

POLITECNICO DI TORINO

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Master's Degree Thesis

Influence of atmospheric conditions on the investigation of drone aerodynamics and flight dynamics

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Abstract

Multicopter unmanned aerial vehicles are increasingly used in outdoor applications, where their aerodynamic and flight-dynamic behaviour is affected by atmospheric wind and turbulence. Although quadrotor modelling and control are often studied under idealized or indoor conditions, real low-altitude operations expose the vehicle to unsteady inflow, gusts, and direction-dependent disturbances that modify propeller loading and require continuous compensation by the flight controller. This thesis investigates the influence of atmospheric conditions on the response of a quadrotor platform, with particular attention to the relationship between the measured wind field and the motor RPM variations commanded by the onboard controller.

The study is based on an outdoor experimental campaign conducted at the von Karman Institute for Fluid Dynamics using a Holybro X500 V2 quadrotor equipped with a Pixhawk 6X flight controller. The three-dimensional wind velocity is measured by a LI-550P TriSonica™ Mini ultrasonic anemometer mounted on a fixed pole near the flight region, while the drone telemetry provides time-resolved motor RPM, attitude, inertial, and altitude data. A dedicated acquisition procedure based on a radio-channel trigger is used to define common start and stop events for the anemometer measurements, the PC-side telemetry stream, and the onboard flight-controller log.

A physical interpretation framework is first developed to relate wind disturbances to quadrotor dynamics, propeller loading, and flight-controller response. The measured wind vector is distinguished from the relative inflow experienced by the vehicle, and the role of axial, in-plane, and non-axial inflow components is introduced to support the interpretation of wind-induced RPM variations. The experimental data are then processed through a synchronization and resampling pipeline, allowing wind statistics, turbulence descriptors, RPM variability, wind–RPM correlations, geometry-dependent lag interpretation, spectral content, and gust-induced transient responses to be analysed on a common time base.

The resulting methodology provides a physically grounded approach to assess how wind intensity, direction, and turbulent fluctuations affect propeller loading and flight-controller activity during outdoor quadrotor operation. It also establishes an experimental and data-processing basis for future aerodynamic coefficient identification and for the development of more realistic data-driven models of drone flight dynamics under atmospheric disturbances.

Dedicato alla mia famiglia

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Acronyms

ATT

attitude

BARO

barometer

CEP

circular error probable

DC

direct current

EKF

Extended Kalman Filter

ESC

Electronic Speed Controller

GNSS

Global Navigation Satellite System

GPS

Global Positioning System

IMU

Inertial Measurement Unit

LiPo

lithium polymer

MAVLink

Micro Air Vehicle Link

MEMS

Micro-Electro-Mechanical System

PC

personal computer

PSD

power spectral density

PWM

pulse-width modulation

QZSS

Quasi-Zenith Satellite System

RC

radio control

RH

relative humidity

RPM

revolutions per minute

RS-232

Recommended Standard 232

RS-422

Recommended Standard 422

SBAS

Satellite-Based Augmentation System

UAV

unmanned aerial vehicle

UART

Universal Asynchronous Receiver-Transmitter

VKI

von Karman Institute for Fluid Dynamics

Chapter 1

Introduction

Unmanned aerial vehicles (UAVs), and quadrotors in particular, have seen rapid growth in both commercial and scientific applications over the past decade [1]. Their ability to perform vertical take-off and landing, hover, and execute precise trajectories makes them attractive platforms for inspection, delivery, mapping, and atmospheric sensing. However, much of quadrotor design, modelling, and control validation is conducted under idealized or simplified wind conditions (calm air, indoor environments, or numerical simulations) that differ from the turbulent, unsteady atmospheric boundary layer [2] in which real-world operations take place. Atmospheric turbulence introduces unsteady inflow to the propellers, alters the effective angle of attack of each blade, and generates fluctuating forces and moments that the flight controller must continuously compensate for. This compensation manifests directly in the propeller RPM commands issued by the controller: gusts cause rapid RPM variations that, if not properly understood, can degrade attitude stability, increase power consumption, and in severe cases lead to loss of control. Despite this, the aerodynamic and flight dynamic response of quadrotors to atmospheric disturbances remains incompletely characterized experimentally. A common approach is to represent atmospheric disturbances using simplified gust or spectral models, such as the Dryden or von Kármán models [3, 4, 5], applied numerically rather than validated against measured atmospheric conditions.

This thesis addresses that gap through an experimental campaign conducted at the Von Karman Institute for Fluid Dynamics (VKI). An X500 quadrotor is flown outdoors under varying atmospheric conditions while a LI-550P TriSonica™ Mini ultrasonic anemometer, mounted on a fixed pole in the proximity of the flight envelope, measures the three-dimensional wind velocity vector [6]. The concurrent telemetry stream from the Pixhawk 6X flight controller provides time-resolved RPM data for all four propellers, along with attitude and IMU measurements. By correlating the wind measurements with the flight controller output, this work investigates how wind intensity, direction, and turbulence characteristics influence

propeller loading and the control authority of the drone.



Figure 1.1: VKI experimental campaign

Chapter 2

Quadrotor Flight Dynamics

2.1 Introduction

A quadrotor is a rigid body with six degrees of freedom: three translational and three rotational [7]. These motions are controlled indirectly through the rotational speeds of the four propellers. Each propeller is assumed to generate a thrust force aligned with the body-fixed z^B -axis and a reaction torque associated with its rotation. The sum of the four thrusts determines the total lifting force available to the vehicle, while a thrust difference between the left and right motor pairs generates the roll moment and a thrust difference between the rear and front motor pairs generates the pitch moment. The yaw moment is instead produced by the imbalance of the reaction torques of the counter-rotating propellers. Changing the individual motor speeds therefore modifies both the total thrust and the three control moments about the body axes.

This connection between motor speeds, forces, and moments is central to the present thesis. The experimental analysis does not measure aerodynamic loads directly; instead, it uses the motor RPM signals recorded by the flight controller to infer how the drone reacts to atmospheric disturbances. When wind modifies the aerodynamic forces and moments acting on the vehicle, the flight controller attempts to maintain the commanded flight condition by changing the individual propeller speeds [8, 9, 10]. Consequently, a common variation across all four RPMs can be related to a change in the global thrust demand, a differential variation between the left/right or rear/front motor pairs can be related to roll- or pitch-compensating control action, and a differential variation consistent with the spin-direction convention can be related to yaw-compensating control action.

The purpose of this chapter is to build, step by step, the physical framework needed for this interpretation: the reference frames in which position, attitude, and wind are expressed, the relation between individual propeller thrusts and the total thrust

and control moments, and the rotational and translational dynamics that connect these moments to the observed motion of the vehicle.

2.2 Reference frames

The motion of the quadrotor is described using two main reference frames:

- the inertial frame $\mathcal{F}_I = \{O_I, \mathbf{e}_x^I, \mathbf{e}_y^I, \mathbf{e}_z^I\}$, fixed with respect to the Earth and used to describe the position and trajectory of the drone;
- the body-fixed frame $\mathcal{F}_B = \{O_B, \mathbf{e}_x^B, \mathbf{e}_y^B, \mathbf{e}_z^B\}$, attached to the quadrotor and translating and rotating with it.

Additional wind-related frames are then introduced: the conceptual wind frame $\mathcal{F}_W$, used for inflow decomposition, and the sensor-fixed anemometer frame $\mathcal{F}_A$, in which the wind is measured.

2.2.1 Inertial frame

The inertial frame is a local, Earth-fixed reference frame whose origin O_I is located at a convenient point on the ground, in this case the takeoff location. For the low-altitude and low-speed flight conditions considered in this thesis, the flat-Earth approximation is valid: the Earth's curvature and rotation are neglected, and $\mathcal{F}_I$ is treated as an inertial frame in the Newtonian sense. The x^I -axis and y^I -axis span the local horizontal plane, and the z^I -axis points vertically upward.

In the experimental interpretation used in the following chapters, this local inertial frame is taken as an East–North–Up frame: $\mathbf{e}_x^I$ points East, $\mathbf{e}_y^I$ points North, and $\mathbf{e}_z^I$ points vertically upward. The inertial frame is therefore the natural frame for describing the drone's position and trajectory, and for expressing the wind field in a common, ground-referenced coordinate system that does not depend on the drone's own heading.

2.2.2 Body-fixed frame

The origin of the body frame O_B is taken at the centre of mass of the vehicle. The body-fixed x^B -axis points forward, in the nose direction. The z^B -axis is aligned with the nominal thrust direction of the propellers and points upward in hover. The y^B -axis is chosen to complete a right-handed reference frame; with this convention, it points to the left of the vehicle when viewed from above. The body frame is the natural frame for describing the geometry of the propellers relative to the centre of mass, and is used in Section 2.3 to derive the total thrust and control moments from the individual propeller thrusts.

2.2.3 Anemometer measurement frame

The anemometer measurements are expressed in the sensor-fixed frame $\mathcal{F}_A = \{O_A, \mathbf{e}_U^A, \mathbf{e}_V^A, \mathbf{e}_W^A\}$. This frame is attached to the anemometer, not to the drone, and is therefore fixed in space during each acquisition. The wind velocity measured in this frame is

$$\mathbf{U}_w^A = \begin{bmatrix} U^A \\ V^A \\ W^A \end{bmatrix}, \quad (2.1)$$

where U^A , V^A , and W^A are the wind-velocity components along the three anemometer axes.

The orientation of $\mathcal{F}_A$ with respect to the inertial frame $\mathcal{F}_I$ depends on how the anemometer is installed. In the experimental setup used in this thesis, the anemometer was mounted on top of the pole with its reference mark aligned toward geographic North using a handheld compass. Before the measurements, the mounting was also levelled using a spirit level, so that the anemometer horizontal plane was approximately aligned with the local horizontal plane. With the sensor in its adopted output convention, this installation makes $\mathbf{e}_U^A$ approximately aligned with $\mathbf{e}_x^I$ (East), $\mathbf{e}_V^A$ with $\mathbf{e}_y^I$ (North), and $\mathbf{e}_W^A$ with $\mathbf{e}_z^I$ (upward). Under this alignment, U^A , V^A , and W^A can therefore be interpreted as eastward, northward, and upward wind-velocity components, respectively.

For a general installation, the horizontal orientation of $\mathcal{F}_A$ relative to $\mathcal{F}_I$ is described by the anemometer heading angle ψ_a , defined as the angle from the inertial East axis $\mathbf{e}_x^I$ to the anemometer axis $\mathbf{e}_U^A$. Since the anemometer is assumed to be mounted level, the transformation from the anemometer frame to the inertial frame is treated as a purely horizontal misalignment. Therefore, only a rotation about the vertical axis is required:

$$\mathbf{U}_w^I = \mathbf{R}_A^I \mathbf{U}_w^A = \begin{bmatrix} \cos \psi_a & -\sin \psi_a & 0 \\ \sin \psi_a & \cos \psi_a & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{U}_w^A. \quad (2.2)$$

A rotation of this form, about a single axis by an angle ψ_a , is commonly denoted $\mathbf{R}_z(\psi_a)$. This notation is introduced formally in Section 2.2.5, where it is combined with the analogous rotations $\mathbf{R}_x(\cdot)$ and $\mathbf{R}_y(\cdot)$ to describe the full three-dimensional attitude of the drone.

In Eq. (2.2), no roll or pitch rotation of the anemometer frame is included. This reflects the experimental assumption that the sensor is mounted level. Any residual roll or pitch misalignment of the anemometer housing is not corrected geometrically in the present work; instead, it is treated as an experimental limitation. With the adopted alignment procedure, the anemometer heading is taken as $\psi_a = 0$.

Consequently, the transformation from $\mathcal{F}_A$ to $\mathcal{F}_I$ reduces approximately to the identity, and the measured wind vector can be used as

$$\mathbf{U}_w^I = \mathbf{U}_w^A. \quad (2.3)$$

2.2.4 Aerodynamic wind frame

In rotorcraft aerodynamics, the aerodynamic effect of the incoming flow is often described by introducing a wind reference frame. This frame is not a measurement frame, but an auxiliary frame used to decompose the relative inflow seen by the rotor into two physically meaningful components: an axial component, parallel to the rotor axis, and an in-plane component, parallel to the rotor disk. This decomposition is the basis for the definition of the rotor inflow angle and of the advance ratio used in rotor aerodynamic models [11, 12], developed in detail in Chapter 3.

A conceptual wind frame

$$\mathcal{F}_W = \{O_B, \mathbf{e}_1^W, \mathbf{e}_2^W, \mathbf{e}_3^W\} \quad (2.4)$$

can be defined at the drone by choosing

$$\mathbf{e}_3^W = \mathbf{e}_z^B, \quad (2.5)$$

so that the wind frame shares the body-fixed rotor-axis direction. The axis $\mathbf{e}_1^W$ is aligned with the projection of the relative inflow onto the rotor disk plane, while the remaining axis is obtained from the right-handed convention,

$$\mathbf{e}_2^W = \mathbf{e}_3^W \times \mathbf{e}_1^W. \quad (2.6)$$

Figure 2.1 illustrates the three reference frames: $\mathcal{F}_I$ (ground-fixed inertial), $\mathcal{F}_B$ (body-fixed, attached to the drone), and $\mathcal{F}_W$ (wind frame for inflow decomposition).

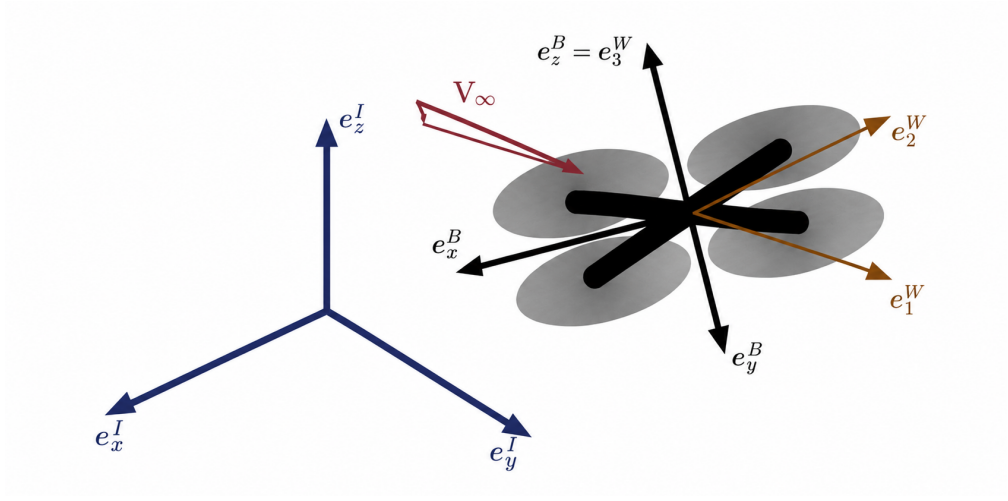


Figure 2.1: Inertial, body-fixed, and wind reference frames.

2.2.5 Position, velocity, and attitude representation

The position vector $\mathbf{r}^I$ connects the inertial origin O_I to the body-frame origin O_B . The position of the quadrotor centre of mass in the inertial frame is

$$\mathbf{r}^I = \begin{bmatrix} x & y & z \end{bmatrix}^T, \quad (2.7)$$

and the corresponding inertial velocity, used in Section 3.2 to relate the measured wind to the relative inflow seen by the rotors, is

$$\mathbf{v}^I = \dot{\mathbf{r}}^I = \begin{bmatrix} \dot{x} & \dot{y} & \dot{z} \end{bmatrix}^T. \quad (2.8)$$

Drone attitude (three-axis rotation). The attitude of the vehicle is represented using the Euler angles roll ϕ , pitch θ , and yaw ψ . Roll is the rotation about the body x^B -axis, pitch is the rotation about the body y^B -axis, and yaw is the rotation about the body z^B -axis. Using the ZYX yaw–pitch–roll rotation sequence, the rotation matrix from the body frame to the inertial frame is written as

$$\mathbf{R}_B^I = \mathbf{R}_z(\psi) \mathbf{R}_y(\theta) \mathbf{R}_x(\phi), \quad (2.9)$$

where

$$\mathbf{R}_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi & \cos \phi \end{bmatrix}, \quad (2.10)$$

$$\mathbf{R}_y(\theta) = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix}, \quad (2.11)$$

and

$$\mathbf{R}_z(\psi) = \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (2.12)$$

The inverse transformation, from the inertial frame to the body frame, is

$$\mathbf{R}_I^B = (\mathbf{R}_B^I)^T. \quad (2.13)$$

All three elementary rotations are required here because the drone attitude changes freely about all three axes during flight. $\mathbf{R}_B^I$ is used in Section 2.5 to project the propeller thrust from the body frame into the inertial frame; its inverse $\mathbf{R}_I^B$ is used in Section 3.2 to express the relative inflow in the body frame.

Angular velocity. The angular velocity of the quadrotor expressed in the body frame is

$$\boldsymbol{\omega}^B = \begin{bmatrix} p & q & r \end{bmatrix}^T, \quad (2.14)$$

where p , q , and r are the roll, pitch, and yaw body rates, respectively. This quantity is used directly in Section 2.4 to write the rotational equations of motion.

2.3 Propeller forces and moments

Having established the frames in which position, attitude, and wind are expressed, we now turn to the propellers themselves: how the four individual thrusts and reaction torques combine into the total thrust and control moments that ultimately determine the vehicle's motion.

The quadrotor considered in this thesis has four propellers arranged in an X-configuration. The physical parameters of the vehicle, namely the mass m and arm length L , are provided in Chapter 5, where the experimental platform is described in detail.

The thrust generated by propeller i is denoted by T_i , and the reaction torque generated by the same propeller is denoted by Q_i , with $i = 1, \dots, 4$.

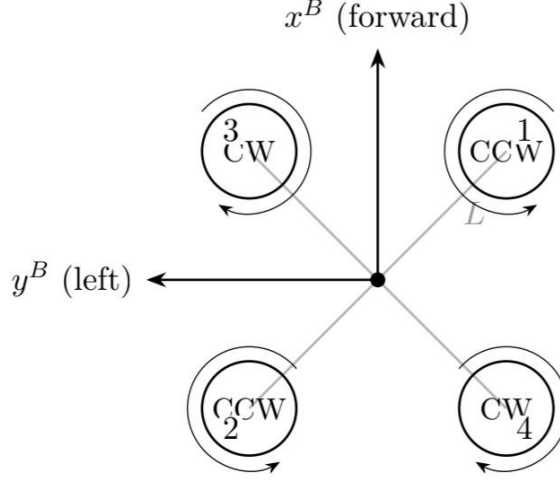


Figure 2.2: Quadrotor motor numbering convention.

The total thrust is

$$T_{\text{tot}} = T_1 + T_2 + T_3 + T_4. \quad (2.15)$$

In the body frame, the thrust vector is assumed to act along the positive body-fixed z^B -axis:

$$\mathbf{F}_T^B = \begin{bmatrix} 0 \\ 0 \\ T_{\text{tot}} \end{bmatrix}. \quad (2.16)$$

Let L be the distance between the centre of mass and each propeller. Since the vehicle is in X-configuration, the roll and pitch moment arms contain the factor $L/\sqrt{2}$. With the motor-numbering convention of Figure 2.2, the roll and pitch moments generated by the thrust forces can be written as

$$\begin{bmatrix} M_\phi \\ M_\theta \end{bmatrix} = \frac{L}{\sqrt{2}} \begin{bmatrix} -1 & 1 & 1 & -1 \\ -1 & 1 & -1 & 1 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix}. \quad (2.17)$$

Here M_ϕ and M_θ denote the control moments about the body x^B - and y^B -axes, respectively. The first row of Eq. (2.17) shows that the roll moment is generated by the thrust difference between the left motor pair (2,3) and the right motor pair (1,4). The second row shows that the pitch moment is generated by the thrust difference between the rear motor pair (2,4) and the front motor pair (1,3).

The yaw moment is generated by the reaction torques of the propellers. With the spin-direction convention of the quadrotor, the yaw moment is

$$M_\psi = -Q_1 - Q_2 + Q_3 + Q_4. \quad (2.18)$$

The control moment vector is therefore

$$\mathbf{M}_c^B = \begin{bmatrix} M_\phi \\ M_\theta \\ M_\psi \end{bmatrix}. \quad (2.19)$$

2.4 Rotational dynamics

The rotational motion of the quadrotor is governed by the Newton–Euler equation for a rigid body:

$$\mathbf{I}\dot{\boldsymbol{\omega}}^B + \boldsymbol{\omega}^B \times (\mathbf{I}\boldsymbol{\omega}^B) = \mathbf{M}^B, \quad (2.20)$$

where $\mathbf{I}$ is the inertia matrix of the vehicle and $\mathbf{M}^B$ is the total moment acting on the quadrotor, expressed in the body frame. Assuming the body axes are aligned with the principal axes of inertia, the inertia matrix is diagonal:

$$\mathbf{I} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix}. \quad (2.21)$$

The total moment can be decomposed as

$$\mathbf{M}^B = \mathbf{M}_c^B + \mathbf{M}_{\text{gyro}}^B + \mathbf{M}_{\text{aero}}^B, \quad (2.22)$$

where $\mathbf{M}_c^B$ is the control moment generated by the propellers (Eq. (2.19)), $\mathbf{M}_{\text{gyro}}^B$ is the gyroscopic moment arising from the angular momentum of the spinning rotors, and $\mathbf{M}_{\text{aero}}^B$ represents additional aerodynamic moments due to wind, body drag, rotor–wake interaction, and blade flapping.

In the present thesis, where the experiments are conducted in near-hover conditions and the focus is on atmospheric disturbances rather than aggressive manoeuvring, the gyroscopic rotor term is neglected because it is small relative to the control moments.

Substituting the diagonal inertia matrix into Eq. (2.20) and neglecting $\mathbf{M}_{\text{gyro}}^B$ gives

$$\begin{aligned} I_{xx}\dot{p} &= (I_{yy} - I_{zz})qr + M_\phi + M_{\text{aero},x}, \\ I_{yy}\dot{q} &= (I_{zz} - I_{xx})pr + M_\theta + M_{\text{aero},y}, \\ I_{zz}\dot{r} &= (I_{xx} - I_{yy})pq + M_\psi + M_{\text{aero},z}. \end{aligned} \quad (2.23)$$

The terms proportional to products of body rates, such as qr , pr , and pq , represent gyroscopic coupling associated with the rigid-body rotational motion. If the additional aerodynamic moments are neglected, the rotational equations reduce to

$$\begin{aligned} I_{xx}\dot{p} &= (I_{yy} - I_{zz})qr + \frac{L}{\sqrt{2}}(-T_1 + T_2 + T_3 - T_4), \\ I_{yy}\dot{q} &= (I_{zz} - I_{xx})pr + \frac{L}{\sqrt{2}}(-T_1 + T_2 - T_3 + T_4), \\ I_{zz}\dot{r} &= (I_{xx} - I_{yy})pq + (-Q_1 - Q_2 + Q_3 + Q_4). \end{aligned} \quad (2.24)$$

These equations show explicitly how the four propellers control the attitude of the vehicle. Roll is controlled by creating a thrust difference between the left and right motor pairs, whereas pitch is controlled by creating a thrust difference between the rear and front motor pairs. Yaw is controlled through the imbalance of the reaction torques of the counter-rotating propellers.

When an aerodynamic disturbance moment $M_{\text{aero},x}$, $M_{\text{aero},y}$, or $M_{\text{aero},z}$ acts on the vehicle, the flight controller acts to keep p , q , and r close to their commanded values by adjusting M_ϕ , M_θ , or M_ψ through Eqs. (2.17) and (2.18). This requires a redistribution of thrust, and therefore of RPM, between the relevant motor pairs: left/right for roll, rear/front for pitch, and the spin-direction groups for yaw. The observed RPM differential is thus an indicator of the control action taken by the flight controller, not a direct measurement of the aerodynamic moment itself. These differential RPM quantities are used in Chapter 6 and Chapter 7 to interpret the directional response of the flight controller to the measured wind field.

2.5 Translational dynamics

The translational motion follows Newton's second law:

$$m\ddot{\mathbf{r}}^I = \mathbf{F}^I, \quad (2.25)$$

where m is the mass of the quadrotor and $\mathbf{F}^I$ is the total force acting on the vehicle in the inertial frame. The thrust force is naturally expressed in the body frame as

$$\mathbf{F}_T^B = \begin{bmatrix} 0 \\ 0 \\ T_{\text{tot}} \end{bmatrix}, \quad (2.26)$$

and is transformed into the inertial frame using the rotation matrix $\mathbf{R}_B^I$ introduced in Section 2.2.5:

$$\mathbf{F}_T^I = \mathbf{R}_B^I \begin{bmatrix} 0 \\ 0 \\ T_{\text{tot}} \end{bmatrix}. \quad (2.27)$$

The gravitational force is

$$\mathbf{F}_g^I = \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix}. \quad (2.28)$$

Additional aerodynamic disturbances are collected in the vector $\mathbf{F}_{\text{aero}}^I$, which includes body drag, unsteady rotor loads, and wind-induced forces. The complete translational equation is then

$$m\ddot{\mathbf{r}}^I = \mathbf{R}_B^I \begin{bmatrix} 0 \\ 0 \\ T_{\text{tot}} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix} + \mathbf{F}_{\text{aero}}^I. \quad (2.29)$$

Neglecting $\mathbf{F}_{\text{aero}}^I$, the scalar equations become

$$\begin{aligned} m\ddot{x} &= (\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi) T_{\text{tot}}, \\ m\ddot{y} &= (\cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi) T_{\text{tot}}, \\ m\ddot{z} &= (\cos \phi \cos \theta) T_{\text{tot}} - mg. \end{aligned} \quad (2.30)$$

These equations highlight the role of attitude in quadrotor motion: the propellers generate thrust along the body-fixed vertical direction, but the orientation of the body determines how this thrust is projected into the inertial frame.

When $\phi = \theta = 0$, the thrust is vertical and the vehicle can hover if

$$T_{\text{tot}} = mg. \quad (2.31)$$

When the vehicle rolls or pitches, the thrust vector is tilted. As a result, part of the thrust contributes to horizontal acceleration, while only its vertical projection contributes to balancing the weight.

In outdoor flight, however, the aerodynamic force $\mathbf{F}_{\text{aero}}^I$ cannot generally be neglected. The vertical component of the force balance can therefore be written as

$$m\ddot{z} = T_{\text{tot}} \cos \phi \cos \theta - mg + F_{\text{aero},z}^I. \quad (2.32)$$

For quasi-hover conditions, where $\ddot{z}$ is small, this relation shows that the required total thrust depends not only on the vehicle weight, but also on the vertical aerodynamic force and on the attitude of the vehicle:

$$T_{\text{tot}} \simeq \frac{mg - F_{\text{aero},z}^I}{\cos \phi \cos \theta}. \quad (2.33)$$

Thus, an increase in mean RPM can indicate an increase in collective thrust demand, but this demand must be interpreted through the full force balance. It

may be caused by a vertical aerodynamic disturbance, by the loss of vertical thrust projection when the vehicle tilts to reject a horizontal wind disturbance, or by a combination of both effects.

This is why the mean RPM signal analysed in Chapter 6 cannot be interpreted independently of attitude and wind direction. The RPM variations are not a direct measurement of aerodynamic loading; they are the closed-loop response required to balance the projected thrust, gravity, and the wind-induced aerodynamic force.

Chapter 3

Rotor Inflow and Loading

3.1 Introduction

A quadrotor generates all of its forces and moments through its four propellers. Chapter 2 described how the individual propeller contributions combine, at vehicle level, into total thrust and control moments, and how variations in motor speed modify the translational and rotational response of the vehicle. However, the same motor speed does not always correspond to the same aerodynamic loading: the forces produced by a rotor also depend on the inflow conditions in which it operates. This chapter introduces the main inflow-related concepts needed to interpret the experimental wind–RPM analysis. The objective is qualitative. No propeller loads, thrust coefficients, or aerodynamic moments are computed; instead, the chapter provides the physical vocabulary required to understand why atmospheric wind can affect the measured RPM signals. In particular, the discussion focuses on the distinction between axial and non-axial inflow, on the directional nature of rotor loading in the presence of horizontal wind components, and on the possible influence of rotor wakes on the wind measurement itself.

3.2 Relative inflow and inflow geometry

The quantity that actually loads the rotors is not the atmospheric wind by itself, but the velocity of the air relative to the vehicle [12, 13].

The wind vector $\mathbf{U}_w^I$ is the atmospheric wind velocity measured at the anemometer location with respect to the ground and expressed in the inertial frame. The relative inflow expressed in the inertial frame is defined as

$$\mathbf{V}_\infty^I = \mathbf{U}_w^I - \mathbf{v}^I, \quad (3.1)$$

where $\mathbf{v}^I$ is the drone velocity with respect to the ground.

The same relative inflow expressed in the body frame, using the inertial-to-body rotation $\mathbf{R}_I^B$ is

$$\mathbf{V}_\infty^B = \mathbf{R}_I^B \mathbf{V}_\infty^I = \begin{bmatrix} V_{\infty,x}^B \\ V_{\infty,y}^B \\ V_{\infty,z}^B \end{bmatrix}. \quad (3.2)$$

The scalar quantity V_∞ denotes the magnitude of this relative inflow:

$$V_\infty = \|\mathbf{V}_\infty^B\|. \quad (3.3)$$

For a propeller with axis $\mathbf{n}_R = \mathbf{e}_z^B$,

$$\mathbf{n}_R = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \quad (3.4)$$

this vector splits naturally into an axial component, along $\mathbf{n}_R$, and an in-plane component, in the rotor disk:

$$V_{\infty,a} = |\mathbf{V}_\infty^B \cdot \mathbf{n}_R| = |V_{\infty,z}^B|, \quad (3.5)$$

$$V_{\infty,h} = \sqrt{(V_{\infty,x}^B)^2 + (V_{\infty,y}^B)^2}, \quad (3.6)$$

with $V_\infty = \sqrt{V_{\infty,a}^2 + V_{\infty,h}^2} = \|\mathbf{V}_\infty^B\|$. The orientation of the inflow relative to the rotor is captured by a single angle,

$$\alpha_i = \text{atan2}(V_{\infty,h}, V_{\infty,a}), \quad (3.7)$$

illustrated in Figure 3.1. $\alpha_i = 0$ corresponds to purely axial inflow, as in ideal hover; $\alpha_i > 0$ indicates oblique inflow, produced by horizontal drone motion, a tilted attitude, or lateral wind.

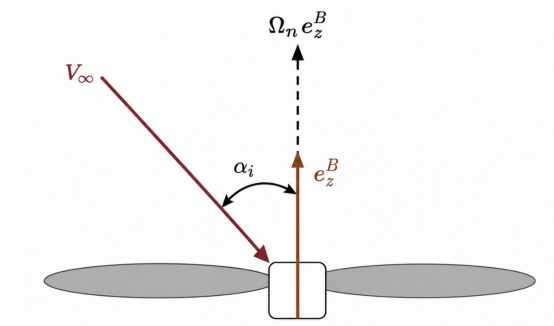


Figure 3.1: Rotor inflow angle geometry.

3.3 Edgewise loading

When the in-plane component of the relative inflow is non-zero, the rotor operates in edgewise flow [12, 14, 13]. In this condition, the air does not approach the propeller only along the rotor axis, as in ideal hover, but also has a component in the rotor plane.

The physical mechanism can be understood by considering a blade section during one revolution. The section has a tangential velocity due to the rotation of the propeller, while the incoming air has an additional in-plane velocity component. On one side of the rotor disk, the blade motion and the in-plane flow component act in the same sense, increasing the local relative velocity seen by the blade section. On the opposite side, they partially oppose each other, reducing the local relative velocity. As a result, the aerodynamic loading is not uniform around the azimuth of the rotor disk.

For the present thesis, the important consequence is not the detailed blade-element distribution, but its vehicle-level effect. A propeller subjected to edgewise flow may produce a different effective force and moment contribution than the same propeller operating at the same RPM in purely axial inflow. Therefore, a horizontal wind component can disturb the attitude and translational equilibrium of the quadrotor even without an initial change in the commanded motor speeds.

The onboard controller then reacts to the resulting attitude or position error by changing the motor commands. Since roll and pitch control are obtained by redistributing thrust between opposite rotor pairs, this compensation is expected to appear mainly in the differential-RPM quantities rather than only in the mean RPM. A lateral wind component, for example, may require a roll correction, while a longitudinal wind component may require a pitch correction. This provides the physical reason for analysing the wind components in the body-heading frame and comparing them with the corresponding differential-RPM signals in Chapter 6.

3.4 Rotor wake effects and anemometer contamination

The wake generated by the four rotors is present whenever the propellers produce thrust, also in ideal hover. Non-axial inflow does not generate the wake itself, but it modifies its orientation and transport. In hover with no horizontal wind, the rotor-induced flow is mainly directed downwards along the rotor axes. When a horizontal wind component or vehicle motion is present, the wake can be tilted and convected downstream with respect to the drone.

This point is important for the present experimental setup because the wind is measured by a fixed anemometer placed near the flight region, not directly at the

rotors. If the drone operates sufficiently close to the anemometer, the sensor may measure a flow field that is partly affected by the drone-induced wake. In that case, the measured velocity would no longer represent only the undisturbed atmospheric wind, but rather a combination of the ambient wind and the local flow disturbance produced by the vehicle.

For this reason, the drone–anemometer separation is treated in this thesis as an experimental design parameter. A shorter separation improves the physical relevance of any wind–RPM delay estimate, because the wind is measured closer to the drone. At the same time, it increases the risk that the anemometer measurement is contaminated by near-field aerodynamic interference from the vehicle. Conversely, a larger separation reduces the risk of rotor-wake contamination, but makes the connection between the measured wind fluctuation and the inflow actually experienced by the drone less direct.

A related but distinct effect concerns the interaction between the rotors of the same vehicle [15, 16]. In the presence of a horizontal inflow component, the wake shed by one rotor may be convected towards a neighbouring rotor. As a result, two rotors operating at the same commanded RPM may experience different local inflow conditions. This rotor-to-rotor interaction is not resolved by the present setup, which provides only a single vehicle-level inflow estimate from the fixed anemometer, and is therefore not quantified further in this thesis.

Chapter 4

Atmospheric Wind Characterization

4.1 Introduction

Chapter 3 showed that a non-zero in-plane component of the relative inflow $\mathbf{V}_\infty$ places a rotor in edgewise flow and, through the resulting azimuthal asymmetry in blade loading, forces the flight controller to redistribute thrust between motor pairs. That argument was expressed in terms of $\mathbf{V}_\infty$, the velocity of the air relative to the vehicle – a quantity not measured directly in this campaign. What is measured is the wind vector recorded by a fixed anemometer at a different location from the drone.

This chapter first establishes the condition under which the measured wind vector can represent $\mathbf{V}_\infty$, and then builds, step by step, the description of that measured signal used throughout the wind–RPM analysis of Chapter 6 and the case studies of Chapter 7.

4.2 Measured wind vector and the quasi-hover approximation

The atmospheric wind measured by the anemometer is a three-dimensional velocity vector. In the anemometer frame $\mathcal{F}_A$ introduced in Chapter 2, it is written as

$$\mathbf{U}_w^A(t) = \begin{bmatrix} U^A(t) \\ V^A(t) \\ W^A(t) \end{bmatrix}, \quad (4.1)$$

where U^A , V^A , and W^A are the signed wind-velocity components reported by the sensor. As established in Chapter 2, the anemometer reference mark was aligned with geographic North before each session, so that $\psi_a = 0$ and $\mathbf{U}_w^I = \mathbf{U}_w^A$: the anemometer-frame components coincide with the geographic components U_E and V_N used in Chapter 6. This vector is the experimental wind input available in the thesis; it should not be interpreted as a direct measurement of the aerodynamic force acting on the drone, nor as the exact inflow at each rotor.

Chapter 3 defined the relative inflow in the inertial frame as $\mathbf{V}_\infty^I = \mathbf{U}_w^I - \mathbf{v}^I$ (Eq. (3.1)), where $\mathbf{v}^I$ is the drone ground velocity. Evaluating this relation would require subtracting the GPS-derived drone velocity from the measured wind at every sample, which introduces its own noise and is unnecessary when the drone is commanded to near-stationary flight. Since all sessions analysed in this thesis are flown in altitude/position-hold or equivalent low-drift modes, $\|\mathbf{v}^I\|$ is small compared with the wind speeds encountered, and the relative inflow is approximated by the measured wind alone:

$$\mathbf{V}_\infty \approx \mathbf{U}_w^I = \mathbf{U}_w^A, \quad \text{valid when } \|\mathbf{v}^I\| \ll \|\mathbf{U}_w^I\|. \quad (4.2)$$

This quasi-hover approximation is what justifies using the anemometer record directly as the wind-RPM correlation input without a per-sample drone-velocity correction.

4.3 Three-dimensional wind-speed descriptors and turbulence intensity

From the measured wind components, the instantaneous three-dimensional wind-speed magnitude is defined as

$$S(t) = \|\mathbf{U}_w^A(t)\| = \sqrt{(U^A(t))^2 + (V^A(t))^2 + (W^A(t))^2}. \quad (4.3)$$

This scalar quantity describes the overall intensity of the measured wind. In this thesis, $S(t)$ is mainly used to identify strong wind-speed excursions and to compare scalar wind-intensity variations with the mean-RPM response. However, because it contains no information about the wind direction, it cannot by itself explain pitch- or roll-related RPM asymmetries.

The mean three-dimensional wind-speed magnitude over an acquisition window is

$$\bar{S} = \frac{1}{N} \sum_{i=1}^N S(t_i), \quad (4.4)$$

where N is the number of samples in the triggered acquisition interval.

Since the wind measured during a flight session is not steady, separating the mean operating condition from its unsteadiness is necessary [2] because two sessions may have similar mean wind speeds but very different fluctuation levels. For a generic wind-related signal $x(t)$, the Reynolds decomposition separates the mean and fluctuating parts [17, 18]:

$$x(t) = \bar{x} + x'(t), \quad (4.5)$$

where $\bar{x}$ is the average over the acquisition window and $x'(t)$ is the instantaneous deviation from that average. Applied to the three measured wind components, this gives

$$U^A(t) = \bar{U}^A + u'(t), \quad (4.6)$$

$$V^A(t) = \bar{V}^A + v'(t), \quad W^A(t) = \bar{W}^A + w'(t). \quad (4.7)$$

The corresponding mean components are

$$\bar{U}^A = \frac{1}{N} \sum_{i=1}^N U^A(t_i), \quad \bar{V}^A = \frac{1}{N} \sum_{i=1}^N V^A(t_i), \quad \bar{W}^A = \frac{1}{N} \sum_{i=1}^N W^A(t_i). \quad (4.8)$$

The fluctuation level of each component is quantified by its sample standard deviation over the same window:

$$\sigma_u = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (U^A(t_i) - \bar{U}^A)^2}, \quad \sigma_v = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (V^A(t_i) - \bar{V}^A)^2}, \quad (4.9)$$

$$\sigma_w = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (W^A(t_i) - \bar{W}^A)^2}. \quad (4.10)$$

Normalizing these fluctuation levels by the mean wind-speed magnitude gives the component turbulence intensities

$$I_u = \frac{\sigma_u}{\bar{S}}, \quad I_v = \frac{\sigma_v}{\bar{S}}, \quad I_w = \frac{\sigma_w}{\bar{S}}. \quad (4.11)$$

A scalar three-dimensional turbulence intensity is then defined as

$$TI = \frac{\sqrt{\frac{\sigma_u^2 + \sigma_v^2 + \sigma_w^2}{3}}}{\bar{S}}. \quad (4.12)$$

This quantity provides a compact measure of the overall unsteadiness of the measured three-dimensional wind vector [19, 20]. Unlike a descriptor based only on the horizontal plane, TI includes the fluctuation level of all three measured

velocity components and is therefore useful for comparing the global atmospheric unsteadiness of different sessions.

In this thesis, TI is used together with the horizontal turbulence intensity TI_h , introduced in the following section. The two quantities are not interchangeable. TI characterizes the fluctuation level of the full measured wind vector, whereas TI_h focuses only on the variability of the horizontal wind-speed magnitude, which is more directly related to the in-plane inflow responsible for pitch- and roll-related RPM responses.

4.4 Horizontal wind forcing, direction, and horizontal turbulence intensity

The horizontal component of the wind is the part most directly connected to the in-plane inflow and the resulting edgewise loading discussed in Chapter 3 (Section 3.3). For this reason, the horizontal wind-speed magnitude is defined as

$$S_h(t) = \sqrt{(U^A(t))^2 + (V^A(t))^2}. \quad (4.13)$$

The quantity $S_h(t)$ describes the intensity of the horizontal wind forcing. It is the main scalar wind descriptor used to compare the strength of the horizontal disturbance between acquisition sessions. Nevertheless, $S_h(t)$ is still a magnitude: it does not indicate whether the wind acts mainly along the drone forward direction, along the lateral direction, or from an intermediate angle. Therefore, the associated wind direction must be considered separately.

The horizontal wind direction in the anemometer frame is defined, using the vector *toward* convention, as

$$\chi_w^A(t) = \text{atan2}(V^A(t), U^A(t)). \quad (4.14)$$

This angle gives the direction toward which the horizontal wind is blowing. It is needed because the drone response depends not only on wind intensity, but also on the orientation of the wind relative to the vehicle. In Chapter 6, χ_w^A is used to classify the anemometer–drone geometry and to project the horizontal wind into the drone body-heading frame before comparison with the pitch- and roll-related RPM differentials.

The mean horizontal wind-speed magnitude over an acquisition window is

$$\overline{S_h} = \frac{1}{N} \sum_{i=1}^N S_h(t_i). \quad (4.15)$$

This quantity is used to compare the average horizontal wind forcing between different acquisition sessions and mast heights.

The absolute fluctuation level of the horizontal wind-speed magnitude is quantified by

$$\sigma_{S_h} = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (S_h(t_i) - \bar{S}_h)^2}. \quad (4.16)$$

However, σ_{S_h} alone is not sufficient to compare sessions with different mean wind levels. The same absolute fluctuation may be more significant in a low-wind session than in a high-wind session. Therefore, the horizontal turbulence intensity is defined as

$$TI_h = \frac{\sigma_{S_h}}{\bar{S}_h}. \quad (4.17)$$

While TI describes the overall fluctuation level of the measured wind vector, TI_h isolates the variability of the horizontal wind-speed magnitude.

4.5 Short-duration wind-speed excursions

The mean wind descriptors introduced above, such as $\bar{S}$, $\bar{S}_h$, TI , and TI_h , characterize the overall wind condition during an acquisition window. However, they do not identify individual transient events. A session may have a moderate turbulence intensity but still contain one strong, short-duration wind-speed increase. Conversely, a session with a high fluctuation level may not contain a single clearly isolated event. For this reason, additional metrics are introduced to identify the strongest wind-speed excursions within each session.

The first metric is the maximum instantaneous wind-speed increase above the session mean:

$$\Delta S_{\max} = S_{\max} - \bar{S}, \quad S_{\max} = \max_t S(t), \quad (4.18)$$

where $\bar{S}$ is the mean three-dimensional wind-speed magnitude over the same acquisition window. The quantity $\Delta S_{\max}$ measures how much the largest instantaneous wind-speed value exceeds the average wind level of the session. It is therefore useful for identifying the absolute strength of the strongest measured peak.

However, because $\Delta S_{\max}$ is based on a single maximum value, it may be dominated by a very short spike. Such a spike does not necessarily represent a wind event long enough to produce a coordinated attitude or RPM response. To distinguish isolated peaks from more sustained wind-speed increases, a moving average of the wind-speed magnitude is introduced.

For a window duration $T_w = 3$ s, the three-second moving average is defined in continuous form as

$$S_{3s}(t) = \frac{1}{T_w} \int_{t-T_w/2}^{t+T_w/2} S(t') dt', \quad T_w = 3 \text{ s}. \quad (4.19)$$

This operation assigns to each time instant t the average value of the wind speed over a three-second interval centred on that instant. In other words, $S_{3s}(t)$ is a smoothed version of $S(t)$: the window is placed around the current time, the average wind speed inside the window is computed, and the window is then moved forward along the signal.

In the discrete post-processing, the wind signal is available on the common analysis grid introduced in Chapter 6. If the sampling interval is $\Delta t = 1/f_{\text{com}}$, the number of samples in the moving window is approximately

$$N_w = T_w f_{\text{com}}. \quad (4.20)$$

For the analysis frequency used in this thesis, $f_{\text{com}} = 10$ Hz, a three-second window therefore contains approximately 30 samples. The discrete moving average can be written schematically as

$$S_{3s}(t_i) = \frac{1}{N_w} \sum_{j \in \mathcal{W}_i} S(t_j), \quad (4.21)$$

where $\mathcal{W}_i$ is the set of samples contained in the three-second window centred around t_i .

Practically, this is not a block average over separate intervals such as 0–3 s, 3 s–6 s, and so on. Instead, the window slides along the signal. At 10 Hz, the window is shifted by one sample, namely $\Delta t = 0.1$ s, at each step. For example, the first window may cover approximately 0–3 s and be associated with its central time $t = 1.5$ s; the next window covers 0.1 s–3.1 s and is associated with $t = 1.6$ s; the procedure is then repeated over the full acquisition window.

The strongest sustained short-duration wind event in the session is defined as

$$S_{3s,\text{max}} = \max_t S_{3s}(t). \quad (4.22)$$

The quantity $S_{3s,\text{max}}$ is therefore the largest three-second averaged wind speed observed during the acquisition. It identifies the interval in which the wind speed remains most elevated over a duration comparable with the transient RPM and attitude responses analysed in Chapter 7.

In this thesis, $S_{3s,\text{max}}$ is not used as an official meteorological gust statistic. It is an experimental descriptor adapted to the duration of the acquisition windows and to the objective of the wind–RPM analysis. Its role is to locate the strongest short-duration wind event that can be compared with the simultaneous mean-RPM, differential-RPM, and attitude signals.

4.6 Integral time and length scales

ΔS_{max} and $S_{3s,\text{max}}$ describe the amplitude of a wind excursion, but they do not provide information about the characteristic time over which turbulent fluctuations

remain correlated. This time scale is useful to assess whether a 60 s acquisition window contains many independent turbulent structures, or whether it is dominated by only a few large-scale events.

The temporal persistence of the turbulence is quantified through the normalized autocorrelation function of the along-wind fluctuation $u'(t)$:

$$\rho_{uu}(\tau) = \frac{\langle u'(t) u'(t + \tau) \rangle}{\sigma_u^2}, \quad (4.23)$$

where τ is the time lag and $\langle \cdot \rangle$ denotes the time average over the session. By definition, $\rho_{uu}(0) = 1$, because the signal is perfectly correlated with itself at zero time lag. As τ increases, the correlation usually decreases: values of $u'(t + \tau)$ become progressively less related to values of $u'(t)$. The first zero-crossing τ_0 is the first positive time lag at which the autocorrelation reaches zero, or changes sign from positive to negative. It therefore represents the first time lag at which the fluctuation can be considered decorrelated from its initial value.

The integral time scale is then defined as the area under the positive part of the autocorrelation curve:

$$T_u = \int_0^{\tau_0} \rho_{uu}(\tau) d\tau. \quad (4.24)$$

Integrating only up to the first zero-crossing avoids including the noisy or negative tail of the autocorrelation function, where the signal has already lost its physical memory of the initial fluctuation.

Through Taylor's frozen-turbulence hypothesis [21], which assumes that turbulent structures are advected past the sensor by the mean flow without evolving significantly during that advection, the integral time scale can be converted into an integral length scale:

$$L_u = \bar{S} T_u. \quad (4.25)$$

Here, L_u represents the characteristic streamwise size of the turbulent structures associated with the measured along-wind fluctuation, under the frozen-turbulence assumption.

In this thesis, T_u and L_u are not used as inputs to the wind-RPM correlation itself. They are diagnostic quantities, computed for each session in Chapter 6, and used in the limitations discussion of Chapter 8. Their role is to assess whether the 60 s acquisition window is long enough to contain several independent turbulent structures and whether the frozen-turbulence assumption underlying L_u and the convective-delay estimate is reasonable relative to the anemometer-drone separation.

4.7 Spectral content of the wind

The descriptors introduced so far are time-domain quantities. They quantify mean values, fluctuation levels, gust amplitudes, and characteristic time scales, but they do not indicate how the fluctuation energy is distributed over frequency. This information is important because the drone response depends not only on the amplitude of a wind disturbance, but also on how rapidly that disturbance varies in time. Slow wind variations may be followed by the flight controller through attitude and thrust adjustments, while faster fluctuations may be attenuated by motor dynamics, rotor inertia, onboard filtering, and controller bandwidth.

For this reason, the wind signal is also examined in the frequency domain through the power spectral density, PSD. For a fluctuating signal $u'(t)$, the PSD $\Phi_{uu}(f)$ describes how the variance of the signal is distributed among frequencies. It satisfies

$$\sigma_u^2 = \int_0^\infty \Phi_{uu}(f) df, \quad (4.26)$$

meaning that the area under the PSD curve is equal to the variance of the fluctuating signal.

In practice, the PSD is estimated from the sampled time series. First, the mean value is removed from the signal, so that only the fluctuation is analysed:

$$u'(t_i) = u(t_i) - \bar{u}. \quad (4.27)$$

The fluctuating signal is then transformed from the time domain to the frequency domain using a Fourier transform. For a discrete signal, this operation decomposes the time history into sinusoidal components at different frequencies. The squared magnitude of each Fourier coefficient gives the contribution of that frequency to the signal variance, after the appropriate normalization by the sampling frequency and record length.

In this thesis, the PSD is estimated using Welch's method [22]. Instead of computing one spectrum from the entire 60 s record, the signal is divided into shorter, partly overlapping segments. Each segment is multiplied by a window function, transformed into the frequency domain, and converted into a periodogram. The final PSD estimate is obtained by averaging the periodograms of all segments. This averaging reduces the variability of the spectral estimate compared with a single Fourier transform of the full signal.

Schematically, for a sampled fluctuation signal u'_n with sampling frequency f_s , the Fourier transform of one windowed segment is

$$\hat{u}_k(f_m) = \sum_{n=0}^{N_s-1} w_n u'_{k,n} e^{-i2\pi mn/N_s}, \quad (4.28)$$

where w_n is the window function, N_s is the number of samples in one segment, and k identifies the segment. The corresponding periodogram is proportional to

$$P_k(f_m) \propto |\hat{u}_k(f_m)|^2. \quad (4.29)$$

Welch's PSD estimate is then obtained by averaging these periodograms:

$$\Phi_{uu}(f_m) = \frac{1}{K} \sum_{k=1}^K P_k(f_m), \quad (4.30)$$

where K is the number of segments. The exact normalization depends on the sampling frequency and on the chosen window, and is handled in the numerical implementation.

In this thesis, the PSD is used only as a qualitative frequency-domain comparison between wind and RPM signals. It is not used to validate an inertial subrange [23] or to estimate a wind-to-RPM transfer function. The purpose of the spectral comparison is to check whether the wind and RPM signals contain energy over comparable frequency ranges. If they do, this provides supporting evidence that the controller is responding to wind-induced disturbances, although it does not by itself establish causality, because the RPM response also depends on flight-controller logic, motor dynamics, rotor inertia, and sensor filtering.

Chapter 5

Experimental Setup

5.1 Introduction

The objective of the experimental campaign is to measure the atmospheric wind field near a quadrotor during outdoor flight and to analyse the corresponding response of the onboard flight controller through the motor RPM signals. The setup is therefore built around two synchronized measurement systems: a fixed ultrasonic anemometer, which provides the three-dimensional wind velocity near the flight region, and the drone telemetry/logging system, which provides the motor speeds, attitude, altitude, inertial quantities, and position information.

The anemometer is not mounted on the drone. Instead, it is installed on a fixed pole located in the proximity of the commanded flight region. This choice allows the atmospheric wind to be measured independently from the drone-mounted hardware and avoids modifying the vehicle mass, inertia, centre of gravity, and aerodynamic configuration. The measured wind is therefore treated as an external atmospheric reference signal, while the RPM signals represent the controller-mediated response of the quadrotor to the measured wind conditions.

The experimental setup must satisfy three practical requirements. First, the wind measurements and the flight-controller data must be synchronized accurately enough to allow time-domain comparison, cross-correlation, and spectral analysis. Second, the quadrotor must be mechanically prepared so that systematic RPM offsets due to mass imbalance or propeller-axis misalignment are minimized before the outdoor tests. Third, the relative position between the anemometer and the drone must be documented, because it determines the geometric interpretation of the measured wind signal in the analysis.

This chapter describes the quadrotor platform, the wind measurement system, the anemometer mounting configuration, the flight mission, the pre-test preparation, and the experimental procedure followed during the campaign.

5.2 Quadrotor platform

The UAV used in the experimental campaign is a Holybro X500 V2 quadrotor [24] equipped with a Pixhawk 6X flight controller [25]. The vehicle has four brushless motors arranged in an X-configuration, each driving a two-bladed fixed-pitch propeller. This configuration is the same one used in Chapter 2 to define the motor-numbering convention and the relation between individual propeller thrusts, total thrust, and roll, pitch, and yaw control moments.

In this thesis, the quadrotor is not used to directly measure aerodynamic forces or moments. Instead, it is considered as an instrumented closed-loop system. The wind disturbs the vehicle, and the flight controller reacts by changing the individual motor speeds. The RPM signals are therefore the main response variables of the experiment. The mean RPM is associated with the collective thrust demand, while differential-RPM quantities are associated with roll-, pitch-, and yaw-compensating control actions.



Figure 5.1: Quadrotor platform

5.2.1 Physical parameters

The physical parameters of the Holybro X500 V2 platform are summarized in Table 5.1. The mass determines the hover thrust requirement, the arm length determines the moment generated by a given thrust imbalance.

Table 5.1: Physical parameters of the Holybro X500 V2 quadrotor.

Parameter	Symbol	Value
Airframe mass without battery	m_{frame}	1.214 kg
4,000 mAh battery mass	m_{bat}	0.414 kg
Propeller-axis to propeller-axis distance	$2L$	500 mm
Arm length, centre of mass to motor	L	0.250 m

5.2.2 Propulsion system

The X500 V2 is powered by a lithium polymer battery mounted below the central body of the vehicle. A battery capacity of 4,000 mAh is used during the campaign with nominal voltage 14.8 V. The battery voltage decreases during flight as the charge is depleted; for this reason, the voltage is monitored in the telemetry data to verify that the tests are performed within normal operating conditions.

The platform is equipped with four Holybro 2216-920KV brushless DC motors. The designation 920 KV indicates the approximate no-load rotational speed per volt of supply. Two motors rotate clockwise and two counter-clockwise, following the yaw-torque balance convention introduced in Chapter 2. Each motor drives a Holybro 1045 two-bladed fixed-pitch propeller, with a diameter of 10 in.

The propellers are the aerodynamic actuators of the vehicle. Variations in their rotational speed change the thrust and reaction torque generated by each motor. For this reason, the four RPM time series are the central output signals used in this thesis to analyse the response of the flight controller to atmospheric wind disturbances.



(a) Holybro 2216-920KV brushless motor.



(b) Holybro 1045 fixed-pitch propellers.

Figure 5.2: Propulsion system components used on the Holybro X500 V2 platform.

5.2.3 Flight controller and onboard telemetry

The Pixhawk 6X flight controller is the core of the onboard sensing and control system. It stabilizes the vehicle by fusing inertial, barometric, magnetic, and GNSS measurements, and by computing the motor commands required by the selected flight mode. The controller also records the onboard telemetry to a `.BIN` log file, which is the primary source of the drone data used in the analysis.

The onboard sensors used in the present thesis are:

- the IMU stream, which provides body angular rates and specific force;
- the attitude estimate, which provides roll, pitch, and yaw;
- the barometric altitude estimate, used to verify altitude-hold behaviour;
- the GNSS data, used to reconstruct the drone position relative to the anemometer;
- the ESC telemetry, which provides the individual motor RPM signals.



Figure 5.3: Pixhawk 6X Flight Controller

The RPM signals used in the analysis are extracted from the onboard `.BIN` log rather than from the real-time MAVLink telemetry stream received on the ground-station PC. The telemetry radio link is mainly intended for flight monitoring and has limited bandwidth; therefore, the RPM messages received in real time may be downsampled, delayed, or affected by communication dropouts. The onboard `.BIN` log is instead recorded directly by the flight controller and contains the ESC telemetry in the onboard time base, making it the most reliable source for the individual motor RPM signals.

The PC-side MAVLink stream is used for synchronization rather than for RPM analysis. In particular, it provides the RC10 trigger information associated with the SA switch movement and allows the `TEST_START` marker to be recorded on the PC side. This marker is then used to align the anemometer data, the PC-side

telemetry file, and the onboard .BIN log, as described in Chapter 6.

5.3 Wind measurement system

The atmospheric wind is measured using a LI-550P TriSonica™ Mini ultrasonic anemometer [26]. The sensor provides the three-dimensional wind velocity in the anemometer-fixed frame introduced in Chapter 2, together with environmental quantities such as air temperature, pressure, and relative humidity.

The primary wind variables used in this thesis are the velocity components

$$U^A(t), \quad V^A(t), \quad W^A(t), \quad (5.1)$$

from which the wind-speed magnitude $S(t)$, the horizontal wind-speed magnitude $S_h(t)$, and the horizontal wind direction $\chi_w^A(t)$ are derived. The anemometer is configured to output serial data through the RS-232 interface at 40 Hz.



Figure 5.4: LI-550P TriSonica™ Mini

5.3.1 Anemometer specifications

The main specifications of the LI-550P TriSonica™ Mini used in the campaign are summarized in Table 5.2.

The sensor also provides pitch and roll tilt indicators of the anemometer body. These quantities are not related to the drone attitude. They are retained as measurement-quality indicators because they describe the inclination of the sensor body during the acquisition.

Table 5.2: LI-550P anemometer specifications.

Parameter	Value
Measurement principle	Ultrasonic time-of-flight
Wind-speed range	0 m/s to 50 m/s
Wind-speed accuracy, 0 m/s to 10 m/s	± 0.2 m/s
Wind-speed resolution	0.01 m/s
Horizontal direction accuracy	$\pm 1^\circ$
Vertical wind-component accuracy	± 0.2 m/s
Maximum output rate	40 Hz
Temperature accuracy	$\pm 2^\circ\text{C}$
Pressure accuracy	± 1.0 kPa
Relative humidity accuracy	$\pm 3\%$ RH
Output interface	RS-232, RS-422, UART

5.4 Anemometer mounting configuration

During the experiments, the LI-550P anemometer is mounted on top of a pole at the nominal flight altitude of each test configuration. The campaign uses three mast heights:

$$h = 2.2 \text{ m}, \quad h = 5.35 \text{ m}, \quad h = 15.35 \text{ m}. \quad (5.2)$$

These heights are selected to sample different low-altitude wind conditions while keeping the anemometer and the drone at comparable nominal heights during each test.

Before each measurement session, the anemometer reference mark is manually aligned toward geographic North using a handheld compass. The mast verticality and the sensor mounting are also checked using a spirit level. With this alignment, the anemometer components can be interpreted according to the convention defined in Chapter 2: U^A approximately eastward, V^A approximately northward, and W^A upward.

The drone is flown at prescribed positions relative to the pole. The horizontal drone–anemometer separation and the mean wind direction are later used in Chapter 6 to classify each session as upstream, crosswind, or downstream. This geometric classification determines how the measured wind time series is compared with the RPM response in Chapter 7.

5.5 Ground station, mission, and acquisition logic

The ground station software used during the campaign is Mission Planner, connected to the Pixhawk 6X flight controller through a telemetry radio link. Mission Planner is used before flight to configure the autopilot, verify sensor calibration, check the GNSS fix, monitor the battery status, and upload the waypoint mission to the vehicle.

The onboard firmware is ArduCopter, part of the ArduPilot autopilot suite. ArduCopter performs attitude estimation, altitude and position control, motor mixing, and onboard telemetry logging. During the triggered acquisition itself, Mission Planner is closed because the Python acquisition script requires direct access to the telemetry serial port.

5.5.1 AUTO mission sequence

The flight tests are performed using an ArduPilot AUTO mission. The purpose of the mission is to place the drone at a prescribed location and altitude relative to the anemometer, align its yaw, and maintain a quasi-stationary condition during the acquisition window.

The mission sequence consists of:

1. NAV_TAKEOFF: the drone takes off to the prescribed altitude;
2. NAV_WAYPOINT: the drone flies to the target position relative to the anemometer;
3. CONDITION_YAW: the drone heading is commanded to align with geographic North;
4. NAV_DELAY: the drone holds the target position and altitude for a duration longer than the acquisition window;
5. NAV_LAND: the drone lands after completion of the mission.

The yaw command is included so that the drone heading is aligned with the anemometer reference direction before the acquisition begins. This simplifies the interpretation of the body-heading wind components introduced in Chapter 6.

During the NAV_DELAY phase, the drone holds the commanded position and altitude. The triggered acquisition is started only once the vehicle has reached this hold phase and the operator has verified that the flight condition is stable.

5.5.2 Radio-channel trigger

The acquisition trigger is assigned to the transmitter switch SA, connected to radio channel RC10. This channel is not used for flight-control commands during the experiment; it is used only to trigger the data acquisition.



Figure 5.5: Remote controller

The trigger logic is:

- SA in the neutral position: pre-trigger idle condition;
- SA moved down: RC10 crosses the start threshold and the acquisition script writes a `TEST_START` marker;
- after 60s: the acquisition script automatically writes a `TEST_END` marker and saves the data files.

The stop time is therefore not defined by a manual switch movement, but by the fixed-duration timer of the acquisition script. This creates a repeatable 60 s acquisition window for each test. The same trigger marker is recorded in the anemometer serial log and in the PC-side MAVLink telemetry file, providing the synchronization information used in Chapter 6.

5.5.3 Flight modes

Most acquisitions are performed during the AUTO mission hold phase. In some sessions, the pilot switches to alternative flight modes when operational conditions require it. The two relevant modes are:

- `POSHOLD`, in which the flight controller maintains horizontal position and altitude using GNSS-aided feedback;
- `ALTHOLD`, in which the flight controller maintains barometric altitude but does not actively hold horizontal position through GNSS.

The active flight mode is retained in the telemetry data and considered when selecting and interpreting the representative sessions analysed in Chapter 7.

5.6 Pre-test preparation

Before the outdoor flight tests, mechanical preparation procedures are performed to reduce systematic RPM asymmetries unrelated to wind disturbances. This step is important because the thesis interprets differential-RPM signals as indicators of controller compensation. Persistent mass imbalance or propeller-axis misalignment would introduce a baseline RPM differential that could mask the wind-induced response.

5.6.1 Mass balancing

The centre of gravity of the drone is adjusted to be as close as possible to the geometric centre of the rotor plane. If the centre of gravity is offset, the controller must produce an asymmetric thrust distribution even in calm hover, generating a persistent RPM bias.

For the balancing procedure, the drone is suspended using ropes attached to the arms of the vehicle. A spirit level is placed on the frame to check whether the vehicle hangs horizontally. If an imbalance is observed, the battery position is adjusted and small balancing weights are added where needed until the vehicle is approximately level.

5.6.2 Propeller-axis alignment

The propeller axes are checked before flight testing. If a propeller axis is not parallel to the nominal body-fixed vertical direction, the generated thrust has a small horizontal component and can produce a spurious moment. The flight controller compensates for this by changing the motor speeds, creating a systematic RPM asymmetry.

The alignment procedure consists of observing the RPM distribution during hover and adjusting the corresponding motor mount when a persistent imbalance is detected. Thin shims are inserted between the motor mount and the arm connector to slightly correct the propeller-axis orientation. The procedure is repeated until the residual RPM differences between motors are reduced to an acceptable level for the outdoor campaign.

5.7 Experimental procedure

Each test followed a repeatable experimental procedure designed to obtain synchronized wind and drone measurements under controlled acquisition conditions. At the beginning of each measurement session, the anemometer pole was positioned at the selected test location and the LI-550P anemometer was mounted at the target height. The sensor reference mark was aligned toward geographic North using a handheld compass, while the mast verticality and sensor mounting were checked with a spirit level. Once the mechanical installation was completed, the anemometer serial acquisition was initialized and the incoming data stream was verified before starting the flight sequence.

The quadrotor was then powered and connected to Mission Planner. Before takeoff, the telemetry stream, GNSS fix, battery status, and onboard sensor calibration were checked to ensure that the vehicle was ready for flight. The waypoint mission corresponding to the selected test configuration was uploaded to the flight controller. After this preparation phase, Mission Planner was closed and the Python acquisition script was launched. This script established its own MAVLink connection through the telemetry radio, allowing the acquisition trigger and the PC-side telemetry stream to be recorded independently during the test.

The drone was then armed and the AUTO mission was started. During the mission, the vehicle took off, flew to the prescribed waypoint, aligned its heading through the yaw command, and entered the timed hold phase. The data acquisition was not started immediately after takeoff, but only once the drone had reached the hold condition and the pilot had verified that the vehicle was sufficiently stable. At this point, the pilot activated the trigger by moving the SA switch to the down position. The acquisition script detected the corresponding RC10 transition, wrote the `TEST_START` marker, and recorded the anemometer and telemetry data for a fixed 60 s window.

At the end of the acquisition window, the script automatically wrote the `TEST_END` marker and saved the recorded data files. The drone then completed the remaining part of the mission and landed. After landing, the onboard `.BIN` log was downloaded from the flight controller and stored together with the anemometer file and the PC-side MAVLink telemetry file. The same procedure was repeated for the remaining mast heights, relative positions, and measurement configurations.

The resulting dataset consists of synchronized anemometer measurements, PC-side MAVLink trigger information, and onboard flight-controller logs. These data are processed in Chapter 6 to construct the common analysis time base and to compute the wind, RPM, attitude, geometry, correlation, and spectral quantities used in Chapter 7.

Chapter 6

Data Analysis

6.1 Introduction

Chapter 5 described the experimental setup and the measurement systems used during the outdoor campaign. The present chapter explains how the raw measurements are converted into a synchronized dataset and how the wind and drone signals are processed to obtain the quantities analysed in Chapter 7.

The analysis starts from three data sources: the anemometer serial log, the PC-side MAVLink telemetry file, and the onboard ArduPilot `.BIN` log. These streams are recorded on different time bases and at different sampling rates. Therefore, they must first be synchronized and resampled onto a common analysis grid before any wind-RPM comparison can be performed.

After synchronization, the raw signals are converted into physically meaningful quantities. The measured wind is described using the descriptors introduced in Chapter 4: three-dimensional and horizontal wind speed, turbulence intensity, short-duration wind-speed excursions, integral-scale diagnostics, and spectral content. The motor signals are decomposed into a mean RPM component, associated with the collective thrust demand, and differential-RPM components, associated with roll-, pitch-, and yaw-related control action. Finally, the horizontal wind is projected into the drone body-heading frame so that the directional wind forcing can be compared with the corresponding differential-RPM signals.

The objective of the analysis is not to reconstruct the exact aerodynamic loads acting on the propellers. Instead, the measured wind is treated as an external atmospheric reference signal, while the RPM signals are interpreted as the controller-mediated response of the vehicle. The workflow therefore provides the common time base, derived variables, and comparison tools required to assess whether changes in the measured wind field are reflected in the motor-speed and attitude response of the drone.

6.2 Acquisition window and time-base synchronization

A central requirement of the experiment is the synchronization between the wind measurements and the drone telemetry. The LI-550P anemometer, the PC-side MAVLink stream, and the onboard flight-controller log are recorded independently. Each source has its own timestamps, sampling rate, and possible communication delays. To compare wind fluctuations with RPM variations, all signals must be referred to the same physical acquisition window and then expressed on a common time base.

6.2.1 Trigger-based acquisition window

The acquisition window is defined by the SA switch of the remote controller, assigned to radio channel RC10. This channel is not used for flight-control commands during the tests; it is used only as an acquisition trigger.

When the pilot moves the SA switch to the trigger position, the RC10 value crosses the start threshold. The PC acquisition script detects this event and writes a `TEST_START` marker together with the current PC time. From this instant, the script records data for a fixed duration of

$$T_{\text{trial}} = 60 \text{ s.} \quad (6.1)$$

At the end of this interval, the script automatically writes a `TEST_END` marker and saves the acquisition files. The stop time is therefore defined by the fixed timer, not by a second manual switch movement. After the acquisition window has closed, the script can re-arm and wait for the next trigger.

The same `TEST_START` and `TEST_END` markers are written in both the anemometer serial file and the PC-side MAVLink telemetry file. The onboard `.BIN` log does not contain these PC markers directly, but it records the same physical SA/RC10 switch transition. This common physical event provides the anchor used to align the PC time base with the onboard flight-controller time base.

The fixed 60s duration is a compromise between statistical content and flight repeatability. At the final analysis frequency of 10 Hz, each session contains approximately 600 synchronized samples. This is sufficient for the session-level wind descriptors, RPM variability, cross-correlation analysis, qualitative PSD comparison, and gust-event inspection used in this thesis. At the same time, the window is short enough to remain within a single hold phase and to reduce the probability of including mission transitions, flight-mode changes, large position drift, or slow non-stationary changes in the atmospheric conditions.

6.2.2 PC-to-BIN time-base mapping

The PC and the Pixhawk flight controller use independent clocks. The PC time is used to timestamp the anemometer serial data and the PC-side MAVLink file, whereas the onboard .BIN log uses the ArduPilot flight-controller time. These two clocks have arbitrary origins and cannot be compared directly.

The SA/RC10 trigger provides the common synchronization event. On the PC side, the trigger is recorded as the `TEST_START` marker at time $t_{\text{pc,start}}$. On the onboard side, the same switch movement appears as a change in the RC10 channel recorded in the .BIN log. The corresponding onboard time is denoted by $t_{\text{bin,start}}$.

For the first trial of each acquisition session, the onboard trigger time is identified as the first significant RC10 transition:

$$t_{\text{bin,start}}^{(1)} = \min \{t_{\text{bin}} : |\Delta \text{RC10}(t_{\text{bin}})| > \delta_{SA}\}, \quad (6.2)$$

where δ_{SA} is the threshold used to distinguish a real switch movement from RC signal noise.

For subsequent trials within the same acquisition session, the expected onboard start time is obtained from the PC elapsed time relative to the first trigger event:

$$t_{\text{bin,start}}^{(k)} = t_{\text{bin,start}}^{(1)} + \Delta t_{\text{pc}}^{(k,1)}, \quad (6.3)$$

with

$$\Delta t_{\text{pc}}^{(k,1)} = t_{\text{pc,start}}^{(k)} - t_{\text{pc,start}}^{(1)}. \quad (6.4)$$

This avoids misidentifying additional SA switch movements that may occur between trials as new synchronization anchors.

The time offset between the PC clock and the onboard clock is

$$\beta_t = t_{\text{bin,start}} - t_{\text{pc,start}}. \quad (6.5)$$

The PC time base is then mapped onto the onboard time base using a fixed-scale translation:

$$t_{\text{bin,est}} = t_{\text{pc}} + \beta_t. \quad (6.6)$$

No clock-drift correction is applied over the 60 s acquisition window, so the scale factor is fixed to unity. The end of the synchronized analysis interval is therefore defined as

$$t_{\text{bin,stop}} = t_{\text{bin,start}} + T_{\text{trial}}. \quad (6.7)$$

The `TEST_END` marker is retained as a diagnostic check on the acquisition duration, but it is not used to rescale the time axis. This avoids introducing timing errors

caused by possible MAVLink queue delays on the PC side. The quality of the synchronization is checked by comparing the expected and recorded acquisition durations in the two time bases.

After this mapping, the anemometer data and the onboard telemetry are expressed in the same onboard time reference. The PC clock no longer appears in the final analysis dataset.

6.3 Telemetry extraction and preprocessing

6.3.1 Onboard-log extraction

The synchronized drone data are extracted from the onboard ArduPilot .BIN log. This log is used instead of the real-time PC-side MAVLink stream because it contains the motor RPM data in the flight-controller time base and at the logging rate required for the analysis. The PC-side MAVLink stream is used mainly to detect the trigger event and to support synchronization.

The extraction is performed within the trigger window defined in Section 6.2. The .BIN file is parsed and the following message groups are retained:

- **ESC**: individual motor RPM signals;
- **ATT**: roll, pitch, and yaw attitude angles;
- **IMU**: body angular rates and specific-force components;
- **BARO**: barometric altitude, pressure, and temperature;
- **GPS**: position and ground-speed information, when available.

The ESC stream provides the main drone-response variables of the thesis. The attitude, barometer, IMU, and GPS signals are used to interpret the flight condition, verify the quality of each session, compute body-heading quantities, and reconstruct the anemometer–drone geometry.

The raw ESC instances are mapped to the motor-numbering convention introduced in Chapter 2, so that RPM_1 , RPM_2 , RPM_3 , and RPM_4 always refer to the physical motors used in the thrust and moment definitions.

6.3.2 Reference-frame and sign conventions

The analysis adopts the same reference-frame convention introduced in Chapter 2. The inertial frame is a local East–North–Up frame, while the body-fixed frame is a forward-left-up frame. Therefore, the body x^B axis points forward, the body y^B axis points to the left of the vehicle, and the body z^B axis points upward in hover. The raw onboard data are recorded by the ArduPilot flight controller, whose logged attitude and inertial quantities follow the autopilot native convention, based on a local North–East–Down inertial frame and a forward-right-down body frame. Therefore, the logged quantities that enter the directional analysis are converted,

when required, to the East–North–Up and forward-left-up convention adopted in this thesis.

For body-frame vector quantities, the conversion from the ArduPilot forward-right-down convention to the forward-left-up convention is obtained by changing the signs of the lateral and vertical components:

$$\mathbf{a}_{\text{FLU}}^B = \mathbf{S}_{\text{FLU} \leftarrow \text{FRD}} \mathbf{a}_{\text{FRD}}^B, \quad \mathbf{S}_{\text{FLU} \leftarrow \text{FRD}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}. \quad (6.8)$$

This transformation is applied only to quantities for which the sign and direction are physically interpreted in the thesis convention. Motor RPM signals are scalar quantities and are therefore independent of the inertial/body-frame sign convention. The GPS position is used to reconstruct the horizontal anemometer–drone geometry in the local East–North plane. The drone heading is used to define the horizontal orientation of the vehicle relative to the measured wind.

This convention is used consistently when defining the body-heading wind components and the pitch- and roll-related RPM differentials. In particular, the horizontal wind is projected onto the drone forward and left directions before being compared with the differential motor-speed quantities. This makes the directional wind–RPM comparison consistent with the equations of motion and with the motor-numbering convention introduced in Chapter 2.

Attitude and IMU quantities are retained as supporting flight-condition indicators. They are not used to reconstruct aerodynamic forces or moments.

Consequently, the main results of this thesis are based on defined wind projections and motor-pair RPM differentials, rather than on a full dynamic reconstruction from logged attitude, angular-rate, or acceleration signals.

6.3.3 Resampling onto the common analysis grid

The anemometer and onboard telemetry streams are sampled at different rates. The LI-550P anemometer records the wind at 40 Hz, while the onboard telemetry messages have different effective logging rates depending on the message type. To compare wind and RPM quantities sample by sample, all signals are interpolated onto a common uniformly spaced time vector.

The common analysis interval is restricted to the time range where both the synchronized anemometer data and the ESC/RPM data are available. This prevents extrapolation beyond the measured data range. The overlap interval is

$$t_{\min} = \max [\min(t_{\text{anemo}}), \min(t_{\text{ESC}})], \quad t_{\max} = \min [\max(t_{\text{anemo}}), \max(t_{\text{ESC}})]. \quad (6.9)$$

The common time vector is then defined as

$$t_{\text{com}} = \left[t_{\text{min}}, t_{\text{min}} + \frac{1}{f_{\text{com}}}, t_{\text{min}} + \frac{2}{f_{\text{com}}}, \dots, t_{\text{max}} \right]. \quad (6.10)$$

In this thesis,

$$f_{\text{com}} = 10 \text{ Hz}. \quad (6.11)$$

This choice matches the attitude-log rate and provides a common bandwidth for the wind-RPM analysis. The corresponding Nyquist frequency is

$$f_N = \frac{f_{\text{com}}}{2} = 5 \text{ Hz}. \quad (6.12)$$

Each signal $x(t)$ is mapped onto the common time vector using linear interpolation:

$$x_{\text{sync}}(t_{\text{com}}) = \text{interp}[x(t), t_{\text{com}}]. \quad (6.13)$$

The common time vector is therefore an analysis grid, not a new measurement: it does not add information to the original signals, but expresses them at the same timestamps. This makes point-wise comparison, cross-correlation, scatter analysis, and spectral comparison possible on a consistent time base.

6.4 Derived analysis quantities

6.4.1 Wind descriptors

The wind descriptors used in Chapter 7 are computed from the synchronized anemometer components $U^A(t)$, $V^A(t)$, and $W^A(t)$ following the definitions introduced in Chapter 4.

For each acquisition window, the following quantities are computed:

- the three-dimensional wind-speed magnitude $S(t)$;
- the horizontal wind-speed magnitude $S_h(t)$;
- the mean values $\bar{S}$ and $\bar{S}_h$;
- the component standard deviations σ_u , σ_v , and σ_w ;
- the three-dimensional turbulence intensity TI ;
- the horizontal turbulence intensity TI_h ;
- the maximum instantaneous wind-speed excursion ΔS_{max} ;
- the three-second moving-average maximum $S_{3s, \text{max}}$;
- the integral time and length scales T_u and L_u , used as diagnostic quantities;
- the wind power spectral density, used for qualitative frequency-domain comparison.

These quantities provide complementary descriptions of the measured wind field. $\overline{S}$ and $\overline{S}_h$ describe the mean wind intensity. TI and TI_h both describe the unsteadiness of the wind relative to its mean level, but over different components of the measured wind vector: TI combines the fluctuation of all three measured components, while TI_h is restricted to the horizontal wind-speed magnitude. Both are retained in the analysis dataset and are used in Chapter 7 according to the specific comparison being discussed. Where the two descriptors differ significantly, the interpretation is given together with the possible role of anemometer tilt and the distinction between three-dimensional and horizontal wind variability.

$\Delta S_{\max}$ and $S_{3s,\max}$ identify short-duration wind-speed excursions. The integral time and length scales are retained as diagnostics of the temporal persistence of the wind fluctuations, while the PSD describes the distribution of wind fluctuation energy over frequency.

6.4.2 RPM decomposition

Using the motor-numbering convention of Chapter 2, the roll-related differential RPM is defined as

$$\Delta RPM_{\text{roll}} = \frac{RPM_2 + RPM_3}{2} - \frac{RPM_1 + RPM_4}{2}, \quad (6.14)$$

and the pitch-related differential RPM as

$$\Delta RPM_{\text{pitch}} = \frac{RPM_2 + RPM_4}{2} - \frac{RPM_1 + RPM_3}{2}. \quad (6.15)$$

The yaw-related differential RPM is defined as

$$\Delta RPM_{\text{yaw}} = \frac{(RPM_3 + RPM_4) - (RPM_1 + RPM_2)}{2}. \quad (6.16)$$

With these definitions, the signs of the differential-RPM quantities are consistent with the control-moment convention introduced in Chapter 2. The roll-related differential compares the motor pairs that generate a roll control moment, while the pitch-related differential compares the motor pairs that generate a pitch control moment.

The differential-RPM quantities should not be interpreted as direct measurements of aerodynamic moments. They are indicators of the motor-speed redistribution commanded by the flight controller in response to disturbances. In the results, ΔRPM_{roll} and $\Delta RPM_{\text{pitch}}$ are the main directional response variables, because horizontal wind forcing is expected to produce primarily roll- and pitch-compensating control action. The yaw-related quantity ΔRPM_{yaw} is retained for completeness, but it is not the primary focus of the present analysis.

6.4.3 Body-heading wind projection

The geographic wind components $U^E(t)$ and $V^N(t)$ describe the horizontal wind in the inertial East–North frame. However, the drone response depends on the wind direction relative to the vehicle heading. Therefore, the horizontal wind is projected onto the drone body-heading axes.

Let $\psi_c(t)$ be the drone compass heading, measured clockwise from geographic North. The forward and left unit vectors of the drone, expressed in the East–North basis, are

$$\hat{\mathbf{e}}_{\text{fwd}} = \sin \psi_c \hat{\mathbf{e}}_E + \cos \psi_c \hat{\mathbf{e}}_N, \quad (6.17)$$

and

$$\hat{\mathbf{e}}_{\text{left}} = -\cos \psi_c \hat{\mathbf{e}}_E + \sin \psi_c \hat{\mathbf{e}}_N. \quad (6.18)$$

Projecting the horizontal wind vector onto these directions gives

$$U_{\text{fwd}}(t) = U^E(t) \sin \psi_c(t) + V^N(t) \cos \psi_c(t), \quad (6.19)$$

and

$$U_{\text{left}}(t) = -U^E(t) \cos \psi_c(t) + V^N(t) \sin \psi_c(t). \quad (6.20)$$

U_{fwd} is the wind component along the drone forward direction, while U_{left} is the wind component toward the drone left side. These components are consistent with the forward-left-up body-frame convention introduced in Chapter 2.

The body-heading projection is essential because the inertial wind components alone do not indicate whether a given wind fluctuation acts mainly as a longitudinal or lateral disturbance on the vehicle. In Chapter 7, U_{fwd} is compared with $\Delta RPM_{\text{pitch}}$, while U_{left} is compared with ΔRPM_{roll} .

The horizontal wind magnitude is conserved by this projection:

$$U_{\text{fwd}}^2 + U_{\text{left}}^2 = S_h^2. \quad (6.21)$$

6.4.4 Quality-control indicators

Before the synchronized dataset is used for wind–RPM analysis, invalid sensor values and quality-control variables are handled consistently.

The LI-550P TriSonica can output a sentinel value close to -99.5 m/s when a wind measurement is invalid. Any wind component value below -90 m/s is therefore replaced by `NaN` before interpolation. This prevents invalid sensor rows from being treated as physical wind measurements.

The anemometer pitch and roll tilt indicators, PI and RO , are retained in the dataset as measurement-quality indicators. They are not used to dynamically correct the wind vector. Their role is to identify sessions in which the anemometer body was significantly tilted during the acquisition. In the present analysis, sessions with a mean tilt indicator above approximately 5° are flagged for cautious interpretation. This threshold is not used to discard a session automatically; it is used only to identify cases in which the vertical wind component and any descriptor involving W^A should be interpreted with additional care.

The GPS position and ground speed are also retained. In principle, the relative inflow at the drone could be estimated as

$$\mathbf{V}_\infty^I = \mathbf{U}_w^I - \mathbf{v}^I, \quad (6.22)$$

as introduced in Chapter 3. In the present analysis, however, the wind–RPM correlations use the measured wind vector as the external atmospheric forcing. This follows the quasi-hover approximation of Chapter 4, where the drone ground velocity is small relative to the measured wind. The GPS-derived position is therefore used for geometry, flight-condition checks, and delay interpretation.

6.5 Wind–RPM comparison

6.5.1 Anemometer–drone geometry and convective-delay estimate

The anemometer and the drone are spatially separated. Therefore, a wind fluctuation measured at the anemometer is not necessarily simultaneous with the disturbance experienced by the drone. A convective-delay interpretation is physically meaningful only when the anemometer is located upstream of the drone with respect to the mean horizontal wind direction.

The geometry is evaluated in the horizontal inertial East–North plane. Since the drone is not perfectly fixed during the acquisition window, a representative session-level geometry is used instead of an instantaneous anemometer–drone vector. Let

$$\mathbf{r}_{A,h}^I = \begin{bmatrix} E_A \\ N_A \\ 0 \end{bmatrix}$$

be the fixed horizontal position of the anemometer, and let

$$\mathbf{r}_{B,h}^I(t_i) = \begin{bmatrix} E_B(t_i) \\ N_B(t_i) \\ 0 \end{bmatrix}$$

be the horizontal GPS position of the drone at the synchronized samples of the analysis window. The representative drone position is computed as the arithmetic mean over the window,

$$\bar{\mathbf{r}}_{B,h}^I = \frac{1}{N} \sum_{i=1}^N \mathbf{r}_{B,h}^I(t_i), \quad (6.23)$$

where N is the number of synchronized samples in the selected window. The representative horizontal separation vector from the anemometer to the drone is then

$$\mathbf{d}_{AB} = \bar{\mathbf{r}}_{B,h}^I - \mathbf{r}_{A,h}^I. \quad (6.24)$$

This vector describes the mean position of the drone relative to the fixed anemometer during the acquisition window. It is therefore a session-level geometric descriptor, not an instantaneous drone position.

The mean horizontal wind vector is computed over the same synchronized window as

$$\bar{\mathbf{U}}_h^I = \begin{bmatrix} \overline{U^E} \\ \overline{V^N} \\ 0 \end{bmatrix}. \quad (6.25)$$

The corresponding unit vector in the direction toward which the wind is blowing is

$$\hat{\mathbf{e}}_{w,\text{mean}}^I = \frac{\bar{\mathbf{U}}_h^I}{\|\bar{\mathbf{U}}_h^I\|} = \begin{bmatrix} \cos \bar{\chi}_w^I \\ \sin \bar{\chi}_w^I \\ 0 \end{bmatrix}, \quad (6.26)$$

where $\bar{\chi}_w^I$ is the mathematical TOWARD angle measured from East toward North, consistently with $\chi_w^I = \text{atan2}(V^N, U^E)$. If the same direction is expressed in compass convention, clockwise from North, the corresponding horizontal unit vector is $[\sin \chi_c, \cos \chi_c, 0]^T$.

The separation angle reported in the results is defined as the angle between the representative anemometer–drone vector and the mean horizontal wind direction,

$$\theta_{\text{sep}} = \cos^{-1} \left(\frac{\mathbf{d}_{AB} \cdot \hat{\mathbf{e}}_{w,\text{mean}}^I}{\|\mathbf{d}_{AB}\|} \right). \quad (6.27)$$

Small values of θ_{sep} indicate that the wind is blowing approximately from the anemometer toward the drone, corresponding to an upstream configuration. Values close to 90° indicate a crosswind configuration, while larger values indicate that the anemometer is not upstream of the drone.

The along-wind projection of the separation is

$$d_{\parallel} = \mathbf{d}_{AB} \cdot \hat{\mathbf{e}}_{w,\text{mean}}^I. \quad (6.28)$$

Equivalently, $d_{\parallel} = \|\mathbf{d}_{AB}\| \cos \theta_{\text{sep}}$. Therefore, the sign of $d_{\parallel}$ determines whether a convective interpretation is admissible. If $d_{\parallel} > 0$, the drone lies downstream of the anemometer in the mean wind direction, and the measured wind can be used as an upstream atmospheric reference. If $d_{\parallel} \simeq 0$, the geometry is approximately crosswind. If $d_{\parallel} < 0$, the anemometer is downstream of the drone and cannot be interpreted as a precursor of the drone response.

For upstream cases only, the convective delay is estimated as

$$\tau_{\text{conv}} = \frac{d_{\parallel}}{U_{\text{conv}}}, \quad d_{\parallel} > 0, \quad (6.29)$$

where the convection velocity is approximated by the mean horizontal wind-speed magnitude [21],

$$U_{\text{conv}} \simeq \overline{S_h}. \quad (6.30)$$

This delay is a geometry-based estimate and is not fitted from the RPM data. It is used only as a physical reference for sessions in which the anemometer is upstream of the drone. Since the estimate uses the horizontal separation and the mean horizontal wind direction, it is a plan-view advection estimate. The vertical wind component is retained in the time-history analysis, but it does not enter the definition of θ_{sep} , $d_{\parallel}$, or τ_{conv} .

6.5.2 Cross-correlation and statistical lag

A complementary, data-driven estimate of the wind–RPM timing is obtained from the normalized cross-correlation. For a wind-related signal $x(t)$ and an RPM-related response signal $y(t)$, the normalized cross-correlation at lag τ is defined as

$$\rho_{xy}(\tau) = \frac{\langle [x(t) - \bar{x}] [y(t + \tau) - \bar{y}] \rangle}{\sigma_x \sigma_y}, \quad (6.31)$$

where σ_x and σ_y are the standard deviations of the two signals over the analysed window. With this convention, a positive lag means that the wind signal leads the RPM response.

The statistical lag is defined as

$$\tau^* = \arg \max_{\tau} |\rho_{xy}(\tau)|. \quad (6.32)$$

This quantity identifies the time shift that gives the strongest linear association between the selected wind and RPM signals. Unlike τ_{conv} , τ^* is obtained from the

data and can be computed for every session, regardless of the anemometer–drone geometry. However, it is a statistical timing indicator, not by itself a physical travel time.

Two main families of cross-correlations are computed. The first uses geographic wind components and scalar wind speed, comparing S , U^E , V^N , and W with $\overline{RPM}$, $\Delta RPM_{\text{pitch}}$, and ΔRPM_{roll} . The second uses body-heading wind components, comparing U_{fwd} with $\Delta RPM_{\text{pitch}}$ and U_{left} with ΔRPM_{roll} . The body-heading correlations are the primary directional result because they compare the wind forcing with the RPM response in the drone frame.

The cross-correlation is evaluated only over a finite 60 s window. At large lags, fewer overlapping samples contribute to the estimate, and the effective number of independent samples is further reduced by autocorrelation in both the wind and RPM signals. For this reason, τ^* and the corresponding correlation coefficients are used as descriptive indicators of timing and association strength, not as formal statistical test results.

6.5.3 Delay-interpretation criteria and shifted overlays

The convective delay τ_{conv} and the statistical lag τ^* are used for different purposes. τ_{conv} is the geometry-based delay expected if a wind structure is advected from the anemometer to the drone. τ^* is the observed lag that maximizes the statistical similarity between a chosen wind signal and a chosen RPM response.

A delay is interpreted as geometry-validated convective only when three conditions are satisfied:

1. the anemometer is upstream of the drone, so $d_{\parallel} > 0$;
2. the convective-delay estimate is well conditioned, so the mean horizontal wind speed is not close to zero;
3. the observed statistical lag τ^* is compatible with τ_{conv} .

In the present analysis, compatibility is assessed within a tolerance of approximately 1 s. This tolerance is not a formal confidence interval; it is a practical band accounting for the finite 10 Hz sampling grid, uncertainty in the GPS-based geometry, evolution of the wind field between the anemometer and the drone, and the finite response time of the controller and propulsion system.

When the three conditions above are satisfied, the timing is interpreted as physically consistent with advection from the anemometer to the drone. When they are not satisfied, τ^* may still be used to align the signals for inspection, but the alignment is treated as statistical only.

After the delay is selected, the wind signal is shifted and overlaid with the RPM response. This shifted overlay is used to inspect whether time-domain features

such as gusts, ramps, and fluctuations appear consistently in the two signals after the selected delay is applied. The overlay is a visual consistency check and does not prove causality.

6.5.4 Scatter analysis

Scatter plots are used to examine the instantaneous relationship between wind and RPM quantities. Each point represents one synchronized sample of a wind-related signal and the corresponding RPM-related response. When a delay correction is applied, the wind signal is shifted before the paired samples are constructed.

The primary scatter analysis compares the body-heading wind components with the corresponding differential-RPM quantities:

$$U_{\text{fwd}} \text{ vs. } \Delta RPM_{\text{pitch}}, \quad (6.33)$$

and

$$U_{\text{left}} \text{ vs. } \Delta RPM_{\text{roll}}. \quad (6.34)$$

These plots show whether longitudinal and lateral wind components tend to be associated with pitch- and roll-related motor redistribution. The corresponding Pearson correlation coefficients are used as descriptors of association strength. They are not interpreted as formal statistical proof of causality.

Additional scatter checks can be performed between S or S_h and mean RPM, to evaluate whether stronger wind intensity is associated with a change in the collective motor-speed level. These comparisons are secondary to the body-heading directional analysis.

6.6 Spectral analysis

The frequency-domain comparison between wind and RPM signals is performed using the power spectral density. The PSD of the wind signals is computed as described in Chapter 4. The same Welch method [22] is applied to the RPM signals, including $\overline{RPM}$, $\Delta RPM_{\text{pitch}}$, and ΔRPM_{roll} .

Before computing the PSD, the mean value of each signal is removed. The signal is then divided into shorter overlapping segments, each segment is windowed and transformed into the frequency domain, and the resulting periodograms are averaged. The PSD comparison is performed on the common 10 Hz analysis grid, so the resolved frequency range is limited to

$$0 \leq f \leq 5 \text{ Hz}. \quad (6.35)$$

The PSD is used only as a qualitative frequency-domain check. The purpose is to verify whether the wind and RPM signals contain fluctuation energy over comparable frequency ranges. It is not used to identify a transfer function between wind and RPM, nor to validate an inertial-subrange turbulence model. Any overlap between the spectra is therefore interpreted as supporting evidence for wind-related controller activity, while the time-domain, body-heading, and geometry-based analyses remain the primary basis for the results.

Chapter 7

Results

7.1 Representative sessions and interpretation strategy

This chapter presents the experimental results obtained from a set of representative acquisition sessions. The purpose is not to perform a statistical survey of the full experimental campaign, but to analyse physically interpretable case studies in which the measured atmospheric wind can be compared with the controller response of the quadrotor. The selected sessions cover the three mast heights used in the campaign, namely 2.2 m, 5.35 m, and 15.35 m, and are chosen to highlight different combinations of wind forcing, turbulence level, anemometer–drone geometry, and motor-speed response.

The interpretation follows the framework developed in Chapters 2–6. The anemometer measurement is treated as a local atmospheric reference for the wind forcing acting near the drone. Under the quasi-hover approximation, this measured wind is used as a proxy for the external wind disturbance experienced by the vehicle. However, it is not a direct measurement of the instantaneous rotor-level inflow: the actual inflow at each propeller also depends on the drone motion, attitude, rotor-induced flow, wake interactions, and on the spatial separation between the fixed anemometer and the vehicle. Similarly, the RPM signals are interpreted as the closed-loop response commanded by the onboard flight controller, not as direct measurements of aerodynamic forces or moments. Consequently, the analysis distinguishes between statistical wind–RPM associations, which can be computed for any synchronized session, and geometry-validated convective-delay interpretations, which are admissible only when the anemometer is located upstream of the drone in the mean wind direction.

7.1.1 Selected sessions

The representative sessions were selected through a two-step procedure. First, all acquisition windows were screened to exclude cases in which the wind–RPM comparison would not be sufficiently reliable. Sessions were discarded when the selected 60 s window contained flight-mode transitions, ambiguous trigger timing, evident synchronization problems, incomplete telemetry, or flight conditions that did not allow a clear interpretation of the measured wind relative to the vehicle response.

Second, the remaining valid sessions were selected according to their relevance for the objectives of this thesis. The selection did not simply retain the cases with the largest correlations, but aimed to build a small set of complementary case studies. The retained sessions therefore combine sufficiently clear wind forcing, measurable motor-speed variability, and different anemometer–drone geometries.

Four sessions were retained for the analysis. The 2.2 m session represents a low-height crosswind case, useful for assessing whether a wind–RPM association is still visible near the lowest measurement height. The 5.35 m session is the only case with an upstream geometry and is therefore the reference case for the geometry-validated convective-delay interpretation. The 15.35 m main session represents a stronger-wind case, but with a crosswind/borderline downstream geometry, so its timing information is interpreted statistically only. The additional 15.35 m session is retained as a gust-event zoom because it contains the strongest short-duration wind-speed excursion and the largest RPM variability of the selected set.

The quantitative indicators used to compare these sessions are introduced in Section 7.2.1. Their numerical values are then reported in Table 7.1, where they provide the basis for the cross-case comparison.

7.2 Wind forcing and motor-response intensity

7.2.1 Cross-case indicators

The selected sessions are compared using a small set of indicators chosen to separate wind forcing, motor-response intensity, directional coupling, and measurement geometry. These indicators are not intended to provide a statistical description of the full campaign. Instead, they provide a compact and physically interpretable basis for comparing the representative case studies.

The wind forcing is described first by the horizontal wind-speed magnitude,

$$S_h = \sqrt{(U^E)^2 + (V^N)^2},$$

and by its mean value $\bar{S}_h$ over the synchronized analysis window. This quantity represents the average intensity of the horizontal wind component, which is the

component most directly associated with in-plane rotor inflow and edgewise loading. The relative unsteadiness of the wind is described using the three-component turbulence intensity TI and the horizontal turbulence intensity TI_h :

$$TI = \frac{\sqrt{(\sigma_u^2 + \sigma_v^2 + \sigma_w^2)/3}}{\bar{S}}, \quad TI_h = \frac{\sigma_{S_h}}{\bar{S}_h}.$$

The first quantity accounts for fluctuations of all three measured wind components, whereas the second focuses only on the variability of the horizontal wind-speed magnitude. This distinction is useful because the directional pitch- and roll-related responses are mainly associated with the horizontal wind forcing.

Short-duration wind-speed excursions are quantified by $\Delta S_{\max}$ and $S_{3s,\max}$. The quantity

$$\Delta S_{\max} = S_{\max} - \bar{S}$$

measures the largest instantaneous wind-speed excursion above the session mean. The quantity $S_{3s,\max}$ is the peak of the centred 3-second running mean of the total wind-speed magnitude S , as defined in Chapter 4. It identifies the strongest sustained short-duration wind event within the acquisition window.

The directional wind-RPM association is summarized, for the three main sessions, by $|r|_{\max}$. This quantity is defined as the larger absolute value between the $U_{\text{left}} - \Delta RPM_{\text{roll}}$ correlation and the $U_{\text{fwd}} - \Delta RPM_{\text{pitch}}$ correlation. It is not reported for the gust-zoom session because that case is used only for transient event inspection, not for the cross-case body-heading correlation comparison. The yaw-related differential RPM was also inspected, but its association with the horizontal wind-speed magnitude remained weak. The following analysis therefore focuses on the pitch- and roll-related differential RPM quantities.

The variability of the collective motor-speed level is described by $\sigma_{\overline{RPM}}$. First, the mean motor-speed signal is computed as

$$\overline{RPM}(t) = \frac{RPM_1(t) + RPM_2(t) + RPM_3(t) + RPM_4(t)}{4}. \quad (7.1)$$

Its standard deviation over the synchronized window is then defined as

$$\sigma_{\overline{RPM}} = \sqrt{\frac{1}{N-1} \sum_{i=1}^N [\overline{RPM}(t_i) - \langle \overline{RPM} \rangle]^2}, \quad (7.2)$$

where

$$\langle \overline{RPM} \rangle = \frac{1}{N} \sum_{i=1}^N \overline{RPM}(t_i). \quad (7.3)$$

This quantity does not describe the instantaneous imbalance between the four motors. Instead, it measures how much the average motor-speed level varies in

time, and is therefore used as an indicator of the overall collective RPM variability during the session.

Finally, the anemometer–drone geometry is described by the separation angle θ_{sep} and by the corresponding geometry class. These quantities indicate whether the anemometer is upstream, crosswind, or downstream of the drone with respect to the mean horizontal wind direction. This classification is essential for the interpretation of time lags: a statistical lag can be computed for any synchronized session, but a convective-delay interpretation is physically admissible only when the anemometer is upstream of the drone.

7.2.2 Cross-case overview

Table 7.1 reports the values of the indicators introduced above for the four retained sessions. The table provides the common reference for comparing wind intensity, relative unsteadiness, short-duration wind excursions, body-heading correlation strength, collective RPM variability, and anemometer–drone geometry.

Table 7.1: Representative sessions and selection indicators.

h [m]	Session ID	Role	Geom.	θ_{sep} [°]	$\bar{S}_h$ [m/s]	TI	TI_h	ΔS_{max} [m/s]	$S_{3s,\text{max}}$ [m/s]	$ r _{\text{max}}$	$\sigma_{\overline{RPM}}$ [RPM]
2.2	2026-05-29_16-39-56	Main	Crosswind	94	1.34	0.41	0.55	2.42	2.85	0.47	120.2
5.35	2026-06-03_15-16-18	Main	Upstream	32	1.79	0.56	0.52	1.93	3.10	0.82	112.9
15.35	2026-06-03_15-45-11	Main	Crosswind–downstr.	116	2.76	0.37	0.39	2.82	4.46	0.87	156.8
15.35	2026-06-03_15-44-08	Gust zoom	Downstream	132	3.76	0.32	0.37	4.39	6.25	–	325.4

The 2.2 m case has the lowest mean horizontal wind speed, $\bar{S}_h = 1.34$ m/s, but the largest horizontal turbulence intensity, $TI_h = 0.55$. It therefore represents a low-height condition with relatively strong fluctuations compared with its mean wind level. The 5.35 m case has a moderate mean wind speed, $\bar{S}_h = 1.79$ m/s, and remains strongly unsteady ($TI = 0.56$, $TI_h = 0.52$), while also providing the cleanest upstream geometry. The 15.35 m main case has the highest mean horizontal wind speed among the three main sessions, $\bar{S}_h = 2.76$ m/s, but lower relative turbulence levels ($TI = 0.37$, $TI_h = 0.39$). The gust-zoom session at the same height reaches the largest sustained short-duration wind-speed event, with $S_{3s,\text{max}} = 6.25$ m/s.

This distinction between absolute wind forcing and relative fluctuation level is central to the interpretation of the results. The largest collective RPM variability, quantified by $\sigma_{\overline{RPM}}$, occurs in the high-mast cases, even though their relative turbulence intensities are lower than those of the lower mast-height sessions. This suggests that, for the selected sessions, the motor response is more closely associated

with the absolute level of the wind forcing and with the amplitude of the wind-speed excursions than with relative turbulence intensity alone.

The selected sessions also differ in measurement geometry. The 5.35 m case is the only upstream configuration and is therefore the reference case for lag interpretation. Conversely, the 2.2 m and 15.35 m main sessions remain essential because they show whether wind–RPM associations are still visible when the geometry does not support a convective interpretation.

The quantities in Table 7.1 provide a compact session-level comparison, but they do not show how the wind and motor signals evolve within each 60 s acquisition window. For this reason, the following subsections examine the time histories of the three main sessions. These figures are used to identify when the strongest wind events occur, how the measured wind is resolved into geographic and body-heading components, and whether the corresponding RPM variations appear primarily as collective changes or as motor-pair redistributions.

7.2.3 Time-domain inspection of the main sessions

The time-history figures are read using the interpretation framework developed in Chapters 2 and 6. The geographic wind components describe the wind measured by the fixed anemometer in the inertial East–North frame. The body-heading components, U_{fwd} and U_{left} , show how the same horizontal wind is resolved along the drone forward and left directions. This projection is required because the motor response is not expected to depend directly on U^E or V^N alone, but on the wind direction relative to the vehicle heading.

The RPM signals are interpreted in two complementary ways. The mean RPM describes the collective motor-speed level, whereas the differential-RPM signals describe how the controller redistributes motor speed between opposite motor pairs. Therefore, the individual motor traces are used as supporting information, whereas the physical interpretation is based primarily on ΔRPM_{roll} and $\Delta RPM_{\text{pitch}}$, because these quantities are directly related to the roll- and pitch-related motor-pair redistributions introduced in Chapter 2.

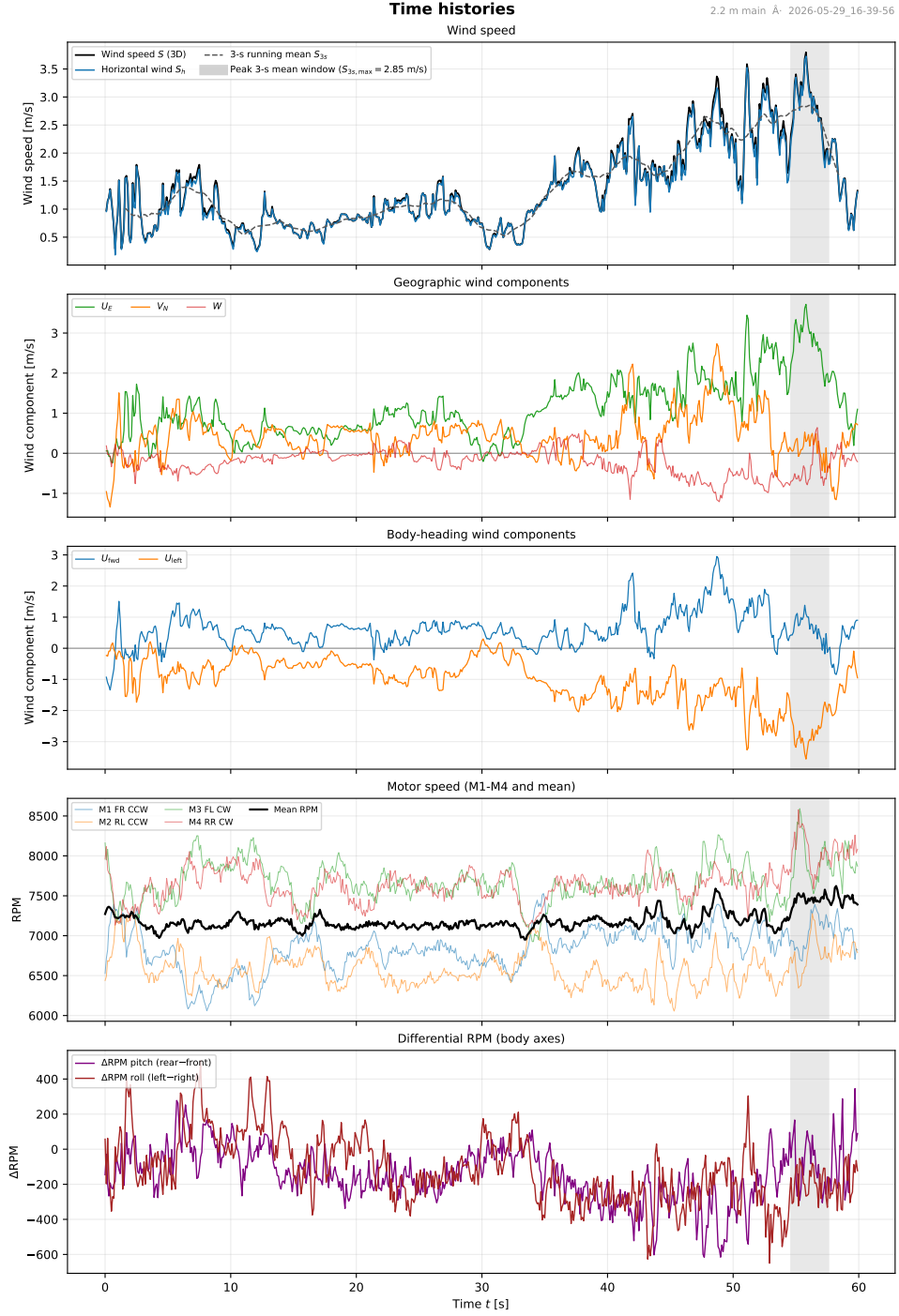


Figure 7.1: Time histories for the 2.2 m main session.

2.2 m main session. For the 2.2 m session, the strongest 3-second wind-speed window occurs near the end of the acquisition, with $S_{3s,\max} = 2.85 \text{ m/s}$ at approximately $t = 56.1 \text{ s}$. In the geographic frame, this event is mainly associated with an increase of the eastward wind component U^E . However, the body-heading projection shows that the same wind event has both longitudinal and lateral content relative to the drone. In particular, the late part of the record contains a positive U_{fwd} component together with a negative U_{left} component, indicating that the wind is not acting as a purely forward or purely lateral disturbance in the drone frame. Motors M3 and M4 reach comparatively high values during parts of the record, but this should not be interpreted directly as a pure roll or pitch response: M3 is the front-left clockwise motor, whereas M4 is the rear-right clockwise motor, so they form a diagonal pair and enter the roll- and pitch-related differential RPM definitions with opposite signs. The differential-RPM panel is therefore the physically relevant quantity for interpreting the controller response. In this session, both ΔRPM_{roll} and $\Delta RPM_{\text{pitch}}$ remain moderate, consistent with the lower absolute wind forcing, although the presence of visible differential-RPM fluctuations confirms that the controller is already redistributing motor effort in response to the measured wind variations.

Results

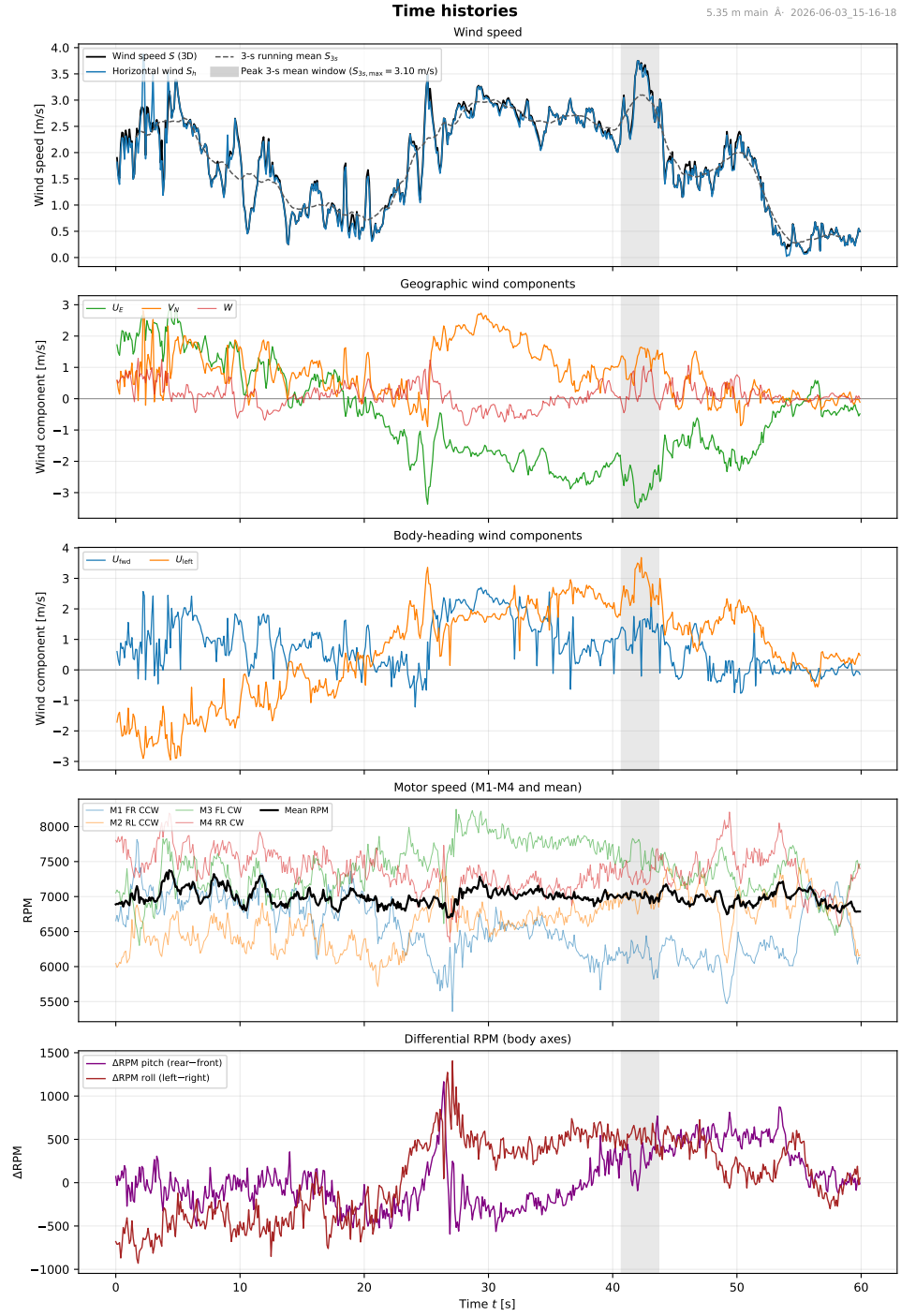


Figure 7.2: Time histories for the 5.35 m main session.

5.35 m main session. For the 5.35 m session, the peak 3-second wind-speed event reaches $S_{3s,\max} = 3.10$ m/s at approximately $t = 42.2$ s. The geographic wind components show a clear change in wind direction during the acquisition: after the first part of the record, the eastward component becomes negative while the northward component remains positive over a significant interval. Once this wind is projected into the body-heading frame, the lateral component U_{left} becomes the dominant directional contribution over much of the central part of the record and reaches its largest values around the highlighted wind-speed event.

This body-heading structure is reflected in the RPM response. The roll-related differential RPM shows a pronounced positive excursion in the same part of the record in which U_{left} is large, whereas the pitch-related differential remains less coherent and changes sign more locally. This makes the 5.35 m case particularly important: it shows a clear directional motor redistribution in the roll channel, and it is also the only selected case for which the anemometer–drone geometry is upstream. The time history therefore anticipates both results developed later in the chapter: the dominance of the $U_{\text{left}}-\Delta RPM_{\text{roll}}$ relationship and the possibility of a geometry-validated convective-delay interpretation.

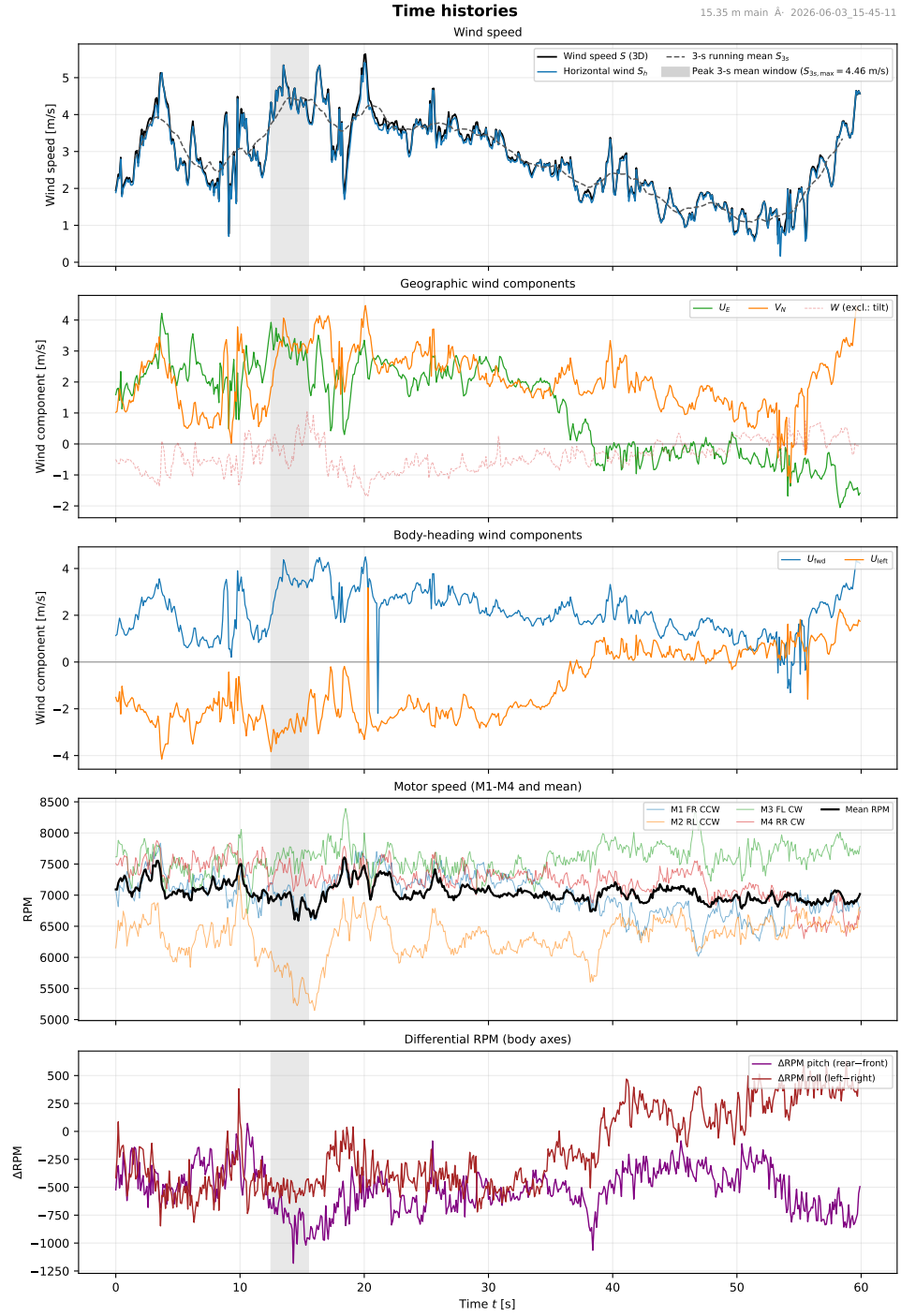


Figure 7.3: Time histories for the 15.35 m main session.

15.35 m main session. For the 15.35 m main session, the mean horizontal wind speed and the differential-RPM fluctuations are the largest among the three main cases. The strongest 3-second window reaches $S_{3s,\max} = 4.46$ m/s at approximately $t = 14.0$ s. The vertical wind component W is de-emphasised in the interpretation because the anemometer tilt indicators show a persistent mast tilt at this height. The directional analysis therefore relies primarily on the horizontal body-heading components.

The body-heading panel shows that the high wind-speed interval is not only a scalar increase of S , but also a strongly directional event. During the first half of the acquisition, U_{fwd} remains largely positive, while U_{left} is predominantly negative. Later in the record, U_{left} increases toward zero and then becomes positive. This change in the lateral wind component is accompanied by a marked change in the roll-related differential RPM, which evolves from mostly negative values in the first part of the record to positive values in the second part. The sign and amplitude evolution of ΔRPM_{roll} therefore provide a clearer interpretation of the motor response than the individual motor traces alone.

The individual RPM signals confirm that the controller response at this height is substantial, but they should again be interpreted through the motor-pair definitions. A high value of a single motor, or of a diagonal pair such as M3 and M4, does not directly identify a roll or pitch moment. The physically meaningful quantities are the pairwise redistributions: left–right for ΔRPM_{roll} and rear–front for $\Delta RPM_{\text{pitch}}$. In the 15.35 m main session, these differential signals show the largest amplitudes of the three main cases, consistent with the stronger absolute wind forcing at this mast height. However, because the anemometer–drone geometry is crosswind/borderline downstream, the timing of these variations is interpreted statistically only and not as a convective travel time from the anemometer to the drone.

7.3 Directional response in the body-heading frame

The previous section showed that the time histories contain visible motor-speed redistributions during the selected wind events. The next step is to interpret these redistributions directionally. This requires expressing the measured horizontal wind in the drone body-heading frame, because the inertial components U^E and V^N alone do not indicate whether the wind acts mainly as a longitudinal or lateral disturbance on the vehicle.

Following the convention established in Chapter 6, the horizontal wind is therefore projected onto the drone forward and left directions, giving U_{fwd} and U_{left} . These quantities are compared with the pitch- and roll-related differential RPM signals according to the control geometry of the quadrotor. A longitudinal wind component, U_{fwd} , is expected to require mainly a pitch-related compensation [8, 10], because forward–aft acceleration in near-hover is produced by pitching the vehicle and tilting the thrust vector in the longitudinal direction. It is therefore compared with $\Delta\text{RPM}_{\text{pitch}}$, which represents the rear–front motor-speed redistribution. Conversely, a lateral wind component, U_{left} , is expected to require mainly a roll-related compensation, because lateral acceleration is produced by rolling the vehicle and tilting the thrust vector sideways. It is therefore compared with $\Delta\text{RPM}_{\text{roll}}$, which represents the left–right motor-speed redistribution.

This pairing does not imply that the response is dynamically decoupled. Secondary associations between U_{left} and $\Delta\text{RPM}_{\text{pitch}}$, or between U_{fwd} and $\Delta\text{RPM}_{\text{roll}}$, may occur because of controller coupling, attitude variations, yaw dynamics, oblique inflow, and motor-allocation effects. However, the selected pairs provide the most direct physical interpretation of the directional wind–RPM response.

In the scatter plots shown below, r denotes the Pearson correlation coefficient computed between synchronized samples, without applying any time shift. The sign of r indicates the direction of the linear association: positive values mean that the two quantities tend to increase together, whereas negative values indicate an opposite trend. In the cross-case comparison, the absolute value $|r|$ is used because the objective is to compare the strength of the directional association independently of its sign. The sign itself depends on the adopted conventions for the body-heading wind components and for the differential RPM definitions.

In the cross-correlation panel, instead, the lag τ is the time shift applied between the wind signal and the RPM signal before computing the correlation. With the adopted convention, the wind signal is compared with the RPM response at $t + \tau$. Therefore, $\tau > 0$ indicates that variations in the measured wind occur before the corresponding variations in the RPM response, meaning that the wind signal leads the drone motor-speed response.

The cross-correlation peak, identified through the largest absolute correlation value, and the corresponding lag τ^* therefore indicate the statistical time shift that gives the strongest alignment between the two signals. This quantity is not the same as the zero-lag Pearson coefficient shown in the scatter plots. The scatter-plot correlation and the cross-correlation peak are therefore complementary quantities and are not expected to have identical numerical values.

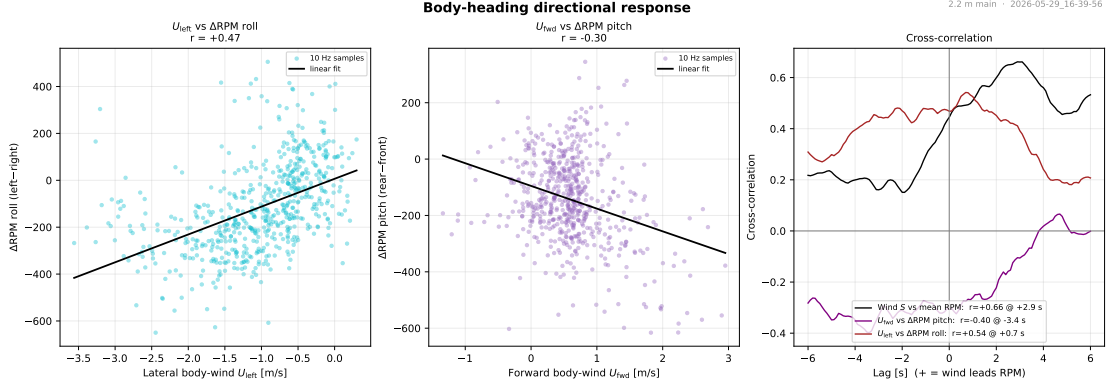


Figure 7.4: Body-heading response for the 2.2 m main session.

2.2 m main session. At 2.2 m, the lateral body-heading relationship is measurable but moderate. The scatter plot shows that increasing leftward body-relative wind is associated with an increase in the left-right motor-speed differential, with a zero-lag correlation of $r = 0.47$. The corresponding $U_{\text{fwd}} - \Delta\text{RPM}_{\text{pitch}}$ relationship is weaker, with $|r| = 0.30$. This indicates that, for this session, the lateral wind component provides a clearer directional organization of the RPM redistribution than the longitudinal component.

The moderate scatter is consistent with the lower absolute wind forcing at this height and with the crosswind measurement geometry. Since the anemometer is not upstream of the drone, the measured wind should not be interpreted as an advected precursor of the vehicle response. The cross-correlation panel is therefore used only to describe statistical timing between the selected signal pairs, not to infer a convective travel time.

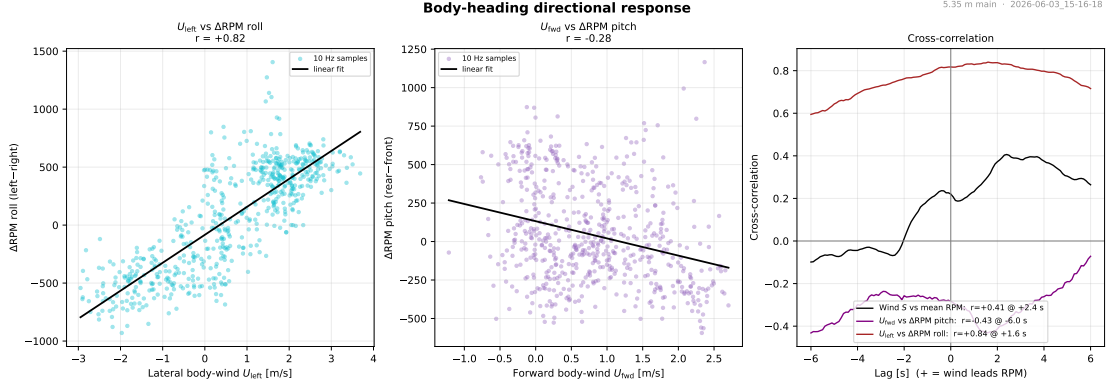


Figure 7.5: Body-heading response for the 5.35 m main session.

5.35 m main session. At 5.35 m, the same lateral relationship becomes much clearer. The $U_{\text{left}}-\Delta\text{RPM}_{\text{roll}}$ correlation reaches $|r| = 0.82$, whereas the pitch-related relationship remains secondary ($|r| = 0.28$). This indicates that the dominant directional redistribution of motor speed occurs in the roll channel, consistently with the fact that the measured horizontal wind projects mainly onto the lateral body-heading direction during this session.

This case is important for two reasons. First, it provides the clearest directional wind-RPM association in an upstream configuration. Second, because the anemometer is located upstream of the drone in the mean wind direction, the timing information can be assessed against a convective-delay estimate. The directional result discussed here therefore complements the geometry-gated delay interpretation developed in Section 7.4.

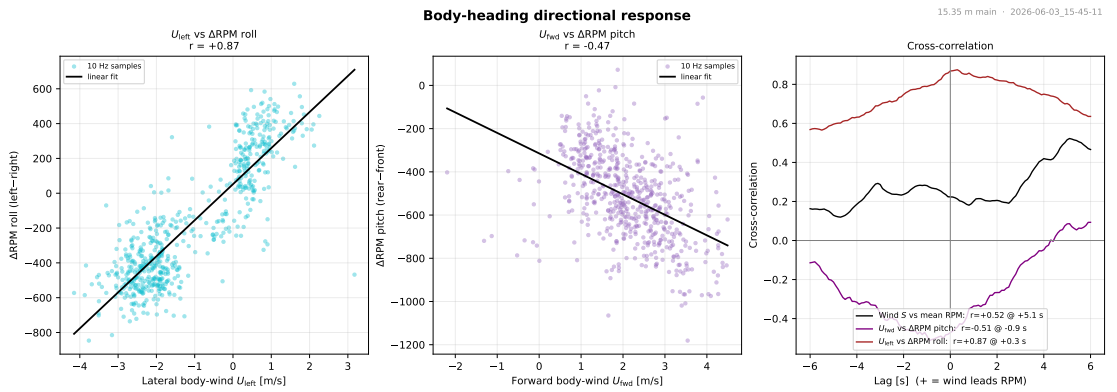


Figure 7.6: Body-heading response for the 15.35 m main session.

15.35 m main session. At 15.35 m, the lateral association is the strongest of the selected set, with $|r| = 0.87$. The pitch-related association also becomes larger than in the two lower-height cases, but remains weaker than the roll-related one ($|r| = 0.47$). This confirms that, under the stronger wind forcing measured in this session, the RPM redistribution has a clear directional structure and is dominated by the lateral body-heading wind component.

The cross-correlation panel must again be interpreted with care. Although the directional roll relationship is strong, the anemometer–drone geometry is crosswind/borderline downstream. Therefore, the timing of the response cannot be interpreted as a convective travel time from the anemometer to the drone. The lag information remains a statistical descriptor of the signal alignment only.

Cross-case synthesis. For the three main sessions, the most robust directional result is the repeated dominance of the $U_{\text{left}}\text{--}\Delta\text{RPM}_{\text{roll}}$ pair. Its strength increases from $|r| = 0.47$ at 2.2 m, to $|r| = 0.82$ at 5.35 m, and to $|r| = 0.87$ at 15.35 m. The corresponding $U_{\text{fwd}}\text{--}\Delta\text{RPM}_{\text{pitch}}$ association remains weaker in all three cases. This roll-dominant behaviour appears in different measurement geometries: the crosswind 2.2 m case, the upstream 5.35 m case, and the crosswind/borderline-downstream 15.35 m case. This consistency shows that the body-heading projection is not only a convenient post-processing step, but a necessary part of the physical interpretation. The inertial wind components alone would not identify whether the measured wind acts mainly as a longitudinal or lateral disturbance on the vehicle. The observed roll dominance should nevertheless be interpreted in the context of the achieved wind directions and drone headings. In the selected sessions, the horizontal wind projects predominantly onto the lateral body-heading direction, so a stronger roll-related RPM response is physically plausible. This does not imply that the platform is generally more sensitive in roll than in pitch for all wind conditions. A broader dataset containing wind approaches aligned with the drone forward or aft direction would be required to test whether a pitch-dominant response emerges in those cases.

7.4 Geometry-gated interpretation of wind–RPM timing

The interpretation of wind–RPM timing depends on the relative geometry between the anemometer and the drone. A statistical lag can be computed for every synchronized session, but it can be interpreted as a convective delay only when the anemometer is located upstream of the drone with respect to the mean horizontal wind direction. In the notation introduced in Chapter 6, this requires a positive along-wind separation, $d_{\parallel} > 0$. This condition is geometrical and is independent of mast height: a high or low mast position does not by itself make a delay physically interpretable.

The three main sessions deliberately illustrate three different situations. The 2.2 m case is approximately crosswind, the 5.35 m case is upstream, and the 15.35 m main case is crosswind/borderline downstream. These geometries are shown in Figures 7.7, 7.9, and 7.11.

The delay-aware figures in this section are intended as visual consistency checks. They do not repeat the complete motor-level time histories shown in Section 7.2. Instead, they focus on the signal pairs used for timing interpretation: the scalar wind-speed/mean-RPM pair and the two body-heading directional pairs. Since these signals have different physical units, they are plotted as z-scores,

$$z_x(t) = \frac{x(t) - \langle x \rangle}{\sigma_x},$$

where $\langle x \rangle$ and σ_x are the mean value and standard deviation of the signal over the analysed window. This normalization allows the temporal alignment of wind and RPM variations to be inspected without comparing their dimensional amplitudes directly.

In each delay-aware figure, the dashed wind curve shows the wind signal shifted by the delay indicated in the subtitle. For non-upstream cases, this delay is the observed statistical lag from the scalar S –mean-RPM comparison and is used only as a diagnostic shift. For the upstream 5.35 m case, the shifted curve uses the geometry-based convective-delay estimate. The lower directional panels are included to show how the same session-level shift appears when applied to the body-heading wind components, but they do not imply that all signal pairs share the same optimal lag.

2.2 m main session. The 2.2 m geometry has a separation angle of approximately 94° . The anemometer is therefore not upstream of the drone, and no physically meaningful convective-delay estimate is defined. The observed statistical lag from the scalar S -mean-RPM comparison is approximately $\tau^* = 2.9$ s, but this value is used only as a diagnostic time shift.

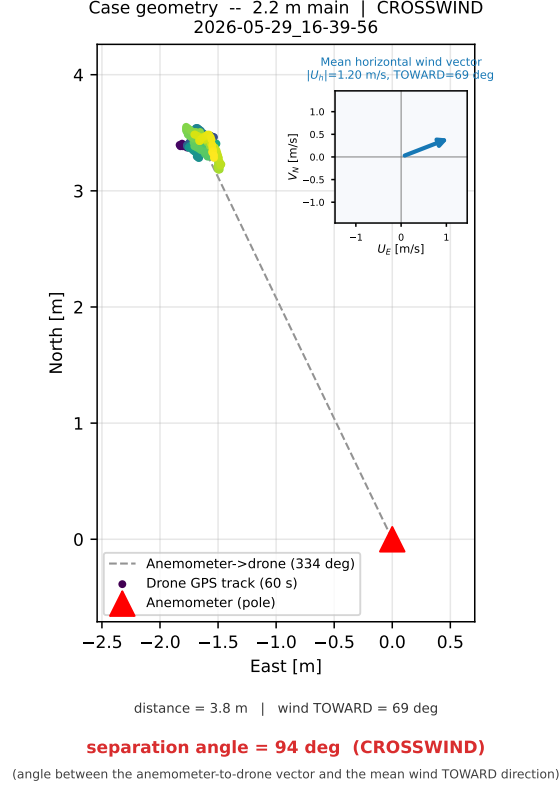


Figure 7.7: Geometry of the 2.2 m main session.

Figure 7.8 shows the effect of applying this statistical shift. The scalar wind speed and the mean RPM show a broad correspondence, especially in the second half of the acquisition. However, this alignment is not interpreted as advection from the anemometer to the drone, because the geometry is crosswind and $d_{\parallel}$ is not positive. The observed alignment may reflect controller response, vehicle correction, filtering, atmospheric evolution, or a combination of these effects. The directional panels provide additional context, but they do not convert the scalar statistical lag into a convective travel time.

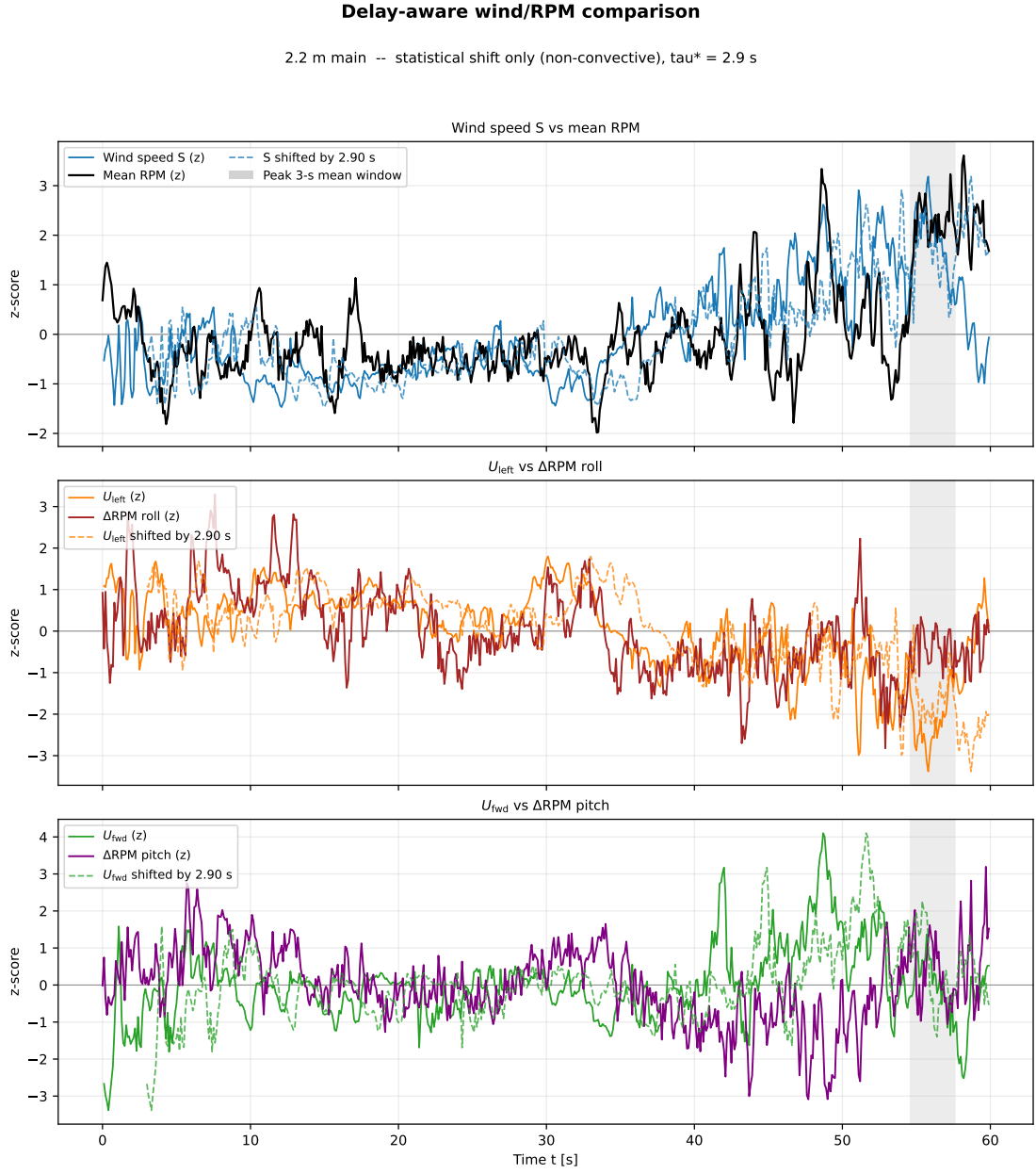


Figure 7.8: Delay-aware wind/RPM comparison for the 2.2 m main session.

5.35 m main session. The 5.35 m case is the only upstream case among the selected sessions. Its separation angle is approximately 32° , and the anemometer is located upstream of the drone in the mean horizontal wind direction. The geometry gives a positive along-wind separation,

$$d_{\parallel} \approx 3.51 \text{ m.}$$

With $\bar{S}_h = 1.79 \text{ m/s}$, the resulting convective-delay estimate is

$$\tau_{\text{conv}} = \frac{d_{\parallel}}{\bar{S}_h} \approx 1.96 \text{ s.}$$

The observed statistical lag from the scalar S -mean-RPM comparison is approximately $\tau^* = 2.4 \text{ s}$. The difference between the two values is about 0.4 s , which falls within the practical compatibility band adopted in the analysis.

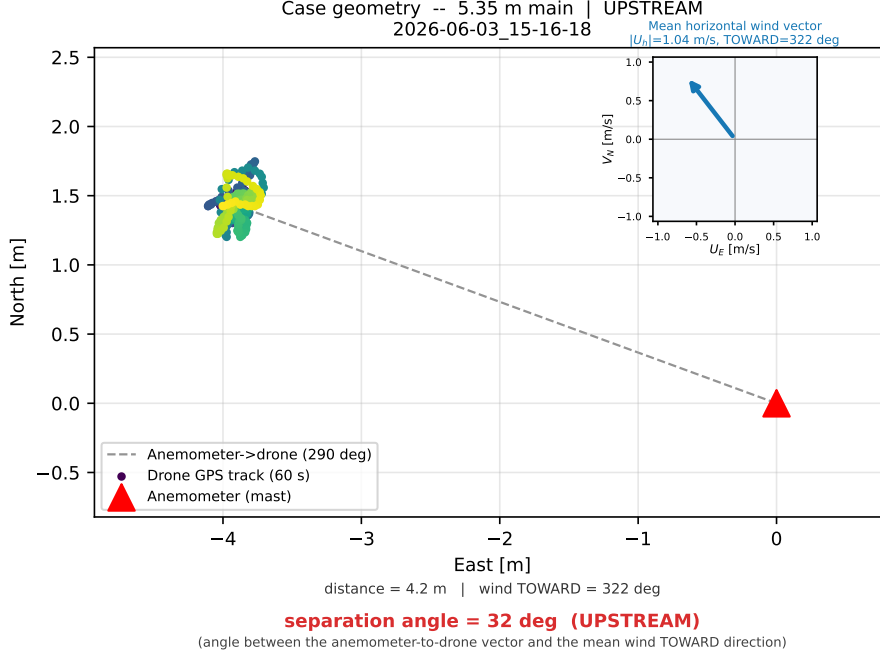


Figure 7.9: Geometry of the 5.35 m main session.

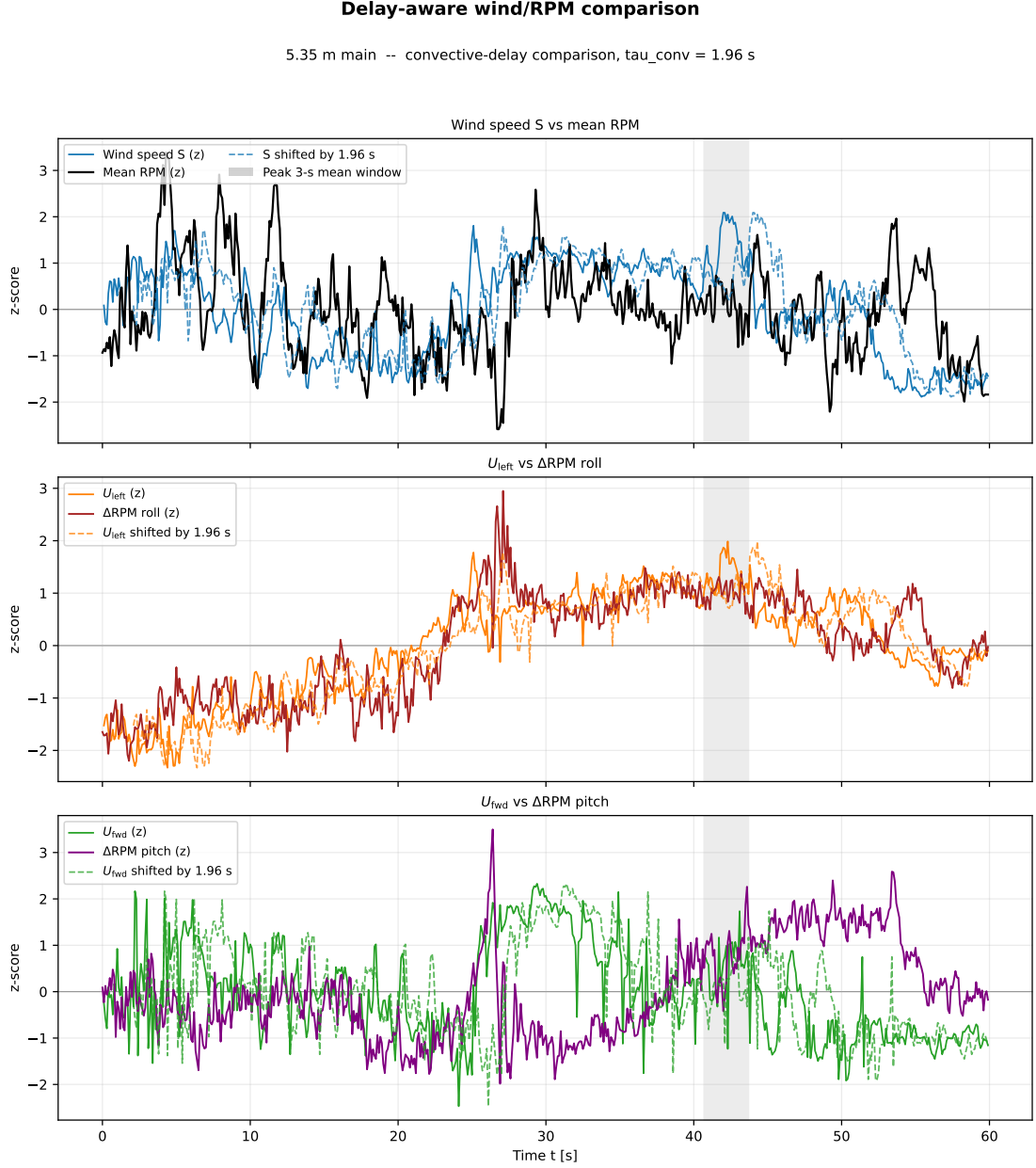


Figure 7.10: Delay-aware wind/RPM comparison for the 5.35 m main session.

Figure 7.10 uses $\tau_{\text{conv}} = 1.96$ s as a physics-based shift. The objective is not to fit the wind and RPM signals a posteriori, but to test whether the geometry-based advection estimate gives a plausible time alignment. In the scalar panel, the shifted wind-speed signal and the mean RPM exhibit a similar slow time evolution over several-second time scales, especially around the main wind-speed variations of the

acquisition window. This agreement is interpreted as a visual consistency check, not as proof of a one-to-one causal relationship between each wind fluctuation and each RPM fluctuation. The directional panels also show that the roll-related response remains the clearest body-heading association, consistent with the $U_{\text{left}}-\Delta\text{RPM}_{\text{roll}}$ result discussed in Section 7.3.

The 5.35 m case is therefore the only case in this chapter described as a *geometry-validated convective-delay* case. This phrase does not imply that the anemometer measures the exact rotor-level inflow or that each RPM fluctuation is caused directly by a measured wind fluctuation. It means that the observed wind-RPM timing is physically consistent with advection from the anemometer toward the drone under an upstream geometry.

15.35 m main session. The 15.35 m main session has a separation angle of approximately 116° . The geometry is therefore crosswind/borderline downstream, and $d_{\parallel} < 0$. No convective-delay estimate is admissible. The observed statistical lag from the scalar S -mean-RPM comparison is approximately $\tau^* = 5.0$ s, but this lag cannot be interpreted as a physical travel time from the anemometer to the drone.

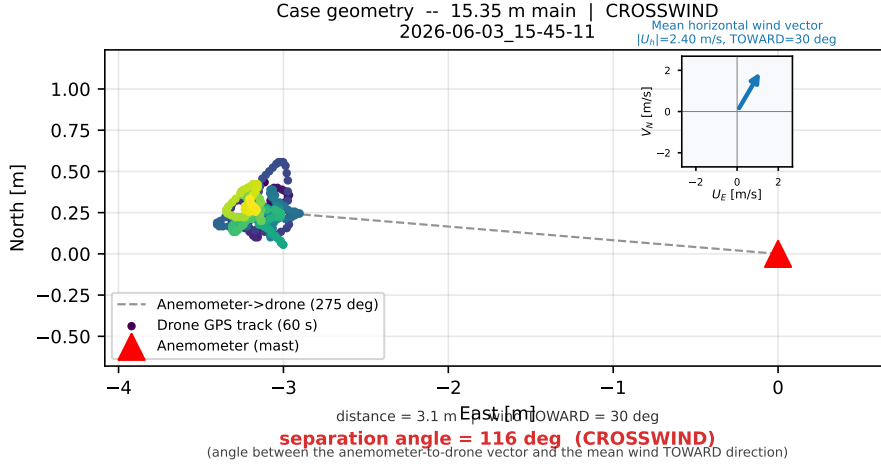


Figure 7.11: Geometry of the 15.35 m main session.

Figure 7.12 shows the scalar statistical shift applied to the 15.35 m main session. Although this shift improves the visual alignment between the scalar wind-speed signal and the mean RPM over parts of the record, it remains a non-convective diagnostic shift. The geometry does not support an upstream advection path from the anemometer to the drone.

The scalar lag at 15.35 m should also be distinguished from the much smaller lag observed in the $U_{\text{left}} - \Delta \text{RPM}_{\text{roll}}$ cross-correlation. The former describes a global wind-intensity/mean-RPM association, whereas the latter describes the directional lateral differential-RPM response. Since the two lags are obtained from different signal pairs, they should not be interpreted as the same physical mechanism. This distinction is also why the directional panels in the delay-aware figure are used as supporting visual context rather than as evidence that all wind-RPM pairs share the scalar lag.

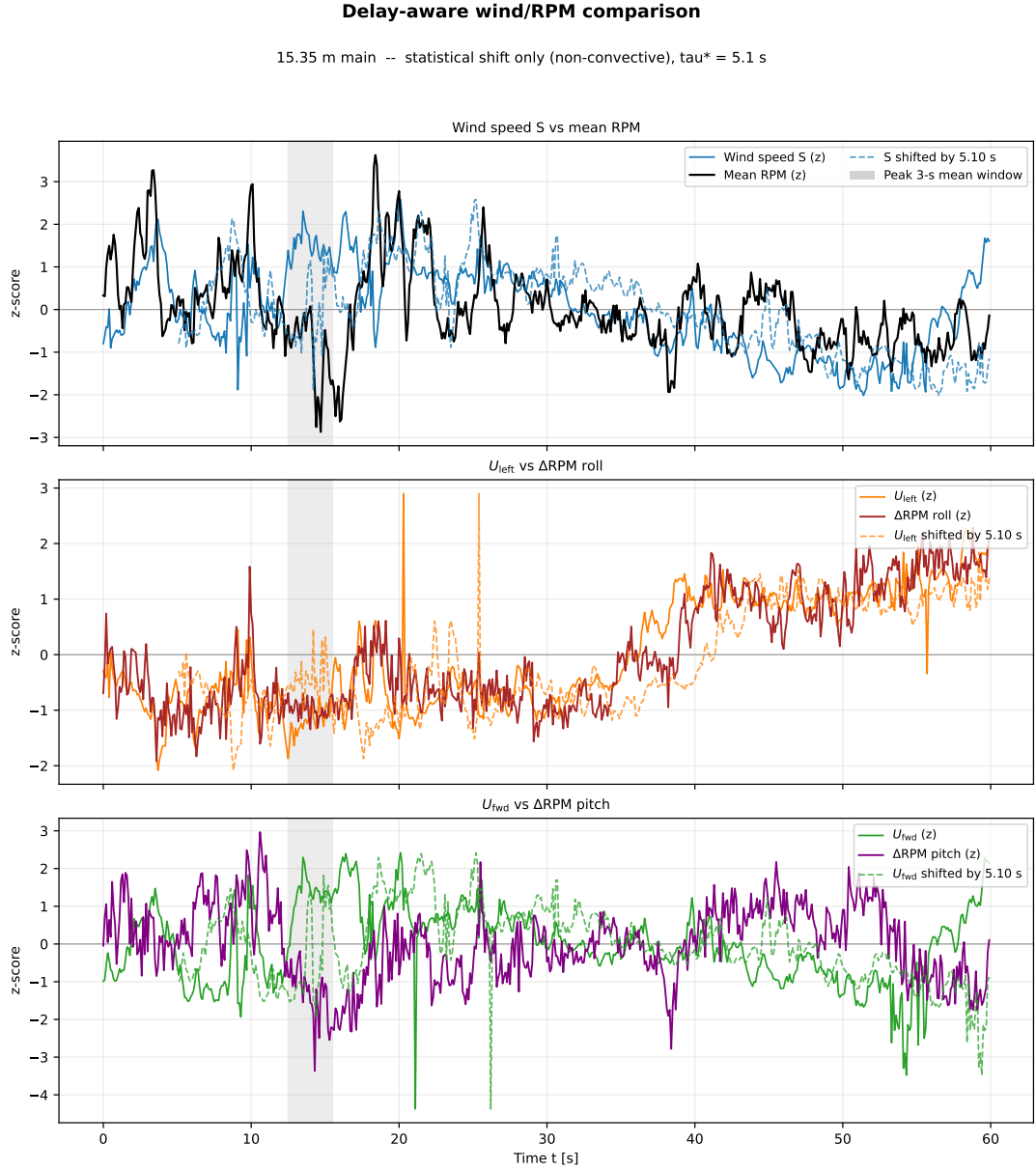


Figure 7.12: Delay-aware wind/RPM comparison for the 15.35 m main session.

The 5.35 m session is the only case for which the convective-delay estimate is physically admissible, because the anemometer is upstream of the drone and $d_{\parallel} > 0$. The 2.2 m and 15.35 m main sessions also show statistical lags, but their geometries do not support an advective interpretation. This distinction is essential: a numerical lag alone is not sufficient to claim a convective delay. A physically admissible convective interpretation also requires an upstream anemometer–drone geometry.

7.5 Gust-response case at 15.35 m

The 15.35 m gust-zoom session, 2026-06-03_15-44-08, is retained as a complementary transient-response case. It is not used as a fourth main mast-height session, because its objective is different from the cross-case comparison developed in the previous sections. The three main sessions are used to compare wind forcing, directional RPM redistribution, and geometry-gated lag interpretation across representative conditions. The gust-zoom session is instead used to inspect the strongest short-duration wind-speed event in the retained set and to verify whether the drone telemetry shows a coordinated response during that event.

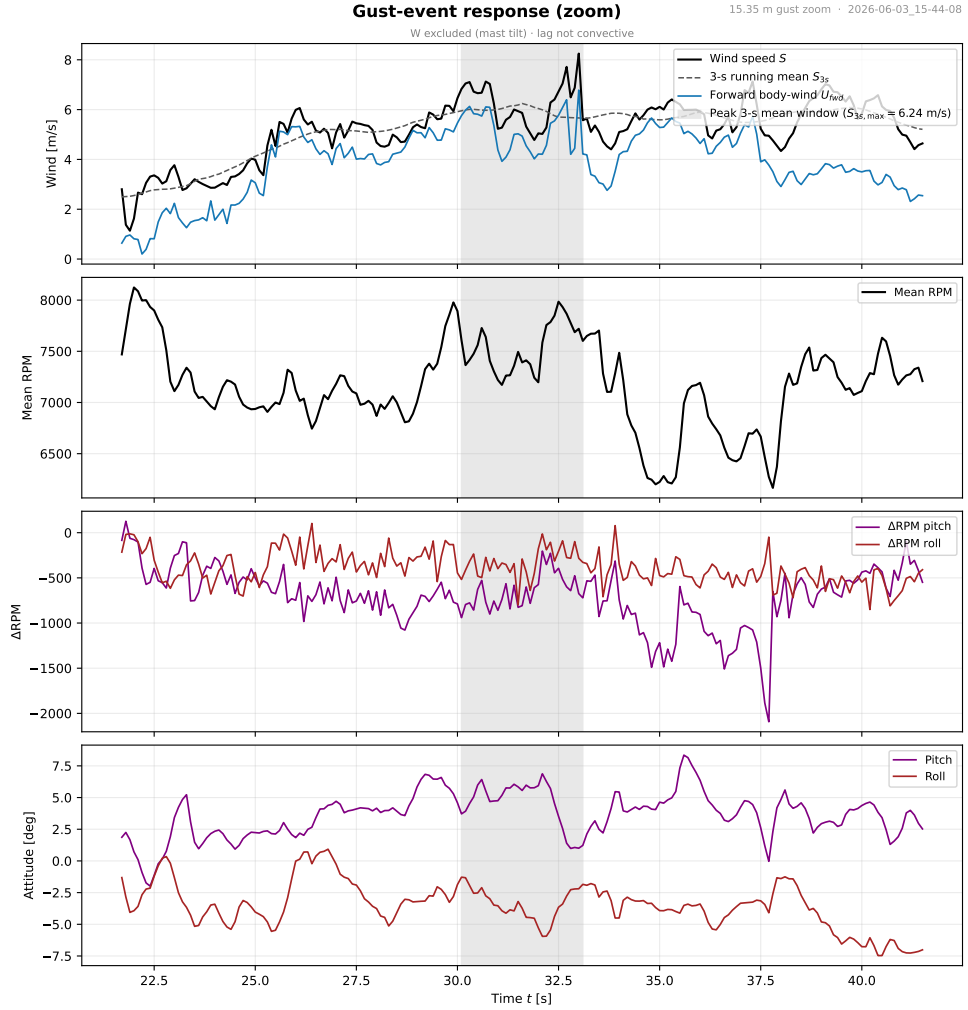


Figure 7.13: Gust-event zoom at 15.35 m.

This session has $S_{3s,max} = 6.25$ m/s at approximately $t = 31.6$ s, together with the

largest collective RPM variability reported in Table 7.1. It also has the largest instantaneous wind-speed excursion of the retained sessions. Therefore, although it is not used for the cross-case body-heading correlation comparison, it provides the clearest example of a short-duration wind event strong enough to produce a visible transient in the motor and attitude signals.

Figure 7.13 shows a zoomed time window around the peak 3-second wind-speed interval. The first panel reports the scalar wind speed S , its 3-second running mean S_{3s} , and the forward body-heading wind component U_{fwd} . The vertical wind component is not used for the physical interpretation of this case because the 15.35 m measurements are affected by the anemometer tilt flag. Under a tilted-sensor condition, the sensor vertical axis is no longer aligned with the true vertical direction, so part of the much larger horizontal wind can be projected onto the measured vertical component. As a result, W may contain a spurious contribution that does not represent true atmospheric vertical velocity. The shaded region marks the interval in which the running-mean wind speed reaches its maximum value.

The telemetry response during and around this shaded interval is not confined to a single signal. The mean RPM changes over the gust window, indicating a variation of the collective motor-speed level. At the same time, the pitch- and roll-related differential RPMs show marked transient variations, indicating that the controller is also redistributing motor effort between opposite motor pairs. The attitude panel shows simultaneous pitch and roll excursions, confirming that the motor-speed changes occur together with a measurable vehicle attitude response. The figure therefore supports the interpretation of the event as a controller-mediated response to a strong short-duration wind-speed excursion.

This interpretation remains deliberately qualitative. The figure does not provide a direct measurement of aerodynamic loads, nor does it isolate the contribution of each individual rotor. It shows that, during the strongest measured gust window, the wind, motor-speed, and attitude signals vary in a coordinated way. This is consistent with the physical framework developed in Chapters 2 and 3: a short-duration change in the external wind forcing can alter the disturbance acting on the vehicle, and the flight controller responds by adjusting both the collective motor-speed level and the differential motor-speed distribution.

Finally, this gust-zoom case must not be interpreted as a convective-delay validation. The session has a downstream anemometer-drone geometry, so no physically admissible τ_{conv} is defined. The figure therefore demonstrates a transient association between a strong measured gust window and the drone telemetry, but it does not establish a travel-time relationship from the anemometer to the drone. Its role is to complement the previous cross-case analysis by showing how the strongest retained wind-speed excursion appears in the synchronized RPM and attitude records.

7.6 Frequency-domain consistency

As a final qualitative check, the wind and RPM signals are compared in the frequency domain using normalized power spectral densities. This analysis is not intended to identify a transfer function between wind and motor response, nor to estimate controller dynamics. Its purpose is to verify whether the wind and RPM-related quantities contain fluctuation energy over comparable frequency ranges, consistently with the time-domain and body-heading results discussed above.

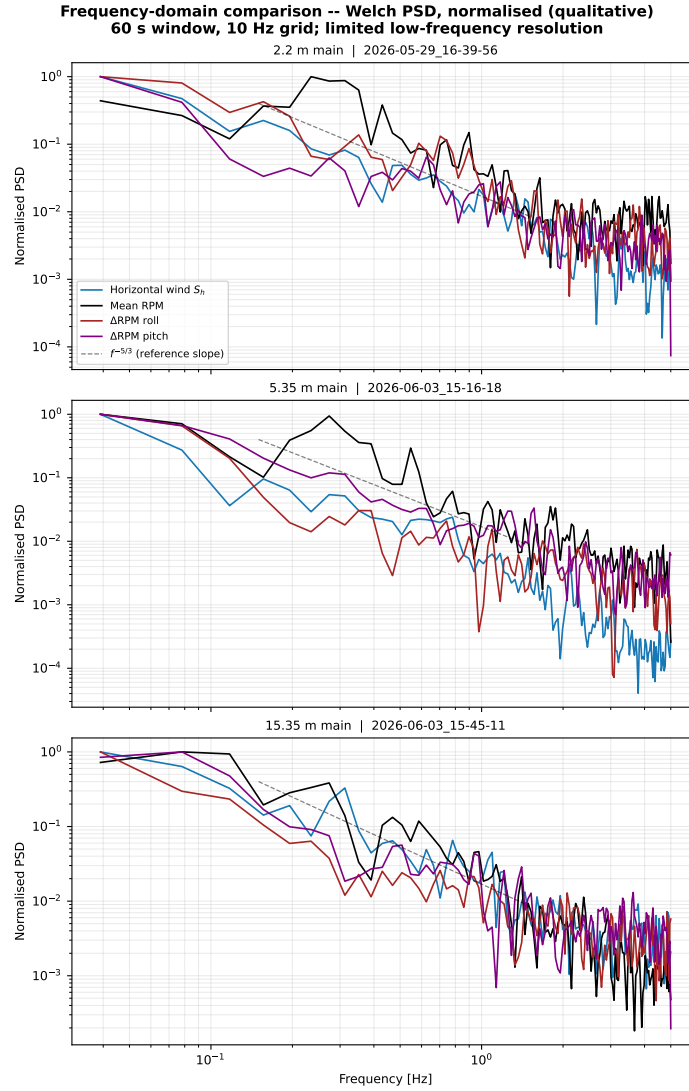


Figure 7.14: Frequency-domain comparison across the three main mast-height cases.

The comparison is performed on the same synchronized 10 Hz analysis grid used throughout Chapter 6. Therefore, the resolved frequency range is limited by the Nyquist frequency of 5 Hz. The PSD results should therefore be interpreted as a qualitative description of the dominant frequency content, not as a precise spectral characterization of atmospheric turbulence or of the closed-loop vehicle dynamics. Figure 7.14 compares the normalized spectra of the horizontal wind speed S_h , the mean RPM, ΔRPM_{roll} , and $\Delta RPM_{\text{pitch}}$ for the three main sessions. Each panel corresponds to one mast-height case, allowing the spectral content of the wind and motor-response signals to be compared within the same acquisition window. Each spectrum is normalized by its own maximum value, so the comparison concerns spectral shape and frequency range rather than absolute fluctuation power.

In all three cases, the spectra are dominated by low-frequency content, meaning that most of the resolved fluctuation energy is associated with slowly varying features rather than with rapid sample-to-sample oscillations. The wind and RPM-related quantities show a broad overlap over part of the resolved frequency range, especially at the lower frequencies where the main time-domain variations are observed. This overlap does not prove a causal wind-to-RPM relationship, but it is consistent with the time-domain interpretation because the measured wind and the controller-mediated RPM response contain relevant variations over comparable time scales. Therefore, the PSD comparison is interpreted only as a supporting consistency check. It shows that the wind and RPM signals do not evolve on completely separate frequency ranges, but it does not provide phase information, coherence, or a transfer function. The physical interpretation remains based on the time-domain response, the body-heading directional correlations, and the geometry-gated delay analysis.

The reference $f^{-5/3}$ slope shown in the figure is included only as a visual guide [23]. It is not used to validate an inertial subrange, because the acquisition windows are short, the measurements are performed close to the ground and near the drone, and the spectra are affected by the finite sampling frequency, controller response, motor dynamics, and signal preprocessing. Therefore, the PSD analysis is retained as supporting evidence only. The primary interpretation of the results remains based on the body-heading directional response and on the geometry-gated delay analysis developed in Sections 7.3 and 7.4.

The frequency-domain comparison therefore concludes the results chapter by showing that the wind and RPM-related signals contain relevant variations over partially common time scales. The interpretation of these results, together with their limitations and implications for future work, is summarized in Chapter 8.

Chapter 8

Conclusions

8.1 Summary of the work

This thesis developed a theoretical, experimental, and data-analysis framework to investigate the influence of atmospheric wind on the aerodynamic and flight-dynamic response of a quadrotor operating in outdoor quasi-hover conditions. The motivation of the work was the need to interpret quadrotor behaviour under realistic low-altitude atmospheric disturbances, where the wind field is unsteady, direction-dependent, and spatially variable.

The theoretical part of the thesis established the physical basis for the interpretation of the measurements. Chapter 2 introduced the quadrotor equations of motion and the relation between individual motor speeds, total thrust, and roll-, pitch-, and yaw-related control moments. Chapter 3 discussed rotor inflow and loading mechanisms, with particular attention to the role of horizontal and non-axial inflow. Chapter 4 then introduced the wind descriptors used to characterize the atmospheric conditions, including wind-speed magnitude, horizontal wind forcing, turbulence intensity, short-duration wind-speed excursions, integral-scale diagnostics, and spectral content.

The experimental work was based on an outdoor campaign performed with a Holybro X500 V2 quadrotor equipped with a Pixhawk 6X flight controller. The atmospheric wind was measured by a LI-550P TriSonica™ Mini ultrasonic anemometer mounted on a fixed pole near the flight region, while the onboard ArduPilot .BIN logs provided motor RPM, attitude, inertial, barometric, and GPS data. The acquisition strategy was designed to obtain repeatable 60 s windows in which the measured wind could be compared with the corresponding closed-loop response of the vehicle.

A dedicated synchronization and processing workflow was developed to align the anemometer measurements, the PC-side MAVLink trigger information, and the onboard flight-controller log. The SA/RC10 trigger provided the common event

used to align the different time bases, and the resulting signals were resampled onto a common 10 Hz analysis grid. From these synchronized data, the analysis extracted wind descriptors, body-heading wind components, mean and differential RPM quantities, anemometer–drone geometry, time-domain correlations, shifted overlays, scatter plots, gust-response indicators, and qualitative power spectral densities.

The results were presented as representative case studies rather than as a statistical survey of the full experimental campaign. One main session was analysed at each of the three mast heights, 2.2 m, 5.35 m, and 15.35 m, together with an additional 15.35 m gust-zoom session. This case-study approach made it possible to interpret the wind–RPM relationship while preserving the physical context of each acquisition, including wind intensity, wind direction relative to the drone, motor-speed response, and anemometer–drone geometry.

8.2 Synthesis of the findings

The main outcome of this thesis is that synchronized outdoor wind measurements and flight-controller telemetry can reveal a physically interpretable response of a quadrotor to atmospheric disturbances, provided that the measurements are interpreted with the correct reference frames and geometric constraints. The anemometer signal cannot be treated as the exact rotor-level inflow, and the RPM signals cannot be treated as direct aerodynamic load measurements. Nevertheless, when analysed together, they provide evidence of how the closed-loop vehicle reacts to measured wind variations.

The first main finding is that the measured atmospheric wind is reflected in the quadrotor telemetry primarily through motor-speed redistribution. The mean RPM remains useful as an indicator of the collective motor-speed level and of the overall thrust demand, but the clearest wind-related responses appear in the differential-RPM quantities. This is consistent with the quadrotor flight-dynamic framework: in near-hover, horizontal wind disturbances are compensated mainly by tilting the thrust vector and by changing the relative speeds of opposite motor pairs, thereby generating roll- and pitch-related control moments.

The second main finding is that the wind must be interpreted in the drone body-heading frame. The inertial wind components U^E , V^N , and W describe the measured atmospheric flow in a ground-fixed frame, but they do not indicate whether the wind acts as a longitudinal or lateral disturbance on the vehicle. Projecting the horizontal wind into U_{fwd} and U_{left} makes it possible to compare the wind direction with the pitch- and roll-related RPM differentials. In the representative sessions analysed here, the most consistent directional association is the $U_{\text{left}} - \Delta \text{RPM}_{\text{roll}}$ relationship, because the measured wind projects mainly

onto the lateral body-heading direction. This result should be interpreted as a consequence of the selected wind directions and drone headings, not as a general statement that the platform is intrinsically more sensitive in roll than in pitch.

The third main finding is that the magnitude of the motor response is more closely associated with the absolute wind forcing and with short-duration wind-speed excursions than with turbulence intensity alone. The high-mast cases show stronger RPM variability and larger differential-RPM excursions even though their relative turbulence intensity is lower than that of the lower-height sessions. For the selected cases, the absolute level of the wind and the amplitude of the individual wind events are therefore more informative than relative fluctuation indicators considered in isolation.

The fourth main finding concerns timing. A statistical lag between wind and RPM signals can be computed for every synchronized session, but it has a physical convective meaning only when the anemometer is upstream of the drone in the mean horizontal wind direction. Among the selected cases, this condition is satisfied only by the 5.35 m main session, for which the observed scalar wind-speed/mean-RPM lag is compatible with the geometry-based estimate $\tau_{\text{conv}} \approx 1.96$ s. In the 2.2 m and 15.35 m main sessions, the wind and RPM signals still show statistical associations, but their crosswind or crosswind/borderline-downstream geometries prevent an advective interpretation of the observed lags.

The gust-zoom session and the frequency-domain comparison support this interpretation without replacing the time-domain and geometry-based evidence. The gust-zoom case shows that the strongest retained short-duration wind-speed excursion is accompanied by coordinated variations in mean RPM, differential RPM, and attitude, which is consistent with a controller-mediated transient response. The normalized PSD comparison shows that wind and RPM-related signals contain relevant variations over partially common frequency ranges. However, neither analysis proves direct causality by itself. The physical interpretation remains based on the combined use of synchronized time histories, body-heading directional response, motor-pair definitions, and anemometer-drone geometry.

Overall, the thesis demonstrates that the influence of atmospheric conditions on quadrotor operation can be investigated experimentally using a fixed anemometer and onboard telemetry, provided that the interpretation remains both geometry-aware and controller-aware. The measured wind provides a local atmospheric reference, while the RPM signals reveal how the flight controller absorbs the disturbance through motor-speed modulation.

8.3 Limitations

The conclusions of this work must be interpreted within the limits of the experimental configuration and of the case-study approach adopted in the results chapter.

First, the analysed sessions do not form a statistically complete dataset. The results are based on representative acquisitions selected because they provide physically interpretable combinations of wind forcing, motor response, and anemometer–drone geometry. The mast-height comparison is therefore not a controlled height sweep under identical atmospheric and operational conditions. In particular, the 2.2 m session was acquired on a different day from the 5.35 m and 15.35 m sessions, and the retained cases are not identical in flight mode. Differences between cases should therefore be interpreted as differences between representative outdoor conditions, not as isolated effects of mast height alone.

Second, the anemometer provides a fixed-point wind measurement. It is used as a local atmospheric reference and, under the quasi-hover approximation, as a proxy for the external wind disturbance near the vehicle. It is not a direct measurement of the instantaneous inflow at each rotor. The actual rotor-level inflow also depends on vehicle motion, attitude, induced flow, rotor wakes, and the spatial evolution of the wind field between the sensor and the drone. This limitation is particularly important in crosswind and downstream configurations, where the measured wind cannot be interpreted as an upstream precursor of the vehicle response.

Third, the RPM signals are closed-loop response variables. They are produced by the onboard controller and are affected by attitude stabilization, position or altitude control, motor dynamics, filtering, and motor allocation. The differential-RPM quantities are therefore indicators of motor-pair redistribution, not calibrated measurements of aerodynamic moments. Similarly, the mean RPM is an indicator of collective motor-speed demand, not a direct measurement of thrust or aerodynamic force.

Fourth, some measurement and processing constraints affect the interpretation. The vertical wind component is affected by anemometer tilt, especially at the 15.35 m mast height, and is therefore de-emphasized in the corresponding results. Residual heading uncertainty of the anemometer may also affect the exact decomposition of the horizontal wind components. In addition, all signals are analysed on a common 10 Hz grid, which limits the resolved frequency range to 5 Hz. Higher-frequency wind–controller or motor dynamics are therefore outside the bandwidth considered in this thesis. The 60 s acquisition windows also limit the convergence of spectral, correlation-based, and integral-scale quantities, which are used as descriptive indicators rather than formal statistical tests.

Finally, no rotor-level aerodynamic validation is performed. The thesis provides a physically grounded interpretation of wind-induced RPM variations, but it does

not measure rotor loads, local rotor inflow, blade-level aerodynamic quantities, or aerodynamic coefficients. The aerodynamic discussion therefore supports the interpretation qualitatively, while quantitative load reconstruction and coefficient identification remain outside the scope of the present work.

8.4 Future work

Future work should first extend the experimental campaign to a larger and more balanced dataset. Repeating the measurements over more days, wind directions, mast heights, drone positions, and atmospheric conditions would make it possible to separate height effects from day-to-day variability and from changes in operational conditions. A larger dataset would also allow the body-heading correlation analysis to be tested statistically rather than only through representative case studies.

The wind-measurement setup should also be improved. Using multiple synchronized anemometers around the flight region would make it possible to observe whether the same wind structure is detected at different locations with a consistent propagation delay. This would provide a more robust estimate of advection direction and convection velocity than a single fixed-point sensor. A stiffer or instrumented mast, together with direct measurements of anemometer heading and tilt, would reduce uncertainty in the wind-vector interpretation, especially at the highest mast height. The directional-response analysis should be expanded to include a wider range of wind-approach directions. The present results are dominated by cases in which the wind projects mainly onto the lateral body-heading direction. Future experiments should include conditions in which the wind approaches primarily from the drone forward or aft direction, so that the pitch-related response can be tested under conditions analogous to the roll-dominant cases observed here.

Future analyses should also make more direct use of attitude, IMU, GPS, and barometric signals. In the present work, these quantities are mainly used to support the interpretation of the RPM response and to verify the flight condition. A more complete dynamic analysis could relate wind events to attitude corrections, angular rates, accelerations, altitude-control transients, and position-hold activity, providing a clearer separation between aerodynamic disturbance, controller response, and vehicle motion.

Finally, the synchronized wind-telemetry dataset provides a basis for model comparison and identification. Low-order rotor-aerodynamic models, higher-fidelity simulations, or data-driven disturbance-response models [27] could be compared with the measured mean and differential RPM responses. Such work would be required to move from the qualitative interpretation developed in this thesis toward aerodynamic coefficient identification and predictive modelling of quadrotor flight dynamics under realistic atmospheric disturbances.

In conclusion, this thesis establishes a physically grounded experimental framework for studying the response of a quadrotor to atmospheric wind. The central finding is that, in outdoor quasi-hover conditions, the measured wind is reflected primarily through controller-mediated differential motor-speed redistribution. This response becomes interpretable only when the wind is expressed in the drone body-heading frame and when any timing information is constrained by the anemometer–drone geometry. These results provide a foundation for future experimental identification and modelling of drone aerodynamic and flight-dynamic response under realistic atmospheric conditions.

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