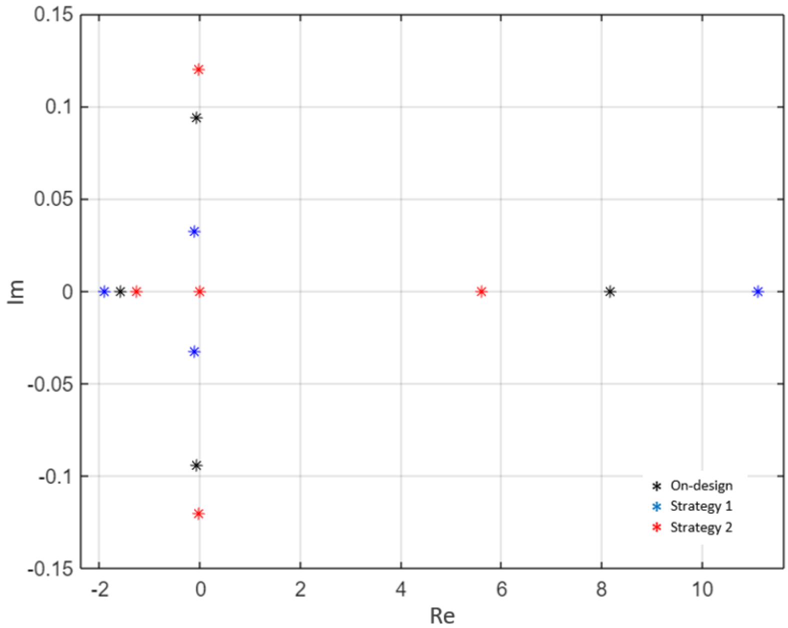

Figure 4.9 *Influence of Strategy 1 and 2 on configuration B, latero-directional plane*

Table 4.20 summarizes the results of the two different applied strategies. The first one, aimed at improving the flying qualities of the Phugoid mode, has the downside of inducing a sensible increase in the instability of the Spiral one, generating a low value of SG. Nevertheless, this strategy induces the stability margin of all the other modes to increase, therefore its application can be considered acceptable. In order to compensate the instability of the spiral mode, it is necessary to implement specific commands and control laws which are out of the scope of this discussion. For the second strategy, an opposite situation occurred. The instability of the Spiral mode is sensibly decreased, and the value of SG is much higher than the one of the first strategy. Unfortunately, this second strategy induces the margin of stability of the other natural mode to decrease as well. But, since all the other natural modes (despite obviously the Phugoid

one) are stable, the application of this strategy is acceptable anyway.
In this chapter is clear that, depending on the mission assigned to the drone, its dynamic characteristics can change. The method proposed in this thesis allows to adapt the design of the drone with respect to the desired objective, calibrating the variation of the considered design value to find a good balance between the flying qualities associated to each natural mode. The designed parameters finally proposed are not the optimal ones to improve the overall flying qualities of the Q4E but are an effective solution to improve its flying qualities with respect to specific necessities and depending on the characteristics of the assigned mission.

Table 4.20 *Strategy Gain Summary*

SG	**Configuration A**	**Configuration B**
Strategy 1	0.20	0.44
Strategy 2	5.37	2.38

Chapter 5
Conclusions

The industry analysis clarified the presence of a diffused industrial interest regarding the employment of UAVs. Even though drones have many potential applicative fields, the current maturity of the technology allows them to be effectively applied foremost in the agriculture and infrastructure industry. The presence of a consolidated demand of UAV-based services is a fundamental boost to their technological development. The engineering research can actually enhance the reliability and the performance of UAVs, promoting their industrial diffusion. Obviously, the number of possible employments of the UAVs increases if their manoeuvrability improves. For this reason, the concept of Flying Qualities results to be an effective framework to study and to evaluate the performance of UAVs and aircraft in general. Therefore, proposing a method useful to improve the flying qualities of the UAVs by means of specific design changes could be an effective way to favour their industrial diffusion. The industry analysis led to the identification of the quadrotors as the category of UAVs with the highest margin of technological growth and future industrial applicability. Therefore, the Q4E was chosen as test case for the development of the enhancement model proposed in this thesis. The parametric analysis proposed in chapter 3 provided the needed tools to evaluate how the design of the Q4E can be changed to improve its flying qualities. Consequently, in chapter 4 the flexibility and adaptability of this analysis were exploited to enhance the flying qualities of the Q4E with two different strategies. In fact, it was successfully employed to enhance the stability characteristics of either the Phugoid mode (stability margin improved of the 16.3% in the best considered case) and the Spiral mode (stability margin improved of the 37.9% in the best considered case). Even though the final configurations proposed in chapter 4 are not the optimal ones, they showed how the design of a selected multirotor can be varied to adapt the configuration of the UAV to the mission requirements. Therefore, following this kind of approach, the design of multirotor UAVs can be adapted to the specific requirements imposed by the mission and by the external industrial environment. There are significative steps which could be followed in order to enhance the results of this thesis, improving their relevance and applicability. This work is focused on studying the flying qualities of the Q4E in hover condition and its results can be considered valid also when flying with advance ratios close to zero. Even though many of the missions assigned to the Q4E include significant hovering phases, there are several employments of quadrotors which require high advance ratios as well. In this sense, one possible further development of this thesis is applying the same analysis also to a forward flight regime. In this way, the design of the Q4E could be optimized for a wider set of different mission and, consequently, for a greater number of industrial applications.

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