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Structural Health Monitoring of Offshore Jacket Platforms

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TABLE OF CONTENTS

1. INTRODUCTION

The existence of great amount of jacket platforms all around the world with estimated 30 years of operational lifetime is a fair reason to study new technologies for its life extension. The prolongation lifetime studies are a consequence of factors like cost saving and increased practices of the subsea connection between new oil and gas discoveries and a present production facility.

SHM is an important utensil for assessing the structural integrity and its lifetime endurance. Thus, it is a method applying strategies to detect damages for lots of engineering fields. SHM installation will possibly affect cost installation, nonetheless it will save operational money and maintenance in the long term. As a result, improvements of sensors efficiencies and costs are done in the SHM field. On top of the integrity evaluation, SHM also is a tool to enhance the designed criteria based on historical data.

The aim of the thesis is to describe and investigate the SHM techniques and strategies, in addition to developed monitoring applications of offshore jackets in cost-effective approaches.

The thesis will include ideas about the knowledge of SHM fields and specially of offshore structures, methods involving steps of monitor planning, data collection, processing data and integrity evaluation, labeling and identifying failure modes types and the parameters influencing them, citations of adequate sensors to detect the influenced parameters and explanation of their procedure measurement techniques, in addition to their suitability.

In the followed chapters, the introduction will be divided in five divisions, starting with some existing general knowledge about SHM, in addition to explanation of prior definitions of this field. Later on, information and facts will be detailed concerning the design concept, parameters damage and failure modes of offshore jackets structures.

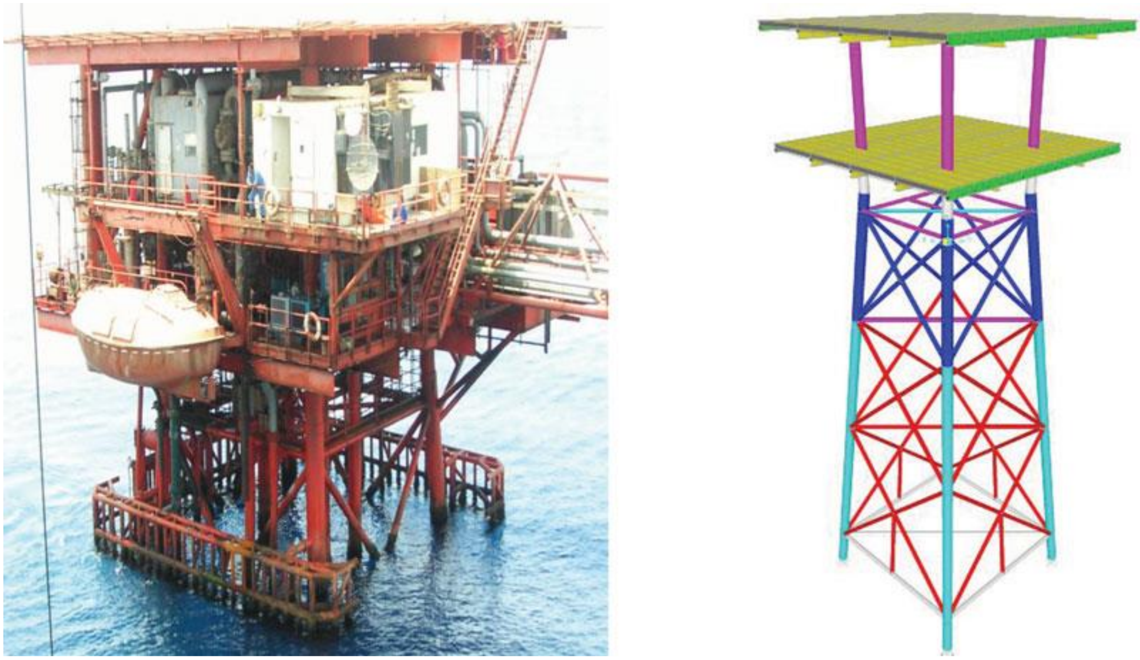


Figure 1: Model of jacket platform [94].

Figure 2: Jacket platform subjected to different mode failures [94].

2. SHM APPROACH IDENTIFICATION

Structural Health Monitoring methods describe the process of the application of strategies and techniques for damage detection and damage classification of an exposed structure to continuous changes. These variations are the cause of ageing processes, environmental influences and also by unpredicted events such as earthquakes or wind buffeting.

These methods have been significant in many different industries: the aerospace industry, offshore industries, civil engineering and mechanical engineering. For instance, bridge monitoring testing techniques are relevant to those techniques on offshore structures. Yet offshore structure monitoring is more challenging than other industries due to the surrounding rough environment.

SHM approach is divided up to four different phases still equally relaying on each other to assess the remaining useful life of the system and can be seen as an iterative process as shown in Figure 3 [1].

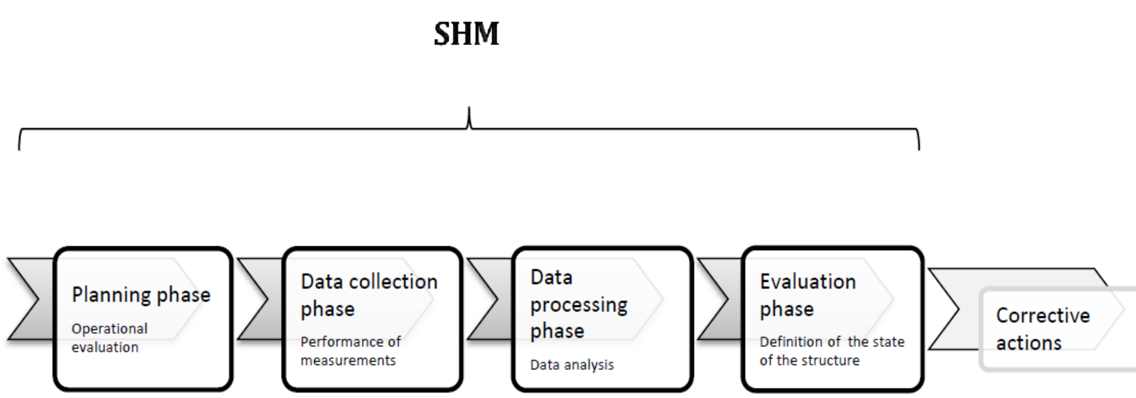


Figure 3 SHM phases

2.1. SHM PHASES

Planning phase

The planning phase is the start of all the SHM phases, also the part that involves developing a plan and setting a strategy once the scope is known and monitoring is required.
The following key questions are substantial to achieve a coherent assessment process:

- **When** do we need to monitor?
- **Why** do we want to monitor? (Reason)
- **What** do we want to monitor? (Set strategy)
- **How** do we want to monitor? (Develop a plan)

Installing a SHM system brings together all aspects of the planning cycle into a clear and unified process. Thereby it will help to ensure that the plan is well focused, resilient, practical, and most important cost-effective.
This implies the importance to acquire information about the motive, in order to establish the failure modes and monitoring techniques, and mainly to reduce costs and risks. Furthermore, costs and human risk can be reduced when using an operational SHM system as a substitute to remote operating vehicles (ROV) and human divers.

Data collection phase

Data collection phase is the process of gathering and measuring information. It is an actual monitoring process establishes on facilitating answers. It involves selecting the measuring methods, the sensor types, number and locations, and the data acquisition/storage/transmittal hardware.

The data acquisition system digitalizes the analogue sensor signals, applies some form of data filtering, transmits the data, records the data and stores the data for further analysis. Frequently, the host processor that commands the hardware running these functions will also be the processor that is used to analyses data in the following SHM phases.

Data collection timing interval is a fundamental part to the acquisition process as well as data storage capacity. It is dependent on the nature of the failure mode and proportionally to the amount of data required as well. It means that the higher the sampling data, the higher the capacity storage needed. Then again, sampling data could be proceeded in a continuous or periodic interval. Periodic measurement will decrease the amount of data collected and automatically will decrease the storage capacity, nonetheless continuous measurement is sometimes needed.

As an example, if SHM operation is to measure fatigue crack growth, it may be essential to monitor continuously the variations in the structural characteristics at relatively short time intervals once the identification of some cracks is critical.

Also, an important manipulation is done by normalization of the data for the suitability of analysis and assessments. As an example, when data are raw, no process can be done for assessment. So, database is constructed to provide better processing methods by collecting more data sources. Attention for problems producing misleading results, thus, they are caused by the poor quality of data prepared.

Data Processing phase

Data processing phase is carried out to extract information from collected data and to be able to evaluate them.

These data are subjected to several processing methods, but the most applied method is based on Fourier Transform (FT), and it basically transforms data signals retrieved from sensors from time domain to frequency domain.

On the other hand, the output needs to be interpreted so it can provide meaningful information. Therefore, choosing the valuable data among a massive quantity of data retrieved is a challenge toward identifying the damage indicator since its sensitivity depends on the damage from vibration response.

Evaluation phase

The evaluation of the processed data is the last step in stating the situation of the structure according to norms and standards, in addition to estimate the immediate outcomes as well as the long-term impact upon the structure overall performance. Numerical models may be applied to categorize and quantify the damage. Damage identification methods can be sorted out in four levels [2].

Level 1: Determination that damage is present in the structure

Level 2: Level 1 plus determination of the geometric location of the damage

Level 3: Level 2 plus quantification of the severity of the damage

Level 4: Level 3 plus prediction of the remaining service life of the structure

2.2. EXPERTISE APPLIED IN A SHM SYSTEM

SHM is a system takes in hand a considerable number of expertise placed within sensing, power, communication, storage, signal processing and algorithms evaluation [3]. These numerous types of technologies render more challenging the construction of a SHM system yet more advantageous. For this reason, in addition to cost reduction of technology, more researches have been developed during the last years.
Further discussion of technology advancements will be seen later in this thesis.

Figure 4 illustrates the expertise and their correlation within SHM system [3].

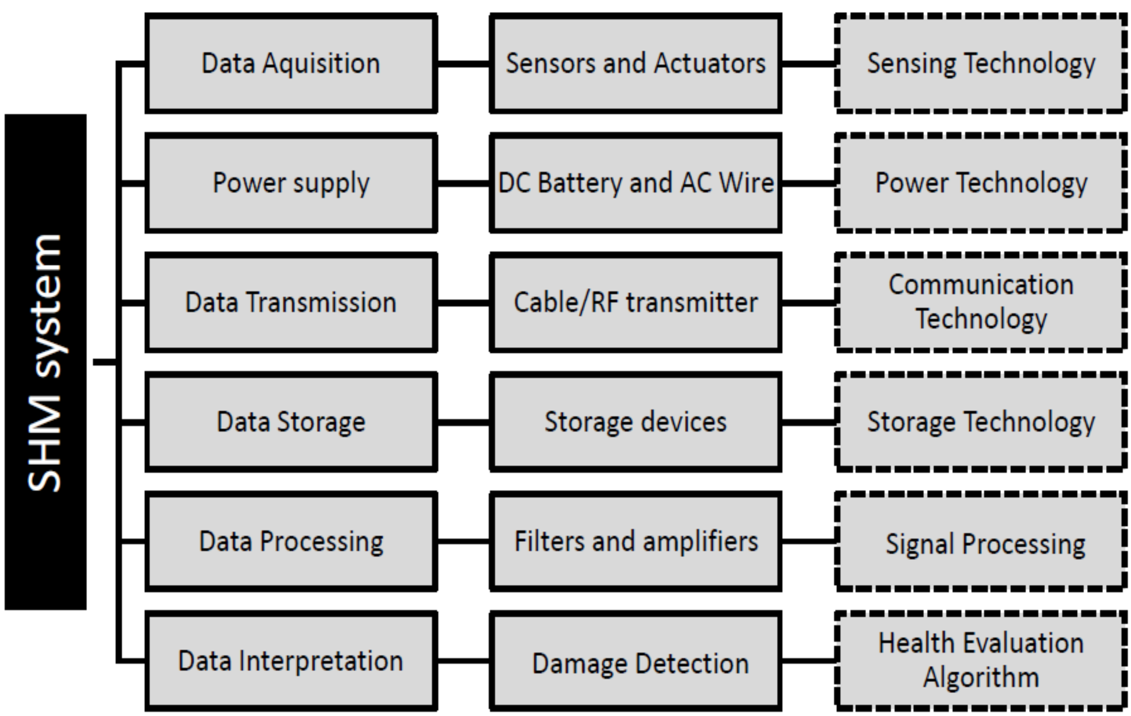


Figure 4: SHM expertise.

3. SHM TECHNIQUES

3.1. LOCAL DAMAGE DETECTION TECHNIQUES

Local damage detection is obtained by non-destructive testing (NDT) techniques that keep, in unaltered condition, the structure being inspected. It is the most used measuring technique in the offshore industry today.

The most frequently used NDT tests are visual, acoustic, magnetic field, strain measurement, eddy current etc.

Local damage techniques are subjected to restriction in detecting damage where the sensor is fixed. The sensors only detect damage at their position or near the surface and require the vicinity of a theoretically known damage and to be very accessible to the examined element. Hence, the application of sensors or manual examination points needs to be high.

However, surface measurements achieved by most NDT techniques cannot supply facts concerning the condition of the internal parts without costly disassembling of the structure.

Even though the damage detection is only on the component examined, they may still be in some point effective in sort of localizing the damage when it is first detected confronted to global damage techniques that requires additional analysis to pinpoint any damage [2].

3.2. GLOBAL DAMAGE DETECTION TECHNIQUES

Global damage detection techniques can identify damage that affects the overall structure or large portions of the structure.

The utmost common global damage detection technique is vibration-based damage detection. This technique uses the variation in dynamic characteristics between an initial state (baseline) and experimental results to pinpoint and quantify damage.

Dynamic characteristics can for example be modal frequencies and mode shapes and can provide information of mass, flexibility and damping of the structure.

Initial assumptions can be obtained from primary testing when structure is in an undamaged condition otherwise they can be calculated in a Finite Element Model (FE-model).

The experimental results are achieved from accelerometers placed on the disturbed structure by either measurable excitation or natural/ambient excitation. On the other hand, the vibration-based damage detection is not capable to enumerate and focalize minor damage in an efficient manner in contrast to the local measuring techniques [4].

As per identifying on which ground the method of SHM should be based on, it is documented that global damage is separated into two types of damages: linear and non-linear.

Linear damage is distinguished from a non-linear one when the structure endures a linear-elastic behavior even after the occurrence of change in the assembly. In this case, the variation in dynamic characteristics is ascribed to the alterations of both the material and the geometry of the assembly. The linear equation of motion is employed to calculate the effect of the latter process. Furthermore, the approach applied in this case play on the reduction in stiffness [5].

In the manner of alternatives, a non-linear behavior occurs after the experience of change in the assembly at the time when the initial behavior was linear-elastic. For instance, the aperture and the closure of fatigue cracks are samples of non-linear damage.

Correspondently to the two types cited before, linear damage detection lay on two additional sub-types: parametric and non-parametric [5].

Wherein the parametric is model fixed in which the shape of data is assumed, thus only the coefficients of the model are to be estimated. Consequently, the non-parametric is non-model fixed in which the shape of data is not assumed, therefore the appropriate model in consort with the coefficients are to be estimated.

Referring to the four levels discussed earlier in section 2.1, which are basically termed as a requisite for the global damage detection methodology, there are progressive problem and the regressive problem. Fittingly, the progressive problem which stands for detecting damage by the utilization of a damage indicant is linked to level 1. Followed by the regressive problem where damage severity in addition to damage location are evaluated. Thus, it resides in both level 2 and 3. In the last place comes level 4, which is linked to fracture mechanics. It includes the study of the crack propagation and the remaining life service of the damage structure [5].

Vibration-based damage detection appears to be a greater challenge to acquire the top reliable damage indicant. According to some collected works, a number of damage indicants are purported like mode shapes, natural frequencies, changes in modal strain energy and adjustments to certain allowed standards.

As it has been clarified, detection technique based on vibrancy perturbations bring into play the dynamic characteristics of the assembly. It is levelheaded when the vibration as an input and the perturbation as an output could be measurable.

For example, it is difficult to determine the excitation measurement of an operational bridge ascribable to constant traffic. Recording the dynamic perturbation of a bridge structure is done with the use of accelerometers without the unknown input as ambient loading. In such a way, the prospect to obtain the modes of the structure and to compare the recorded dynamic characteristics with the prior measurements of the bridge once it was new is possible.

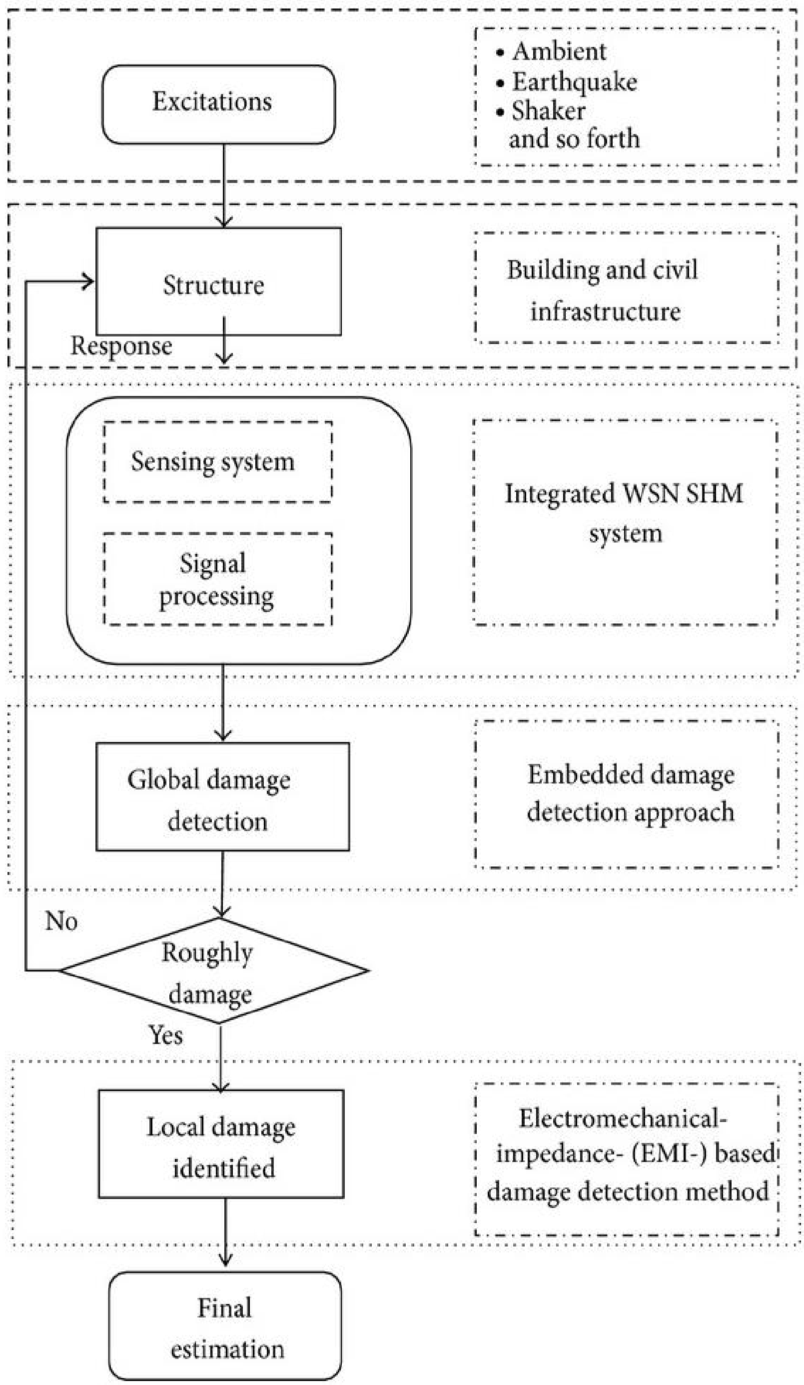


Figure 5: Global-local-integrated damage detection method.

Despite the fact that global damage technique previously discussed has been mostly operated in civil structures, yet engineers has not used it unaided. It is frequently associated with local damage techniques. This Global-local-integrated damage detection approach consists of a regular monitoring using NDT techniques, such as acoustic emission, temperature and strain measurements with the support of developed wireless sensing networks (WSN). Figure 5 shows the integration of global and local damage detection technique [6].

3.3. ACTIVE AND PASSIVE SENSING

Active sensing is determined by means of transmitting energy that needs an external source of power to function. Oppositely to active sensing, passive sensing transmits energy from natural sources. It basically perceives and reacts to certain sort of input from the physical environment.

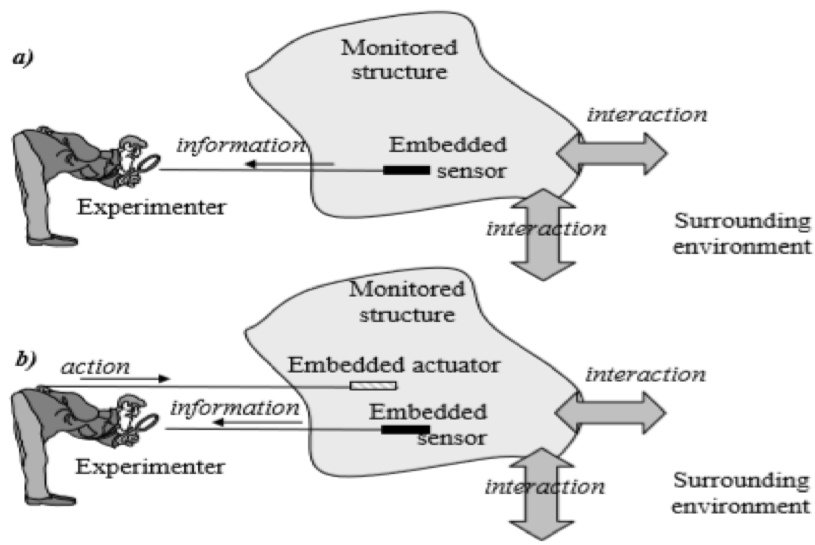


Figure 6: Attitude of the experimenter in a) passive b) active monitoring.

The major dissimilarity between these sensing mechanisms is that active sensing burdens a significant amount of energy measured up to passive sensing. This implies that if the procedure of measurements depends on batteries, the passive sensors would be more advantageous. Notwithstanding what has been said, the passive sensing is considered a major drawback because it counts on getting energy from natural sources. Thus, it brings out a significant amount of noise within the collected data. To all appearances, Non-Destructive Testing (NDT) falls into an active and passive SHM evaluation.

Figure 6 shows the distinct prospective of both passive and active monitoring, involving the experimenter and the examined structure. The latter is fitted out with sensors and linked up with nearby environment, in order that its physical parameter and its state are progressing [7].

If passive monitoring is summoned, the experimentalist must monitor this evolvement on the account of the implanted sensors. In this case, it comes across some SHM techniques like acoustic emission.

On the other hand, if active monitoring is required, the experimentalist needs to monitor the structure with both actuators and sensors. The actuator causes changes in the structure and monitoring response using sensors embedded on the structure.

Some cases in point for passive monitoring, the extension of a loaded structure or the presence of a destructive impact. At whatever time the examination becomes active, the mentioned examples require the addition of an emitter of ultrasonic waves to the acoustic emission detector. Here, damage detection signals are registered by the receiver from the interaction of the emitted waves and the damage structure.

As for fiber-optic technique, the sensor and actuator can be naturally diverse or similar, like excitation by a piezoelectric patch and detecting waves or adding another piezoelectric patch.

On the other hand, a good observation is noted in the flexibility of piezoelectric transducer techniques. Accordantly, these devices can alternate between emitting and receiving.

4. OFFSHORE PLATFORM STRUCTURES

This section concentrates more on offshore platform categories in addition to their failure modes highlighted by codes and standards. Not to forget the important information related to offshore structure selection and jackets design.

4.1. CODES AND STANDARDS

A leading chain of command pyramid outlooking the approved design according to some recommended standards is represented in Figure 7.

On top of the pyramid comes laws and regulations responsible for the operational fields, safety and emergency preparation in petroleum industries. For example, in Norway, the Petroleum Safety Authority (PSA) is a governmental guiding authority that provides industries standards with guidelines to achieve the necessary requirements regarding health, safety and environment in petroleum activities.

In consequence, the industry standards put a set of norms followed by the members of the oil industry concerning the effectiveness and the operational standards in the oil field production. As a case in point, ISO standards is one of the organization with international general standards. Whereas NORSOK organization is an exemplar on guidelines established particularly for offshore structures in Norway.

In the last part of the pyramid, the company internal procedures assist the system with clarifying the standards by the recommended practices.

Here are certain catalogued standards based on a combination of NORSOK and ISO standards with DNV GL recommended practice, in which they are listed in Table 1 concerning design procedures and the integrity evaluation of jacket structures [8] [9] [10] [11] [12] [13].

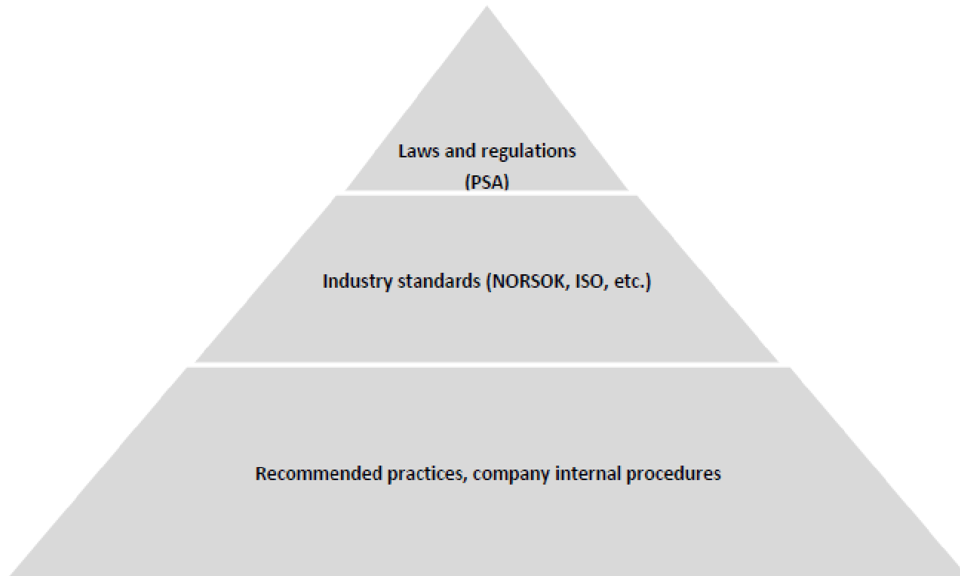


Figure 7: Leading chain pyramid

Table 1: ISO, NORSAK, RP standards

Standard	Title	Content
ISO 19902	Petroleum and natural gas industries — Fixed steel offshore structures	Requirements and recommendations for design of fixed steel offshore structures
NORSOK N-001	Integrity of Offshore Structures	Information of the integrity of offshore structures
NORSOK N-003	Actions and Actions Effects	Information about principals and guidelines for determination of action affects for the structural design of offshore structures
NORSOK N-004	Design of Steel Structures	Information of the guidelines and requirements for design and documentation of offshore steel structures
NORSOK M-101	Structural Steel Fabrication	Requirements for fabrication and inspection of offshore steel structures
DNVGL RP-C203	Fatigue Design of Offshore Steel Structures	Recommendations for fatigue design based on fatigue tests and fracture mechanics

In later sections, SHM method for an offshore jacket platform will be detailed in accordance with the previous discussed plans, categories and techniques in line with the standards provided by the leading chain of command in oil and gas fields. But firstly, besides these tactics, some examples on the existing monitoring situation and

Table 2: monitoring standards.

some valuable SHM projects are revealed and recapped.

Standard	Title	Content
NORSOK N-005	Condition Monitoring of Loadbearing Structures	Annex A "Inspection methods" covers the most used inspection methods today, and also emphasizes on the possibilities of what they call Instrumentation Based Condition Monitoring (IBCM). IBCM can be used as an alternative to the conventional inspection methods. Annex C "Jacket structures" is a normative section of the code, containing additional requirements which is specific to the monitoring of offshore jacket structures.
NORSOK N-006	Assessment of Structural Integrity for Existing Offshore Loadbearing Structures	Summary of monitoring programs.
DNVGL-RP-C210	Probabilistic Methods for Planning of Inspection for Fatigue Cracks in Offshore Structures	Recommended practice for the use of probabilistic methods for inspection planning of fatigue damage.
ISO 13379	Condition monitoring and diagnostics of machines	Explanation of procedures that can be used to condition monitoring of machines.

Table 2 presents the monitoring standards according to NORSOK N-005 with a monitoring program stating that throughout the lifetime activity in petroleum industries, the loadbearing structures should be examined, evaluated, assessed and preserved in line with the general requirement of an offshore platform in ISO 13819-1 [14] [15] [16] [17]. This is done periodically with manual inspections and performed by different NDT techniques. On the other hand, NORSOK N-006 utters a model named risk-based inspection (RBI) that handles the prediction of the inspection intervals. Hence RBI is a tool that enhances more efficiently the inspection method done manually and takes into account the risk of all the evaluated failure modes likelihood of existence and their consequences. But manual inspection is highly-priced and induces human risk, thus SHM systems should be improved significantly.

An example of one method for forecasting the examination interval is illustrated in Figure 8-A, B, C. It is founded on the predicted crack growth caused by fatigue damage in correlation with the inspected intervals. Initially the structure should be inspected before functioning as to determine the size of the initial crack [18].

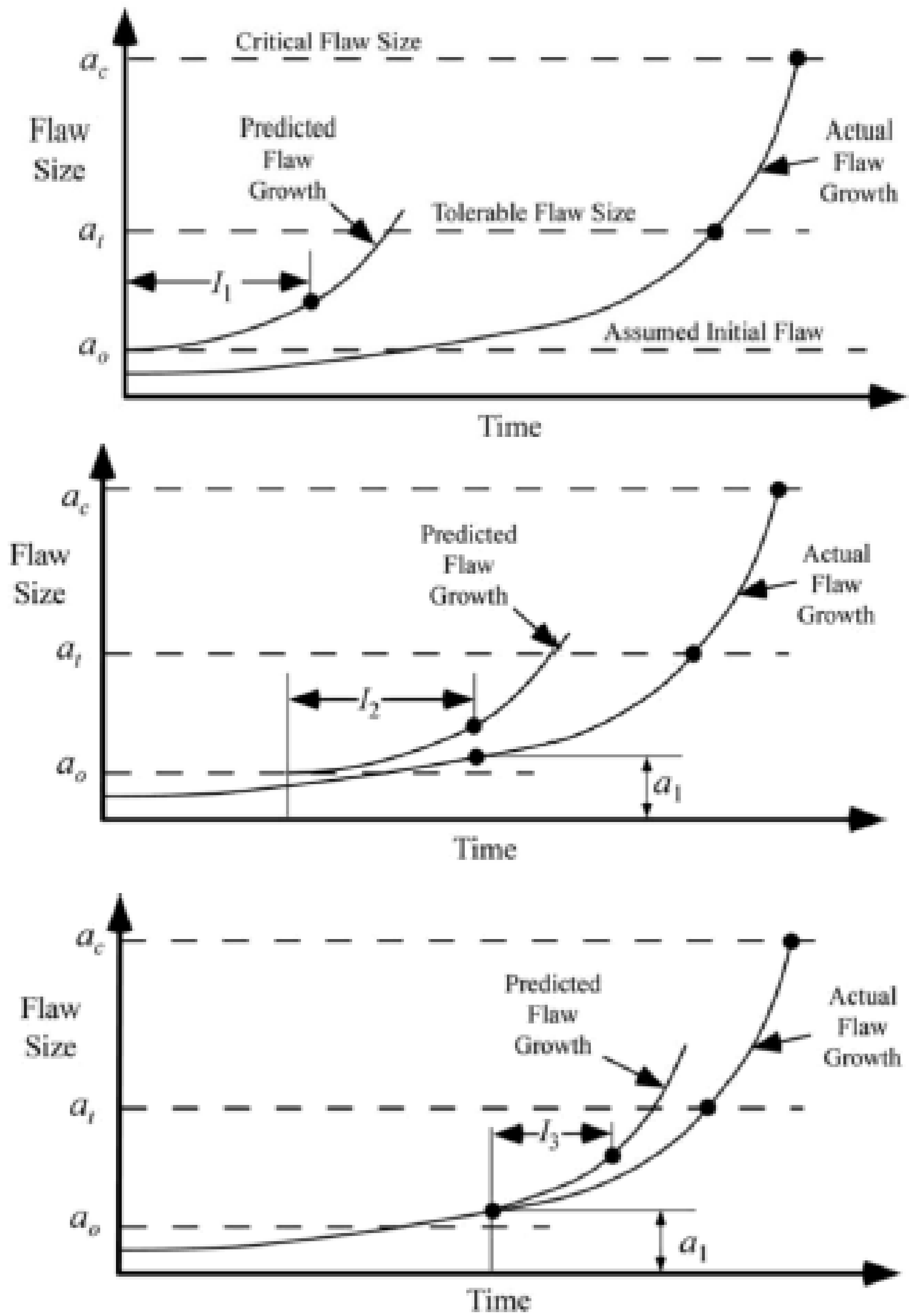


Figure 8: (A) First inspection interval I1; (B) Second inspection interval I2; (C) Third inspection interval I3

The actual crack growth is represented by the lower curve whereas the other curve determines the predicted crack growth. The allowable crack size range needs to be within the largest crack size (a0) missed by NDT techniques and the acceptable crack size (at) otherwise it enters the critical crack zone. Inspection time is calculated when the crack size increases from (a0) to (at) and the first inspection time must be within this time limit. If another crack size (a1) is detected, a new calculation should be required to forecast the second inspecting time for the crack to propagate from (a1) to (at) and therefore a new time limit is defined.

Along these deliberations, another table is presented with a summary on previous SHM projects. Table 3 provides the conclusion of measurements done to each type of failure and the used techniques [19] [21] [23] [24] [25] [43].

Taking notice that these measurements were intended to evaluate the precision of the structural replicas used in design and not directly associated to identify the damage on jacket structures when monitoring. Nevertheless, they contain important realities about instrumentation set-up and monitoring practices.

Table 3: SHM projects.

Article heading	Keywords	Description
Measurement of Fatigue Performance of Forties Bravo	Fatigue, Wave Devices, Forties Bravo, Particle Velocity Meter, Accelerometers, Strain Gauges	Fatigue assessment on a jacket structure by looking at the real time relationship between strain, displacement and wave time histories. Conclusions that were drawn: 1. The strain response were dependent on location. 2. Most of the members had a short time strain amplitude distribution of a Gaussian nature, whilst the strain cycle distribution was of Rayleigh distribution. 3. The results could be explained by drag and inertia coefficients in Morison's equation. 4. Most of the fatigue damaged happened during wave heights over 6 m, hence storms affects fatigue damage tremendously. 5. In general, the measured characteristics matched the theoretical calculations.
Measured Dynamic Behavior of North Sea Jacket Platforms	Jacket, SHM, Dynamics, Morison equation, Environmental monitoring	Describing the structural system behavior (dynamic response) of two platforms in the North Sea. Conclusion that were drawn: 1. Strain was wave induced and quasi static. 2. Structure behaves linear before and after change of mass or stiffness. 3. The soil structure interaction had Coulomb type damping. 4. Nonlinear wave loading.

Article heading	Keywords	Description
Instrumentation of Ekofisk Platforms	Environmental sensors, Jacket, Ekofisk, Strain sensors, Structural repsonse	Explanation of instrumentation set-up, sensors and measurement results on platforms located at the Ekofisk complex. Important conclusions that were drawn: 1. Ratio between predicted and measured deck displacements is similar to the predicted and measured axial stress. 2. The water particle velocity was overestimated compared when using Stokes 5th order wave theory.
Dynamic Behaviour of Kvitebjørn Jacket Structure – Numerical Predictions Versus Full-scale Measurements	Jacket, Dynamic behavior, Kvitebjørn platform, Time domain, Morison equation	This paper compares measured response on the Kvitebjørn platform with predicted response. The overall conclusion was that measured response is less than the calculated response.
Full Scale Measurements at Magnus	Jacket, Dynamic behavior, Magnus Platform, Accelerometers, Strain gauges	This paper describes a SHM system deployment on the Magnus Platform in the North Sea. Conclusions that were drawn: 1. Lower natural frequency than estimated during design. 2. Conservative drag and inertia coefficients in the Morison equation.
Monitoring Structural Integrity of North Sea Production Platforms by Acoustic Emission	AET, Ninian Southern, Jacket, Cost consideration	Description of the use of acoustic emission testing on a jacket in the North Sea. Conclusions that could be drawn: 1. The value of AET monitoring was shown 2. Cost benefit
Online Structural Integrity Monitoring of Fixed Offshore Structures	Vibration based monitoring, Jacket, Ninian Southern,	Description of the use of vibration based monitoring on a offshore jacket in the North Sea. Conclusion that could be drawn: 1. The applicability of vibration based testing and additional software was illustrated 2. The system set-up was effective to detect brace severance on a 4-legged jacket

4.2. OFFSHORE JACKET PLATFORM CATEGORIES

Several structures related to deep water has been designed with significant challenges in petroleum industries.

As most of the times, offshore structures are divided into two groupings, specifically bottom-supported and floating structures. Respectively, they can be distinct as fixed or compliant and neutrally buoyant or positively buoyant.

The fixed structures without compliancy are jacket and tower-type fixed platforms, jack-ups, gravity base structures and subsea production system. As for guyed tower, delta tower and other sub-structures are called compliant structures. The latter structures cause inertia forces because of their movements, which oppose the excitation forces and in doing so the applied loads on the structure decrease.

One the other hand, the neutrally buoyant structures that float freely are FPSO, FPF and SPARs. They have six degrees of freedoms divided into displacement and rotational freedoms. Instead the positively buoyant structures like TBT and BLS have five degrees of freedom but in some others like TLPs, ETLPs and TLWPs have three degrees of freedom [26].

By design, the selected type of offshore structures relies on important factors like well type, depth of water and size of the reservoir. But then again, it relies on selecting between the appropriate offshore structure categories.

Table 4 shows the differences between both categories sited above [27]. The most notable difference is that bottom-supported structures are enduringly mounted in production site and can never be inspected manually after fixing it, e,g piles. On the contrary, floating structures can be repaired by dragging it to shore [26].

Table 4: Bottom-supported structures vs floating structures.

Function	Bottom-Supported	Floating
Payload support	Gravity based with foundation	Buoyancy
Well access	"Rigid" conductors, dry wellhead tree	"Dynamic" risers, wet wellhead tree
Environmental loads	Resisted by strength of structure and foundation, compliant structure inertia	Resisted by vessel inertia and stability, mooring strength
Construction	Tubular space frame: fabrication yards	Plate frame displacement hull: ship yards
Installation	Barge (dry) transport and launch, piled foundations	Wet or dry transport, towing to site and attachment to pre-installed moorings
Regulatory and design practices	Oil industry practices and government petroleum regulations	Oil industry practices, government petroleum regulations and Coast Guard & International Maritime regulations

The instalation technology of jacket structures is usually applied by using cranes to place the fabricated topside platforms onshore onto the jacket structure at the mounting site. The latter shown is made up of rigid structure tubular elements in which it endures for extended period of production. Examples of these structures are shown in Figure 9 [28].

Piled structures are mounted on each leg attached to seabed for safety and stability. They are engaged with axial forces in whichever tension and compression as well as lateral loads. Some main piles are implanted in the leg of the platform and across every skirt piles, and some others are implanted in the seabed in the main legs area called clustered piles. As an alternative, jacket legs are positioned in sizable reversed buckets pierced into the seabed.

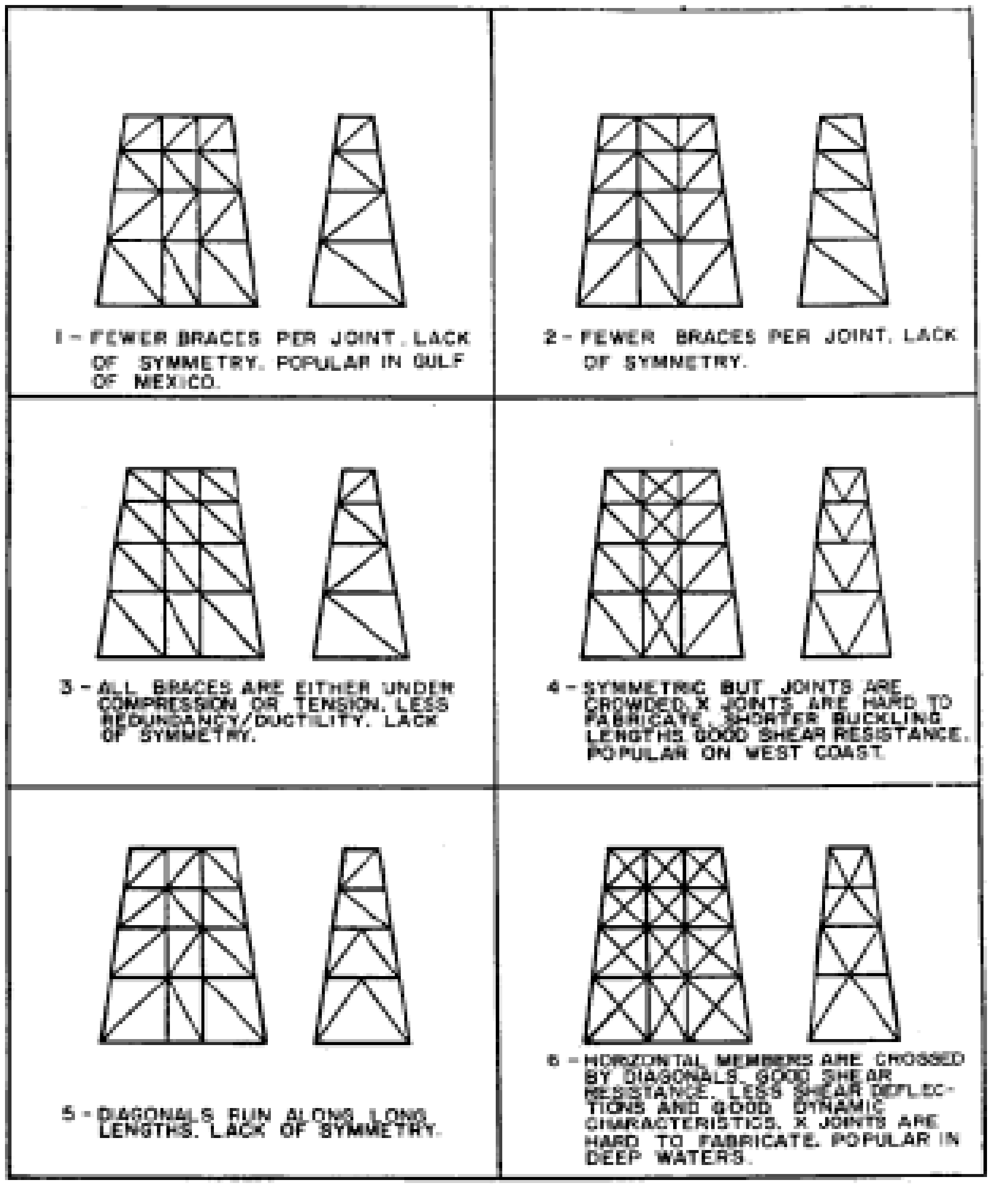


Figure 9: Structures Patterns

Usually, with shallow waters, jacket model is used to avoid resonance among periodic waves and the structure. And it is familiar that the jacket will suffer from bending in the horizontal plane. To understand more about the problem, Figure 10 explains more about the natural periods of offshores structures concepts together with wave ranges for diverse wave heights. Deeper the water, bigger the natural period of offshore structures.

The natural period is minimal in the jacket structure since it is rigid and used in less than 300 m depth of water. On the other hand, structures with less rigidity even with similar concept like compliant tower experience an increase in natural period.

Natural period for bottom-supported structures is expressed in the following equation [29]:

$T_0 = 2\pi\sqrt{\frac{m}{k}}$ where stiffness is expressed: $\mathrm{k} = \frac{F}{x} = \frac{3EI}{h^3}$

F: Force; x: displacement; E: Young's modulus; I: Moment of inertia; h: Height of the jacket structure.

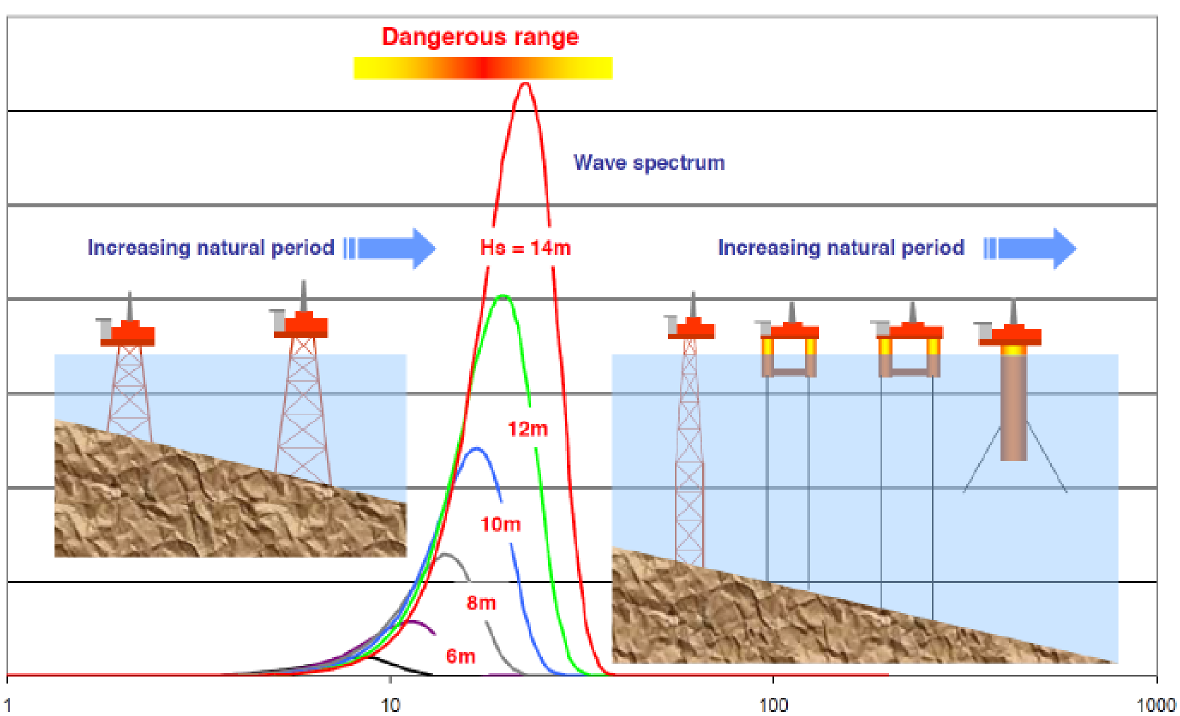


Figure 10: Wave range and natural period of structures.

4.3. OFFSHORE JACKET PLATFORM FAILURE MODES

Previously mentioned, designing jacket structures follows some standards and codes. In accordance with ISO 19902, four limits states are reported to design a jacket platform [8]. Hereafter, the limit states are outlined in Table 5 and they are defined as ultimate limit state (ULS), fatigue limit state(FLS), accidental limit state(ALS), serviceability state(SLS) [30].

Table 5: Limit States

Limit State	Definition
ULS	Ultimate resistance for carrying loads
FLS	Possibility of failure due to cyclic loading
ALS	Failure due to an accidental event or operational failure
SLS	Criteria applicable to normal use or durability

Knowledgeably, SHM is associated with the assessment of structural quality and with forecasting the remaining operational life. Thereupon, the two limit states SLS and ALS are not relevant in this assessment. To make it clear, accidental state is difficult to guess and beyond our control. Then again, serviceability state would not affect the quality assessment of the structure. The major importance in our study is to apply the ULS and FLS criteria in addition to the preservation of what is established regarding the standardized design [31].

Recording to CODAM database, the graph shown in Figure 11 presents various types of damages related to jacket structures in Norway from 1974 till 2016 [32].

Giving an account of the most damages subjected either on braces, jacket legs or nodes. Not to exclude the damages concerning piles and conductors.

The graph interpretation gives facts on number of reported damages for every failure mode. Accordingly, crack damages have the status of the major damage distribution number. However, the reason for this damage is yet to be found. In this occasion, an unknown damage justification conducts to another damage parameter, and then it might be fatigue due to exposure load cycles over time and not a consequence of a single event.

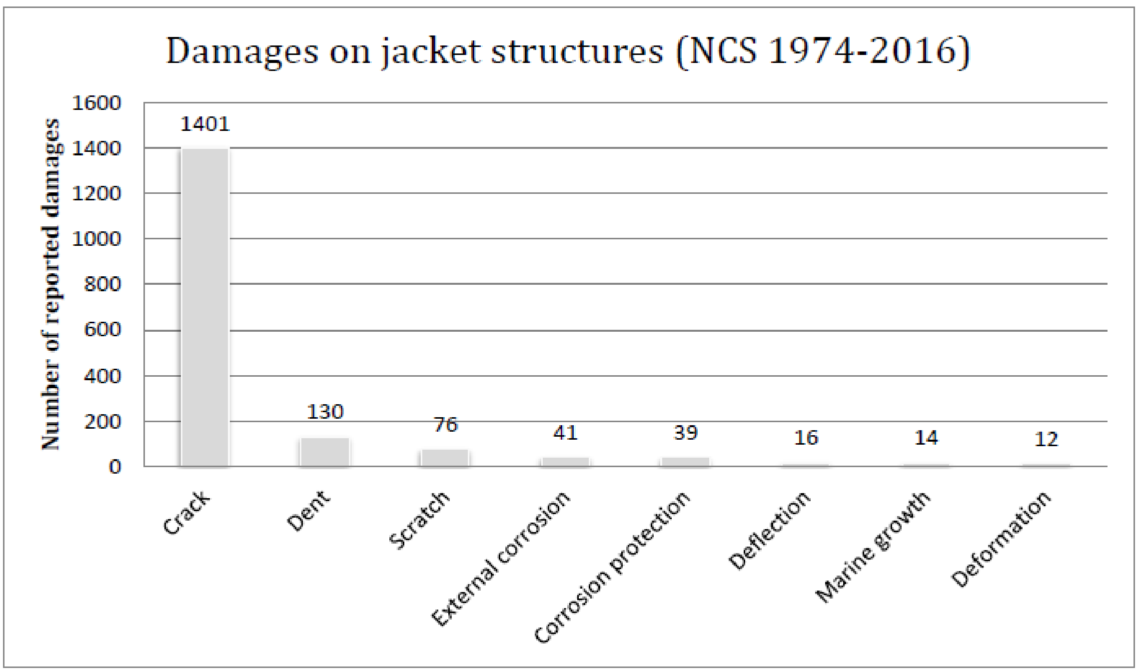


Figure 11: Damages on offshore structures.

Most of the cracks were positioned on the nodes of the jacket structure. Also, approximately all the damages on jacket legs appear to be associated to cracks. On another hand, most of dents were related on the bracings. Reasoning from this fact, bracings are mostly susceptible to denting by released objects. Subsequently, it is reported the presence of external corrosion, deflection and scratches on all nodes, legs and braces. Deformation and marine growth were not reported on the nodes. In the matter of facts, neither corrosion protection nor deformation were stated on braces. These detections are recapped in Table 6.

Table 6: Damage locations

	Node	Brace	Leg	Conductor frame	Pile
Crack	✓	✓	✓	✓	
Dent		✓		✓	
Scratch	✓	✓	✓		
External corrosion	✓	✓	✓	✓	
Corrosion protection	✓		✓		✓
Deflection	✓	✓	✓		
Marine growth		✓	✓		
Deformation		✓	✓		

Again, accounting on CODAM database, Figure 12 demonstrates the annual report of recorded disturbances. When summing up the incidents yearly apiece, an increased distribution in the 1980's is registered and putting this surge down to the fact that jacket structures were increasingly used in that time [32].

Apparently, for offshore jacket structures, crack damage has been the highest recorded failure mode in all past events. And for this reason, it importantly elicits the need to concentrate more on cracks and mainly on fatigue parameter without overlooking on other failure modes.

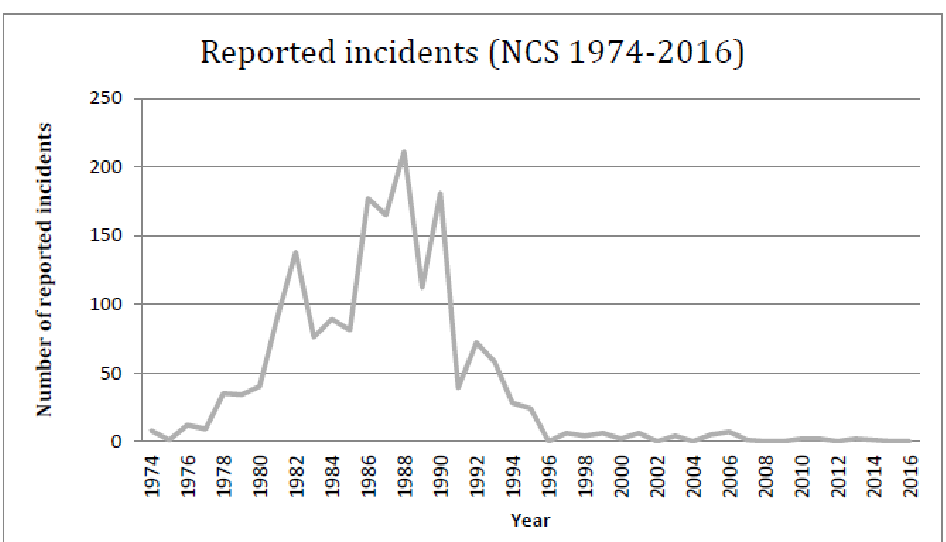


Figure 12 : Distribution of reported incidents

Likewise, NORSOK N-005 refers to the failures modes and damage parameters on jacket structures, with Figure 11 also conferming the malfunctions forms.

NORSOK N-005 damage parameters are cited below:

- *Corrosion,*
- *fatigue,*
- *overloading, accidental actions,*
- *other irregularities as (scouring, marine fouling).*

As per NORSAK N-005 failure modes [14]:

- *Corrosion damage.*
- *joint degradation.*
- *component failure and damage.*

Backslinding to ISO 19902, taking into account the study of ultimate limit state, its failures modes are [8]:

- *Tensile and compressive material yielding of a member's cross-section.*
- *Buckling of a member and the post-buckling redistribution of internal forces that can involve local buckling (for open section this includes Euler and lateral torsional buckling).*
- *Local buckling.*

Table 7: Hazards of offshore structures

Underlying cause	***Source of hazard***	***Specific hazard***
Insufficient strength	Gross error in design, fabrication, installation or operation	Insufficient design capacity Fabrication error Operational damage Modifications
	Degradation	Subsidence Corrosion Fatigue due to: - global cyclic loading - local cyclic loading - vortex induced vibrations - wave slam Widespread fatigue Scour Differential settlement
Excessive load	Environment	Global overload due to: - wave and current load - wave in deck load - wind load - unexpected marine growth - ice and snow loads - earthquake loads Local component overload due to: - wave and current load - wave in deck load - wave slam - vortex induced vibrations - wind load - unexpected marine growth - ice and snow loads - earthquake loads Worsening of wave climate
	Operation	Deck load – weight increase Unsecured objects – center of gravity shift
	Accidental loads	Dropped objects Ship impact Explosion Fire & heat Aircraft impact Iceberg impact Submarine slide/Seabed slope instability

A study worked out an examination on the vulnerability and risk of these failures modes as seen in Table 7 [34]. The latter points out the underlying cause to these failures and their hazards affecting the structure. Note to mention the numerous complexity hazards affecting the structure. Moving forward on NORSAK N-005 damage parameters comprehension, further explanation will be detailed afterwards:

Fatigue

Diminution in strength of an object triggered by cyclic loading leads to fatigue damage. So is the case off offshore fields, where waves and wind causes the cyclic loadings.
In Norway for example waves are considerably high due to ocean existence in comparison to Gulf of Mexico platforms exposure to calm seas. As mentioned in previous chapter, crack spreading is a significant consequence on fatigue loading.
Improvement in fractures mechanics on offshore structures has led to anti-fatigue damage design of offshore jackets, however improbabilities like environmental conditions and actual loading generate difficulties in fatigue design. For this reason, NORSAK N-001 criteria presents a design fatigue factor (DFF) ranging from 1 to 10 to account for unprovabilities [9]. Meaning, higher the design factor, higher the difficulty of monitoring application. Table 8 shows the dependency of DFF with damage consequences and the ability to inspect in splash zone and around it [9].

Table 8: Design fatigue factor

Classification of structural components based on damage consequence	**Not accessible for inspection and repair or in the splash zone**	**Accessible for inspection, maintenance and repair, and where inspections or maintenance is planned**	
		Below splash zone	Above splash zone or internal
Substantial consequence	10	3	2
Without substantial consequence	3	2	1

According to DNVGL-RP-C203 criteria [13], S-N fatigue test is used all through the design phase when analyzing fatigue. This test presents a plot of stress versus failure cycle number. Here, collecting data for long periods is achieved by building up a required stress history distribution for the exact location of the platform. Thus, it must be very important for stress history to be on the stable side. However, if S-N data wasn't enough conducted to the appearance of failure, fatigue analysis could also be done by fracture mechanics FM [13].
Fatigue analysis built on S-N curve applies Miner's rule to estimate fatigue life. Failure occurs when:

$$D=\frac{\sum_{1}^{n} \mathrm{ni}}{\mathrm{Ni}}=1$$

Where:
ni: number of cycles; Ni: total number of cycles.
Fatigue analysis controls all stress locations concentration, which is mostly present in welded connections. In these places, the stress concentration factor (SCF) is high [33].
Note to mention, SCF is expressed as:

$$SCF=\frac{HOT\ SPOT\ STRESS}{NOMINAL\ STRESS}$$

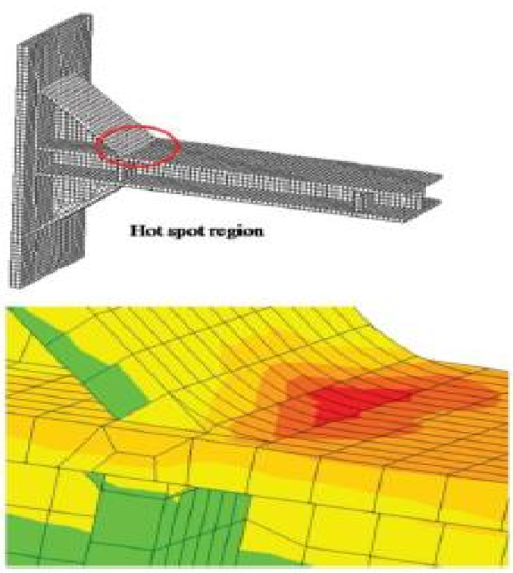


Figure 13: Hot spot region

Figure 13 highlights the hot spots region in red color and nominal stresses region with yellow color [13].
The hot spot stress can be calculated by FE-modelling which adopts the SCF. And by computing the SCF, it is possible to locate critical regions. Hence it facilitates the recognition of fatigue crack location where sensors can be implemented to monitor fatigue cracks. Then again, FM is endorsed by DNVGL-RP-C203 guidelines for the

assessment of fatigue analysis and for the evaluation of the allowed criteria to design and plan a workable inspection method [13]. In later sections, FM calculations will be discussed in details about relationship of the exceeding cracks size and the fracture stability.

Corrosion

Aqueous corrosion is present in offshore platforms and it is due to electromechanical process between a connected anode and cathode (metal) to an electrolyte (seawater) where electrons move from the anode to cathode. Basically, this process is principled on oxidation and reduction reactions thus leading to rusty and corroded elements. In the matter of fact, corroded structures lose their strength and their integrity. Therefore, the presence of oxygen and water in offshore platforms makes it the most destructive environment for jacket platforms. Because of dissolved oxygen is greater near the splash zone (near water surface), it inflicts a greater corrosion in the neighborhood of this region comparing it to the metal existing under the surface. As a result, pitting corrosion can be localized at metal surface of the platform where holes and cavities are formed. Pits can be more dangerous than regular corrosion damage since it is more difficult to predict. Corrosion inside these pits staged in joints or in the imperfection of welding, indicates an irregular corrosion layer on the steel surface of a platform. As time progresses, the increased stresses triggered by pits and other irregularities resultant from electrochemical reactions will expose structures to fractures and breaks within.

In association with corrosion, a new term in the field of fracture mechanics is introduced as environmentally assisted cracking (EAC), and it is split into four types [18]:

- Hydrogen embrittlement (HE) is a process induced by hydrogen atom when presented in high amount around an alloy. Hydrogen atoms fit in metal structure due to its small size. Therefore, a decrease in strength bond caused between the metal atoms lead to occurrence of cracks.
- Corrosion fatigue (CF) is the acceleration of fatigue crack enlargement attributable to the applied load in combination with the environment load.

This explains that when a structure is corroded, it will experience crack growth with lower loads and shorter time.

- Stress corrosion cracking (SCC) is the growth of crack due to an anodic reaction at the crack tip than on other locations wherein it is consumed by a large corrosion mechanism.
- Liquid metal embrittlement (LME) is a process that initiates with a ductile metal and ends up with brittle properties. Ductile to brittle metal transformation experiences a severe loss in tensile ductileness or suffers from brittle fracture when subjected to some kind of liquid metals. This consequence is due either to the presence of tensile stresses internally either externally applied. Aluminum is an exception to the rule where it becomes brittle without any application of stress when in contact with gallium liquid.

To reduce the risk of corrosion and to prevent the structure from induced cracks in offshore platform, some materials like zinc, magnesium, aluminum are used as anodes layers in which they will rust instead of the structure [35].

Overloading

Overloading occurs on the topside of the structure when new updated facilities are in progress. An example to accidental scenarios developing overloading damage:
Supply ship collision and other possible collisions from different structures offshore as floating living quarters.

Wave and wind overloading

The sea current and surface waves effects on the dynamic behavior of an offshore structures are important to offshore industry. Waves and current loads are indirectly proportional to tides in designing the platform. Classification of tides are divided in two categories: First, the tide triggered by the gravitational pull of the moon and sun, and it is called astronomical tides. While the second category is called storm surges, and it is due to wind combined with the differentials barometric pressures in a storm [73].

Continuously, waves create an orbital motion in water during their pathways. Combining this effect with the wind surface, a current is subjected to the wave path causing a wavelength stretches. As for the wind loading, it transforms kinetic energy to potential energy when structure is blocking the wind pathway. Thus, this pressure transformation results in forces damaging the structure. These overloading results in deformation shapes of the platform, in addition to degradation of the structure due to fatigue and corrosion in a non-linear response. In consequence of the latter damages, the ability of the structures withstanding the overloads by waves and currents decreases. This type of failure mode is crucial for the operational platform.
To calculate the forces applied on the platform by the wave loading, Morison's equation is used combined with stokes wave theory of the fifth order [73].

Other irregularities

Marine fouling and scouring are irregular damages with crucial consequence on the health of a jacket platform.
Marine fouling or biofouling is a comprehensible term describing a wide range of organisms appended on immersed surfaces present in the ocean. Consequently, it causes a widespread layer along the jacket with increased loading comparing to wave and current loads. Friction on legs and bracings will increase and similarly affecting the drag force, as specified by Morison equation:

$$F = C_m \rho \frac{\pi}{4} D^2 \dot{u} + C_d \frac{1}{2} \rho D u|u|$$

Where:

C_m and C_d are respectively the inertia and drag forces;

ρ is the density of water;

D is the diameter of a cylindrical component;

u is the velocity of water;

F is the sum of two hydrodynamic forces (inertia and drag).

Marine scouring is a sort of erosion of sediment in seabed that leads to unstable platform foundation. Scouring is the correlation linked to hydrodynamics and geotechnical effects combined. Scouring mechanism happens when the water flow interacts with the vicinity of the foundation sediment of the structure and changes the shape of sediments resulting in compromising the structure stability.

In Figure 14, various damaged structures are illustrated. (A) illustrates a damage tubular joint due to fatigue through crack. (B) illustrates an air gaped damage due to corrosion. (C) illustrates a buckled damaged tubular member caused by overloading. (D) illustrates an example of marine fouling on jacket legs [36] [37] [38] [39].

(A) Fatigue through crack

(B) Corrosion

(C) Buckling

(D) Marine fouling

Figure 14: Damage on jacket

A briefed discussion to what have been said on the failure modes of jacket structures is deliberated in this summary.
Corrosion is relatively controllable in comparison with cracks caused by fatigue. Fatigue cracks is a dangerous mechanism and uncontrollable in case of sudden accidents and environmental events [15]. NORSAK N-005 guidelines objectify some monitoring conditions to endure an acceptable level of the structure integrity. it claims the determination of the existence, the degree and the consequence of [14]:

- degradation or deterioration due to fatigue or other time dependent structural damage
- corrosion damage
- fabrication or installation
- damage or component weakening due to strength overloading
- damage due to man-made hazards
- excessive deformations.

5. SHM APPROACH FOR AN OFFSHORE JACKET PLATFORM

In this section, a cost-effective SHM method for an offshore jacket platform will be detailed in accordance with the previous discussed plans, categories and techniques in line with the standards provided by the leading chain of command in oil and gas fields. In accordance with NORSAK N-005 program, monitoring loadbearing structures relies on [14]:

- Design and maintenance based on guided principles studies.
- Up-to-date condition
- Competence of the assessment approaches available
- Intentional utilization of the structure.

Consequently, a flowchart is presented in Figure 15 with an organized procedure of a SHM system of a jacket structure. Reciprocally, it is followed by a clarification of the steps for the design and the execution needs to achieve the method.

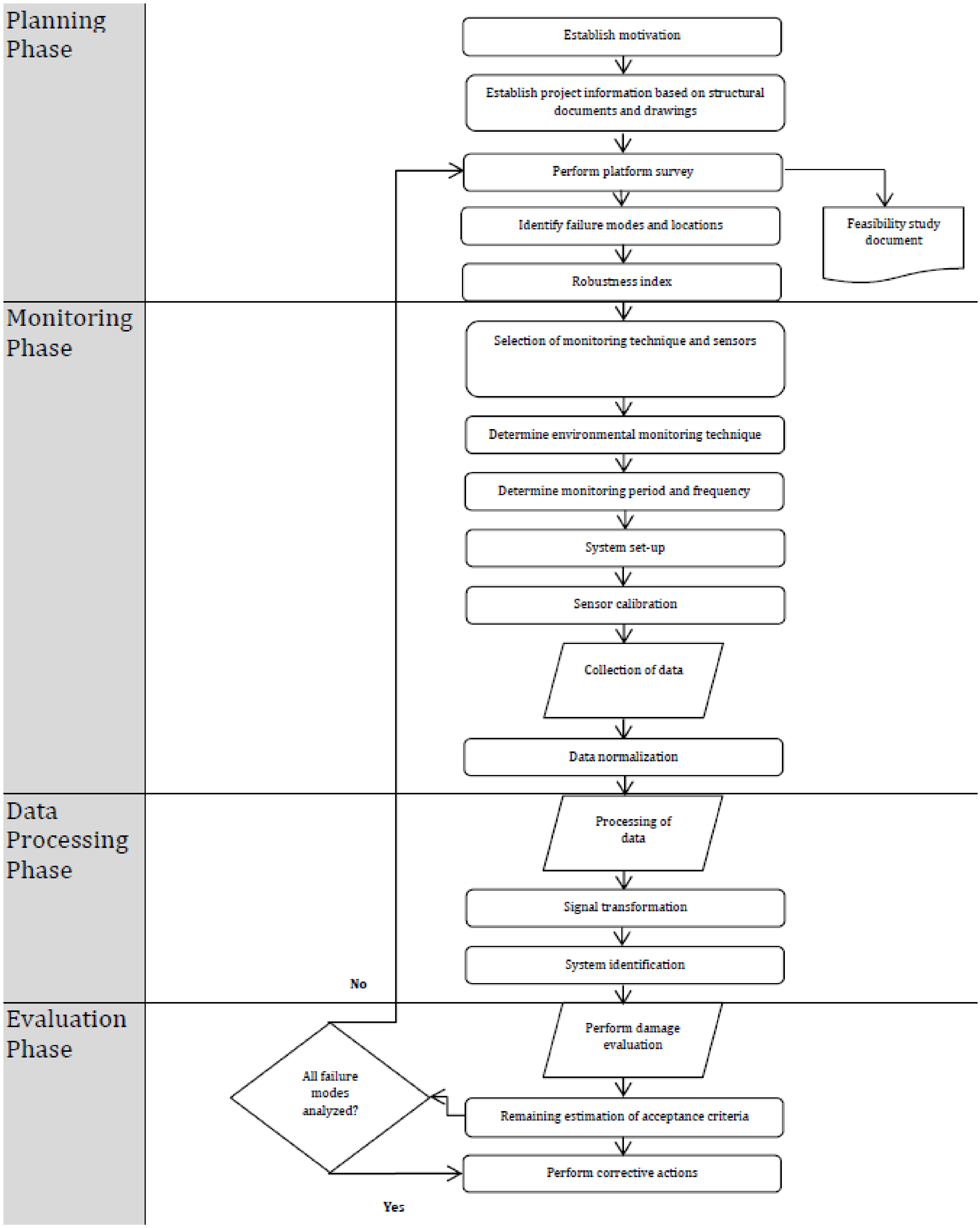


Figure 15: Flowchart of SHM

5.1. PLANNING PHASE

Establish motivation

Establishing motivation to be considered before taking into account any study regarding the asset in occupation. In history, SHM of offshore structures have been incredibly high-priced with relatively minor quantity of jacket equipped with SHM system. Most of the jackets are manually monitored and based on RBI method. Nonetheless, the capacity to long-lasting life of a jacket is as result of a SHM system.

ISO 19902 grants a table with various motives for examination on jacket structures, and it covers [8]:

- Manufacture imperfections or installation damage.
- Degradation or weakening of the structure.
- Design uncertainties or miscalculation.
- Environmental or weight overload.
- Accidental events.
- Variations in stable actions.
- Monitoring of acknowledged defects or reparation success.
- Change of proprietorship.
- Legal requirements.
- Reuse.

Establish project information based on structural documents and drawings

Before classifying the serious failure mode of the structure, gathering data is a necessity to be carried out. In NORSOK N-006, a list of the information that shall be available for assessment of offshore structures is given. The list is countable for all offshore structures therefore the list below is modified to only include the information needed for a steel jacket platform [16]:

- Built drawings of the structure.

- Updated info on environmental data, if important.
- Stable and variable actions.
- Previous well-designed requirements and future functional necessities.
- Design and construction specifications.
- Initial management study of corrosion.
- Design, construction, transport and assembling statements which provide information about material properties (e.g. structure strength elongation properties and structure toughness test values), welding techniques qualifications, specifications and modifications, welding maintenances during construction, non-destructive testing, archived pile driving action impacts data.
- Design presumptions.
- Updated reports on weighs.
- Information on functional inspections on marine growth, corrosion, cracks, dents and deflections, scour damages due to frost, impact, erosion/abrasion, leakages.
- Measurements and observations data on dynamic response performance in place.
- Information and prediction for seabed sediment.
- Info on adjustments and restoration for the structures during its service life.
- Consolidation, pore pressure and soils conditions.
- Instability of an incline, erosion at pile foundations, disparity settlement.
- Similar structures experiences.

In any case, and according to NORSOK N-006, the absence of any acknowledgment is to be substituted with assumptions.

Perform platform survey

A platform survey is a method performing a prior assessment on any type of SHM system before execution. In the courtesy of this survey, a comprehensible method is followed up in dealing with the number of sensors needed and their positions. Make to mention, pictures from platforms are collected helping with an achievable system set-up [40].

Identify Failure Modes and Locations

As referred in previous sections, NORSOK N-005 recommends the identification failures modes and their damage parameters through ULS analysis combined with FE-model [14].

This implies the installation should be applied in critical locations as a new structure design in addition to structures subjected to difficult environment. Stating some accidental examples with major importance in monitoring systems: in Alexander Kielland platform in the North Sea in 1980, a recent new installation of hydrophone developed a fatigue crack that lead to a breakdown of the platform [43].

Also, according to NORSOK N-006, attention should be made from risking fatigue damage in the splash zone due to load waves and not to forget ship collisions.

Robustness assessment

The robustness assessment of jacket structures is performed with a non-linear analysis or so-called pushover analysis [42]. Gravity loading and wave loading are added to the structure. The latter is continuously increased horizontally or by elastic and non-elastic behavior until the ultimate limit is reached where collapse is evident.

Potentially, such analysis is already done during design by checking the redundancy index (SR) and residual strength factor (RSF), which are defined as:

$$SR=\frac{\mathrm{CLi}}{\mathrm{Lfi}} \qquad ; RSF=\frac{\mathrm{CLdi}}{\mathrm{CLnd}}$$

Where:

CL_i: collapse load;

Lf_i: first failure member occurrence;

CL_{di}: collapse load of the ith damaged member;

CL_{nd}: collapse load of the ith undamaged member.

The SR index represents the difference between the collapsed load and the occurrence of the first failure member, and it is a helpful in measuring structure robustness.

On the other hand, RSF designates the capacity reduction state for undamaged member and damaged member. Put it differently, the damage tolerance and the degree of redundancy increase proportionally with SR and RSF values.

5.2. DATA COLLECTION PHASE

<u>*Selection of monitoring techniques and sensor technologies*</u>

As described in previous sections, both local and global monitoring techniques should be operated to pinpoint the failures modes and to define the capacity of the monitoring system. Managing data is significant for processing and interpretation, indeed, data should be properly collected. It is important to select a suitable technology used in different industries to apply it in oil and gas industry. The techniques available are divided into three categories and they are addressed in Table 9 regarding their maturity of establishment level [33].

Table 9: Overview of structure monitoring techniques

Response	Maturity	Techniques	Detection capability
Structural	Proven	Acoustic emission testing (AET)	Cracks Corrosion[1)] Strain
		Strain measurement	Strain
		Accelerometer[2)]	Member severance
		Flooded member detection (FMD)	Member leak Through cracks
	Unproven	Electrical resistance based corrosion Sensors	Corrosion
		Ultrasonic testing (UT) and Guided wave testing (GWT)	Cracks Corrosion
		Fatigue gauge	Cracks
	State of the art	Acoustic fingerprinting	Cracks Corrosion Strain
		Smart sensors	Cracks Strain

1) Difficult in a noisy offshore environment

2) When used with a vibration based damage detection method

As a definition of maturity of use, the proven technologies are applied in SHM of jackets while the unproven technologies are applied in other industries. As for the third classification, the state of the art implies a technique not in comprehension of use in any industry [33].

As a guide to select the right sensor, the summarized Table 10 is made to compare the detection capabilities of each category of maturity of use and their parameters [55] [43] [57] [59] [60] [61] [62]. Generally, sensors for offshore monitoring take into account five parameters. Starting with two noise immunities defined as structural and electromagnetic. Structural noise comes from vibration or sound like wave load on jackets structure or disturbance near the platform by rotors of helicopters or process equipment in use. The similar effect for electromagnetic noise, rather the vibration comes from lightning or from northern light. These noises can have a low, medium or high impact on the gathered data [43].

In order capabilities, mounting parameter is a helpful feature in determining sensors and their mounting positions. It is possible to equip the structure with sensor on its exterior surface or embedded into it. Surface mounted sensors is better in case on an existing structure whilst the embedded technique is more practical to monitor in case of an upbuilded structure and gives more protection to the sensor.

Continuously, wireless sensor network (WSN) parameter compatibility is an important way to achieve an advanced SHM system with MEMS and smart dust.

Finally, and as mentioned above, maturity of use of all sensors comes with levels either low usage, medium or high.

Table 10: Sensors overview

Technology	Sensor	Structural noise immunity	Electrical interference immunity	Mounting	WSN compatibility	Maturity on offshore jacket platforms
Electrical	Foil strain gauge	Low	Low	Surface-mount	N/A*	High
	Vibrating wire gauge	Low	Medium	Embeddable	N/A*	Low
	ER corrosion sensor	High	Low	Surface-mount	✓	Low
	Fatigue gauge (CrackFirst™)	Low	Low	Surface mount	✓	Low
Piezoelectric	PZT strain sensor	Low	Low	Surface-mount	✓	High
	AET	Low	High	Surface-mount	✓	Medium
	PZT acceleration sensor	Low	Low	Surface-mount	✓	High
	Acoustic fingerprinting	Low	High	Surface-mount	✓	Low
Optical	FBG strain sensor	High	High	Surface-mount and embeddable	✓	Medium
	FBG acceleration sensor	High	High	Surface-mount and embeddable	✓	Medium
Ultrasonic	GWT	High	Low	Surface mount	✓	Low
Radiographic	FMD	High	High	Surface mount (but can be embedded)	N/A*	High

Determination of Monitoring Period and Frequency

Determination of monitoring period and frequency is an essential step and unique for each sensor. Usually, low sampling frequency is required for long time failure and oppositely for high sampling to identify short time failure. A balance is needed between high frequency and low frequency samplings, thus, avoiding simultaneously aliasing and needless computational effort. Also sampling periods must be determined and it is either monitored continuously or periodically. Nevertheless, the capacity of processing data should be planned without much of concern on the amount of data storage.

System Set-up

System set-up points out the application of sensory installation, wiring and data acquisition system. Note that the sensor location should be selected wisely to supply information in monitoring damages and not to become a supplier of damage like crack growth.

Perform System Calibration

After setting up the installation on the platform, an authorization of the system should be made by a site acceptance test involved in the following inspections: sensor reaction with the system, system reaction from a repeatable electronic source (AE-sensor only), data transfer, remote control of the workstation, and software checks together with alarm and warning purposes [23] [40].

Data Normalization

Data normalization must be applied before data processing to obtain data signals deprived of noise and also justify sensor malfunctioning. For more understanding about this process, Figure 16-A, B, C exemplifies a comparison between a time domain signal with environmental noise (A) and sensor malfunctioning (B) to an acceptable time domain signal after normalization (C) [45].

An equation used by data normalization to obtain an acceptable processed signal data, and it is defined by: $x(t)=\frac{x(t)-\mu}{\sigma}$

With $x(t)$ is the time domain signal, and μ and σ respectively stand for the mean and standard deviation of the signal.

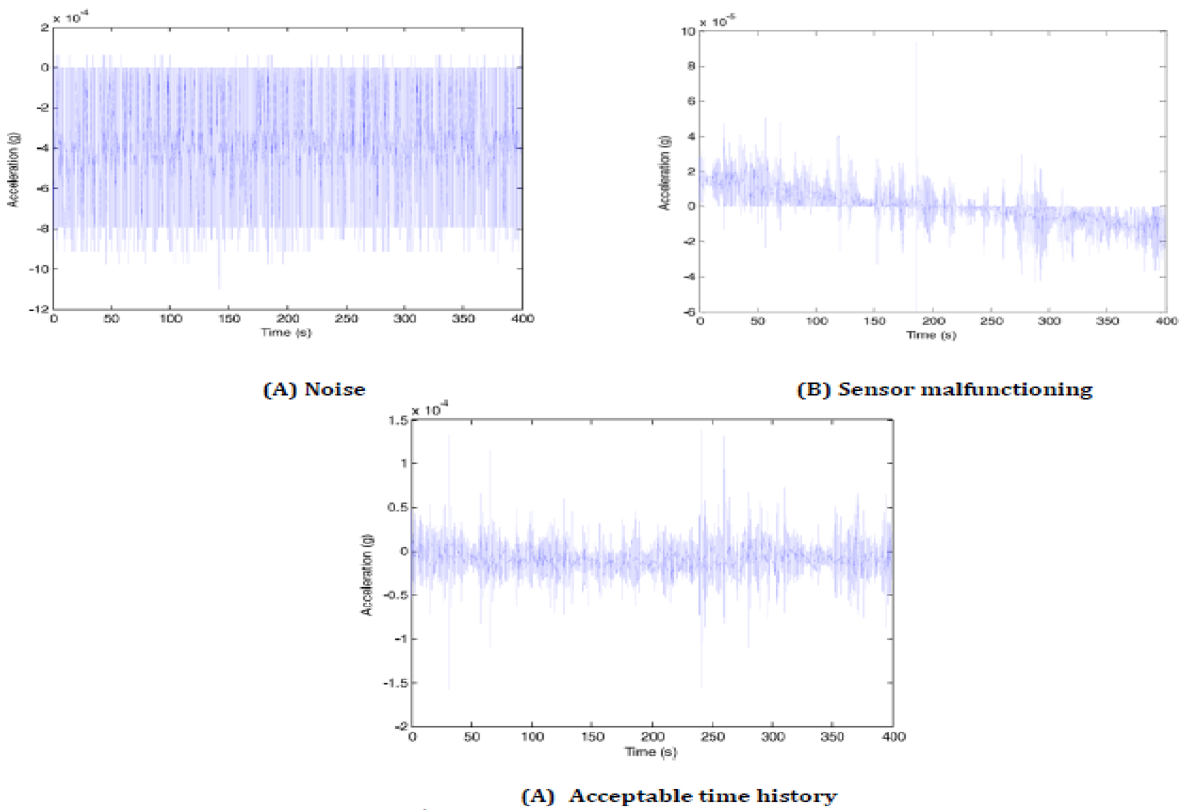


Figure 16: Time domain signal

5.2.1. DATA COLLECTION TECHNOLOGIES

In this section combined with table 9, only proven technologies in monitoring techniques will be further detailed respecting to the three categories of maturity of use.

<u>Proven technologies</u>

Acoustic emission testing (AET) mainly perceives initial fatigue and active fatigue cracks, but also in some circumstances it detects corrosion [44]. The sensors are placed in the surroundings of a structure, whereas the acoustic emission is perceived by the deformation and the crack growth. The latter has a signal amplitude easy measurable within 5 meters of sensors and its perceived frequencies range from 150-300 kHz, nut usually sensors gather up to 1MHz [40] [46] [47]. However, AET sensors from frequencies catalogues may vary according to the position of installation of the sensor. Dissimilarities in frequencies are needed because of the propagation differences in signals in diverse materials plus to the mechanism source of the signal, consequently, Table 11 provides some related examples of VALLEN catalogues [44].

Table 11: Frequency ranges vs application

Application	20-100 kHz	100-400 kHz	>400 kHz
Corrosion screening of flat bottom storage tanks	✓		
Leakage detection in water/oil pipelines	✓		
Hot reheat pipe crack detection		✓	
Integrity testing of pressure vessel		✓	
Partial discharge detection	✓ *	✓	
Integrity testing of metallic structures		✓	
Integrity testing of composite materials		✓	
Integrity testing of concrete structures	✓		
Drying process monitoring of plants/wood		✓	
AE-testing of small specimen			✓

*When noise is low

A report conducted by a European conference for non-destructive testing for the investigation of the applicability of VALLEN product line of AE sensors, preamplifiers and signal processor plus to VALLEN's specified software [40]. This AE system (called AMSY-6) satisfies the standards required to equip and verify the operational characteristics AET [44]. Eventually, it required an acoustic emission expert in incorporation with a viable study to retrieve data without the presence of noise. In addition, it needed further scheme set up for positioning the sensors and directing the cables, and also needed an authorized acceptance test after installation. This test involved with the consecutive checks: remote control of the workstation, system response from a repeatable electronic source, data transfer, and software function checks including alarms, sensor response with the system.

The workstation contained warning systems and automated alarms labeled by the accepted criteria. On the other hand, the warning system was positioned lower to alarm systems and it was suggested the use of manual strain measurements to assess the tip of the crack in case of warning resulting in a simple maintenance of the AET system, thus, the possibility of logging to a processor even onshore. Furthermore, VALLEN software provided a sensor with self-examination role. Thus, each sensor sent out pulsations to be collected by the rest of the sensors. Yet, for the reason of its high cost, this AET system is used in offshore industries only in crucial treatments. In other ways, the surplus of wiring and the necessity of an engineer to interpret the complex signals data combined with noise are the major reasons for cost issues.

Strain measurement is a technology for the evaluation of local loadings resulting in bending (horizontal and vertical), torsion, longitudinal compression force and vertical shear force. These deformations of a structure are triggered by an operational stress. Strain monitoring has two forms either static or dynamic. Static strain monitoring tests are concluded with a test specimen in a lab. By exerting a certain load on the sample, data are collected. Then after new collected data are provided by increasing or decreasing the load. On the other hand, dynamic strain monitoring tests are measured continuously on the actual specimen and plotted in a time-strain diagram. Most of SHM techniques requires the dynamic strain tests to evaluate the diagram time-strain. Note that for dynamic measurements higher sampling frequencies are needed respect to static measurement. Also, the stress-strain function is used in assessing the specimen dynamically during its process.

Sensors detecting strain are: electrical gauge, piezoelectric and optic fiber [48].

Starting with the electrical strain gauges, two types are provided in the industry, specifically metal foil and vibrating wire. Metal foil gauge measures the electrical resistance variances when the metal foil is under strain and proportionally to its length [48]. Instead, vibrating wire sensors measures the frequency changes in the vibrating wire when subjected to a tension load [49]. This latter technique is widely known for its extended time stability.

The piezoelectric strain sensors are applied when strained materials exert an accumulation of electricity resulting from a mechanical stress. This phenomenon is observed when piezoelectrical material like PZT produces electricity when its crystals subject deformation [50].

Concerning the last type, optical fiber sensors are tools dealing with the transmission of light within glass and plastic [51]. This technique employs the Fiber Bragg Grating technology, when it is subjected to a light source, the screen will reflect precise wavelength dependent on the screen properties. As a consequence, strain and temperature will affect the gratings and will modify the space between them. Thus, this change will also lead to a variation in the reflected wavelength that in return could be transformed into a strain value [48]. It is found that FBG sensors are capable in detecting strain and acceleration same as strain gauges, but as a disadvantage, FBG sensors lack the source light that limits the range of flexibility of the fiber cables [52].

Accelerometer is composed of a piezoelectric substance that record the acceleration of a moving structure. An FBG accelerometer is equally effective to piezoelectric sensors, but it doesn’t provide information about damage though it defines the dynamic characteristics [53]. In this respect, these characteristics can identify the damage. Note that accelerometers are widely used in offshore jacket structures thus it is based on vibration method to damage detection.

Flooded Member Detection is based on radiographic method. In other word, radiographic technique depends on the transmission of light across a structure, in return, the structure with its density and composition properties will absorb the light. Thus, the detector will sense the passing light and will configurate the inspected structure [43].

5.2.2. VIBRATION-BASED DAMAGE DETECTION TECHNIQUE

Vibration-based damage detection is the most advanced damage technique in offshore jackets. Initially, the variation in frequency was supposed an indicator of damage. Thus, most researches convinced that this change is effective in measuring damage in the structure. Though, these frequencies changes are relatively dependent on mass and stiffness changes. Naturally, accelerometers are installed on the topside of the structure with continuous monitoring of wave loadings vibration response. Thus, any damage detected will be echoed by a change in structural response. Due to this method sensitivity to frequency change, detection can be accurate of 0.5% of frequency alteration. Though, some requirements are needed for the vibration-based damage method like [63]:

- Ambient excitation to obtain the resonant frequencies,
- Stability of vibration spectra for long periods of time,
- Persistence of the instruments in rough environments,
- Mode shapes identification from measurements taken above water level,
- Financial benefits of the system comparing to the use of divers.

However, this technique is used for global damages and cannot spot minor damages, like small defects and local fatigue cracks.

In this context, examination of modal properties variation is based on modal damping, resonant frequencies and mode shape vectors. Note that frequency shifts are harder to detect or result in fake damage evaluation respect to the other parameters like mass from marine growth, equipment noise and change of center of gravity.

To seize these difficulties, modal shapes are used as an alternative to frequency, because of their excess sensitivity respect to eigen frequencies. Some examples were provided concluding the reduction of frequency by 1-4% due to damage and value of altered modal displacements by 30 to 100% [64].

Basic formulation theory starts with second order equation of motion by n degree of freedom [65] :

$\boldsymbol{M}\ddot{x} + \boldsymbol{C}\dot{x} + \boldsymbol{K}\boldsymbol{x} = \boldsymbol{f}$

Where, respectively, M, C and K are undamaged mass, damping and stiffness matrices, and x position vector, f is the vector of applied forces, and $\ddot{x}$, $\dot{x}$ represent differentiation with respect to time.

In case of structure excitation at same frequency ω, forces and amplitudes then are expressed:

$\boldsymbol{f}(t) = \boldsymbol{F}(\omega)\, e^{i\omega t}$

$\boldsymbol{x}(t) = \boldsymbol{X}(\omega)\, e^{i\omega t}$

where, $\boldsymbol{F}(\omega)$ and $\boldsymbol{X}(\omega)$ are vectors of time independent amplitudes. So, equation of motions becomes [65]:

$$X(\omega) = (K + i\omega C - \omega^2 M)^{-1} F(\omega) \quad i=\sqrt{-1}$$

$$F(\omega) = (K + i\omega C - \omega^2 M) X(\omega)$$

$$H(\omega) = (K + i\omega C - \omega^2 M)^{-1}$$

$$Z(\omega) = (K + i\omega C - \omega^2 M)$$

Where $\boldsymbol{H}(\omega)$ is FRF and $\boldsymbol{Z}(\omega)$ is inverse FRF (Frequency response function).

As for undamaged conditions [65]:

$$F(\omega)_{n\times 1} = Z(\omega)_{n\times n} X(\omega)_{n\times 1}$$

But with damage interference, differential of inverse FRF is introduced and it becomes [65]:

$$F(\omega)_{n\times 1} = \left[Z(\omega) + \Delta Z(\omega)\right]_{n\times n} X(\omega)_{n\times 1}$$

As a result, damage vector is presented as [65]:

$$d(\omega) = F(\omega) - Z(\omega) X(\omega) = \Delta Z \cdot X(\omega)$$

Assuming that at discrete frequencies p, force damage vector can be rewriting as a rectangular matrix [65]:

$$\Delta \boldsymbol{Z}_{n\times n}\boldsymbol{X}_{n\times p} = \boldsymbol{D}_{n\times p}$$

Defining the element modal strain energy ratio (SER) as element modal strain energy of the jth of the ith stiffness of the element divided by the total strain energy of the jth [65]:

$$\mathrm{SER}_{ij} = \frac{\phi_j^{\mathrm{T}} k_i \phi_j}{\phi_j^{\mathrm{T}} K \phi_j} = \frac{\phi_j^{\mathrm{T}} k_i \phi_j}{\omega_j^2}$$

Where k is the stiffness matrix and φ is the mode shape. The latter gives its own influence on the dynamic response of the structure. Each mode is in relation with frequency excitation. Thus, when the latter is near to the system natural frequency, the dynamic response will typically echo the shape of the nearest mode, but in unidentical way. Generally, in the damage detection process, it is noted that the damage location is identified more precisely in the highly strained elements relatively to low strained elements. Therefore, the modal strain energy ratio for each distinct element should be computed before the damage detection. For checking each element, excitation frequency ought to be nearby the mode, wherein the highest modal strain energy.

On the other hand, translational DOF measures only the axial model strain energy in which decreases in an inversely proportionate way to the number of modes. Wisely selected frequency points lead to better results and more efficient detection.

Further problems with locating damage, with the lack of mode shapes quantities and the presence of many members and uncertainties, have been solved by introducing an algorithm with an indicator to localize damage [66]:

$\beta ij = Ej/Ej*$

Damage location indicator is the fraction between material stiffness for undamaged and damaged member. Consequently, the damaged stiffness expresses the damage severity by the change in stiffness αj [66]:

$Ej{*}=Ej(1+\alpha j)$

After testing this theory numerically, the results showed an overestimation of damage. Nevertheless, it managed to locate and assess the damage degree.

As a conclusion, the usage of modal parameters with extracting algorithm can estimate modal frequencies and their shape, as for damage detection algorithm are based on the prior diagnosis of modal properties. So, it is essential to solve the equation of motion with multiple degrees of freedom as to evaluate the dynamic response. Reduction of these degrees is done by modal matrix.

5.3. DATA PROCESSING PHASE

Data processing phase consists of two parts, one is for the transformation of the signal and the other is for the damage identification system in jackets.

Table 12 presents various processing methods or signal transformation techniques applied in SHM of jackets in addition to their appliance [2] [53] [55].

Table 12: Data processing algorithms used in SHM of jackets.

Processing Methods	Application
Fatigue rainflow cycle counting	Fatigue life evaluation
Fourier Transform (FT/FFT)	Modal analysis
Short Time Fourier Transform (STFT)	Modal analysis
Wavelet Transform (WT)	Modal analysis

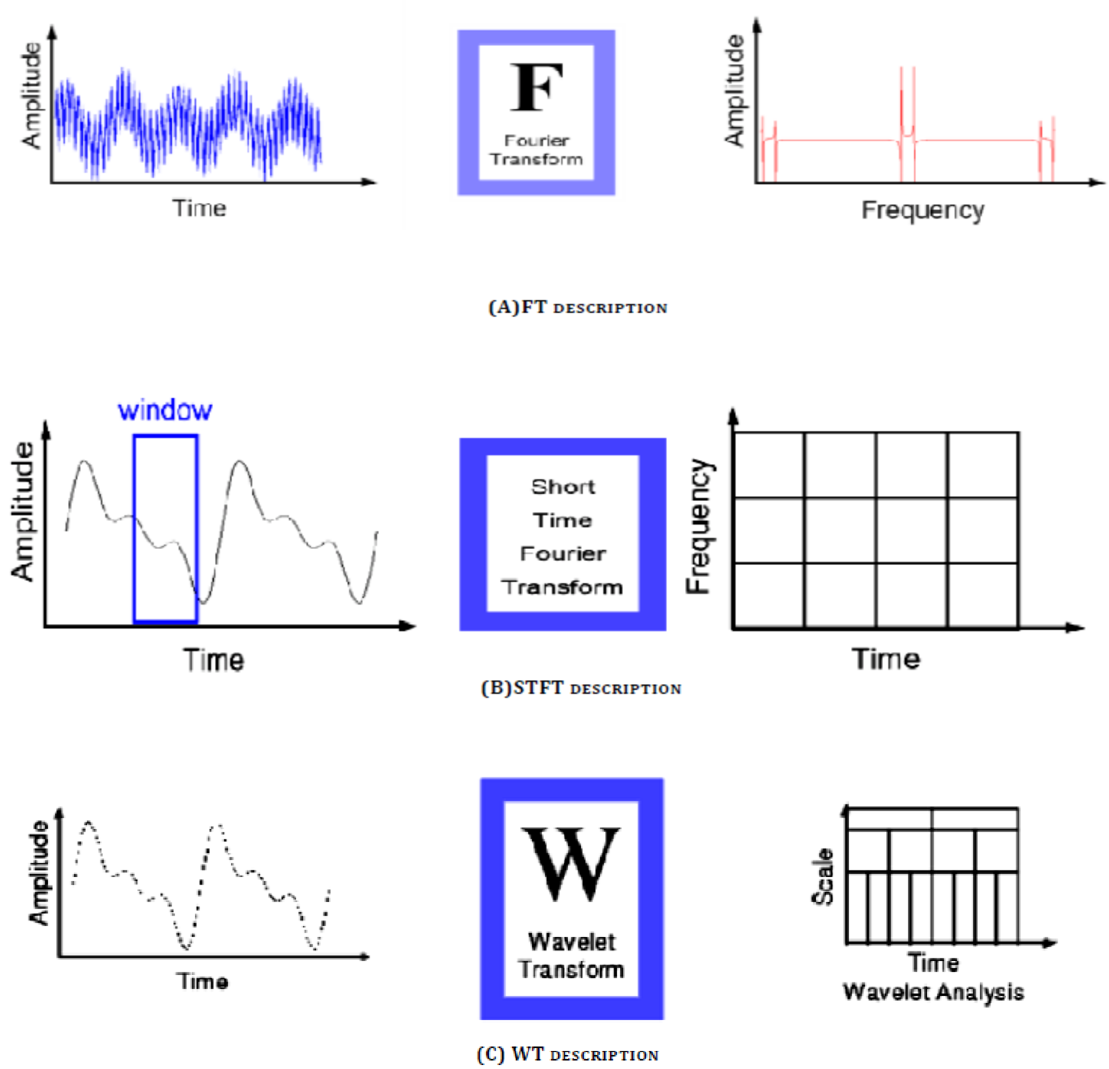
As noticed, most of these methods are relevant to modal analysis application. Evidently, the proper method to select is dependent on the sensor type that collects the data.

The fatigue rainflow cycle counting technique in connection with strain gauges operate in extracting the stress series to be later evaluated for damages using Miner's rule [67].

Alternatively, the other transformation methods are in need when converting to frequency domain. Usually, this transformation is applied when accelerometers are present during modal analysis.

In some references, counting stress cycle techniques are found, namely, reservoir counting, zero-crossing range method, range method and rainflow counting [19]. And the latter was found to be the most used and traditional technique among the others. The process is done by transformation of inconsistent amplitudes to constant amplitudes in stress vs cycle number curve (S-N curve). As a result, Miner's rule evaluates the remaining fatigue life by the input provided as the number of cycle per day [67].

On the other hand, vibration damage detection techniques depend on the transformation from time domain to frequency domain the dynamic modal properties. As some examples, Fourier transform and fast Fourier transform use this kind of process.



(A)FT description

(B)STFT description

(C) WT description

Figure 17: Transformation methods description

Knowingly, vibration-based damage method can detect cracks. To do so, high modes needs to be monitored or in another way said high frequency signals. For that reason, a more efficient method is introduced like short time Fourier transfer. Its algorithm processes high frequency signals by separating the signal in windows and treats them each one at a time. Note that STFT method does not take into account the high and low signals instead it evaluates the signal in a constant resolution.

On the contrary, a new way in processing frequency signals, wavelet transform uses irregular resolutions relatively dependent on high and low signals. Thus, it adjusts the irregular resolution with the capability of detecting different signals.

All these transformations are illustrated in Figure 17 [2].

5.3.1. NUMERICAL ANALYSIS AND STRATEGIES

Validation of numerical model is an important step to predict structural responses and to accomplish a better cost effectiveness analysis. Usually, a system identification domain based on inverse analysis of a structure, measures the input and output signals by tracing the variation of key parameters such as stiffness.

In SHM, some traditional methods are used to extract information from measurements based on mathematical principles like:

instrumental variable method, least squares methods, maximum likelihood method, natural frequency-based method, gradient search methods, filter methods, and mode shape-based methods.

These techniques, despite their success, need an initial good guess for unknown parameters and noise sensitivity. However, input measurement is not always achievable. Thus, only methods with output measurements are chosen. In some experiments aim to identify forces with a known system. While in others measures variations over time of the structure parameters. These measurements mostly include iterative least-squares procedures.

On the other hand, Non-traditional methods based on experimental principles and relies on computational resources and make no assumptions. Some of these non-traditional techniques are: simulated annealing (SA) method, artificial neural networks (ANN) method, particle swarm optimization (PSO) method and genetic algorithms (GA).

SA is a global optimization method [62] but its accuracy of estimating the severity of the damage is influenced by unfinished measurements and noise.

PSO algorithm was widely applied to structural problems but many obvious parameters effected the union of the optimization search.

ANN method, as discussed in the above section, is used for damage detection problems. However, it is very dependent on the guided outlines, thus it is restricted to the number of unknown parameters.

Particularly, GA was successful in many optimization and discovering problems like identification of parameters in non-linear system, damage detection with non-perfect analytical model and detection change with frequency-based and mode shapes-based.

Nevertheless, with large systems with several unknown parameters, it becomes hard to convert using GA methods. Some researchers developed a sub-division method to make it easier to identify the large structural systems. It is done by measuring acceleration between substructures with no approximation of interface forces. A new method is recently termed "search space reduction method" (SSRM), and it applies some improvements on migration and artificial selection by using some local search to adjust the space of global search.

As a matter of fact, the previous researches are mostly applied to land structures. In addition to these developments, offshore structures are more challenging and based on stiffness identification by measuring ambient forces. Some goes with the traditional method, thus requiring assumptions of initial parameters, and some others adjusted to recognize the natural frequencies of offshore structures and comparing them to the measured vibration signals in order to detect damage locations. Nevertheless, this approach is challenging because not every change in stiffness of a member leads to a variation of frequency.

In this section, the identification of sub-division structures in a large platform will be discussed on a jack-up platform with three legs supported and founded in the seabed by spudcan as in Figure 18.

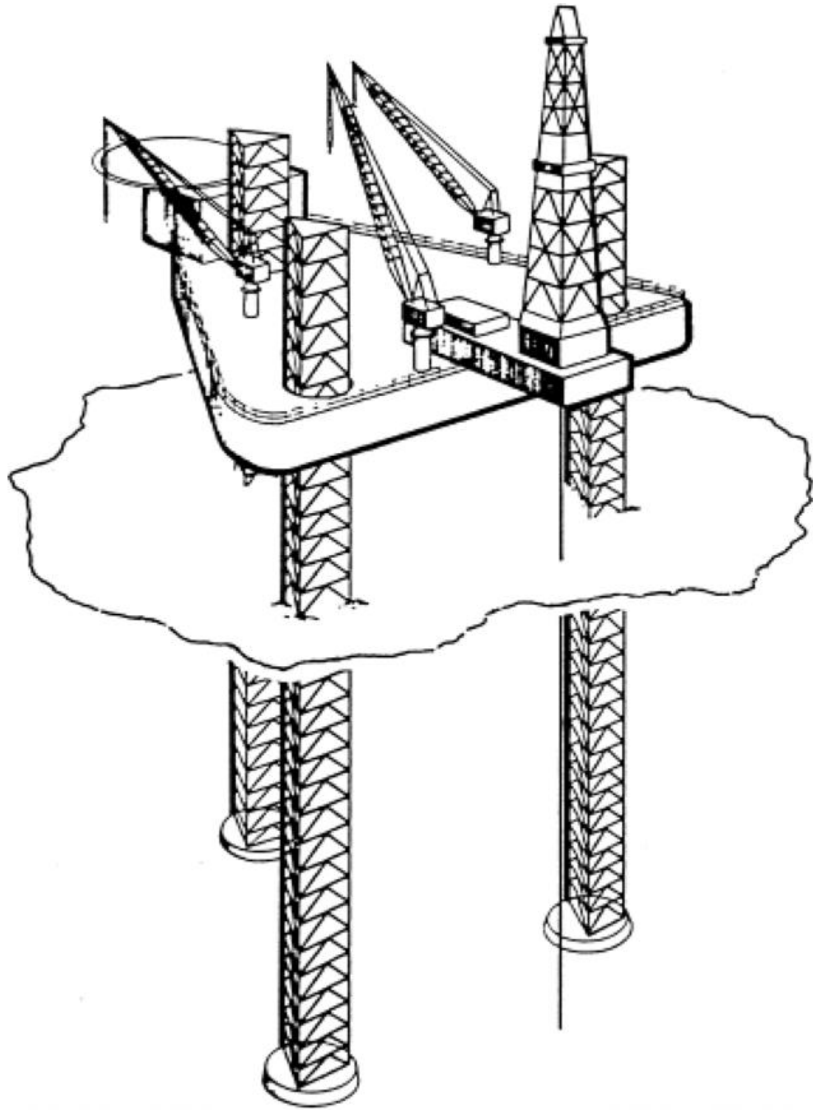


Figure 18: Jacket platform.

Taking into account the importance of dynamic effects, in view of the fact that the natural period increases and overlap the wave periods causing a considerable energy. Assumption of measurements of Spudcan foundation fixity varies in each study. Usually it is considered as trapped with no rotation. In some studies, stiffness levels are determined by comparing measured data and numerical simulation of frequency domain and magnitude.

Some others concentrate on spudcan reactions in various soil conditions and compare the displacement on the hull with numerical simulations with various fixity assumptions. As have been seen, many unknowns are involved and it is not effective for optimization. Furthermore, leg flexibility is very significant for dynamic analysis. In other words, it is important to consider stiffness and spudcan fixity parameters. Also, it is necessary to include the unknown parameters like hydrodynamic effects into the identification of jacket platform.

As a matter of fact, strategies in time domain and frequency domain are proposed to overcome the difficulties with many degrees of freedom and unknows like initial conditions, wave loading, hydrodynamic effects [68].

Forward analysis

First, forward analysis should be taken into account in the study of structural identification. The calculated dynamic response can be manipulated into the numerical simulation as measurements.

An example of a modeled 2D jacket platform structure is depicted in Figure 19 with legs as vertical beams, one as windward leg and the others as leeward legs [81], and an horizontal beam connecting the two vertical beams defined as the hull. The latter connection is presumed to be rigid, and a group of springs displayed as the spudcan fixity. The FE method is used to get the coherent mass matrix and stiffness matrix. Adopting the Rayleigh damping in a way the damping matrix depends on the mass and stiffness matrices. In the numerical simulation, Wave force is displayed by linear wave theory.

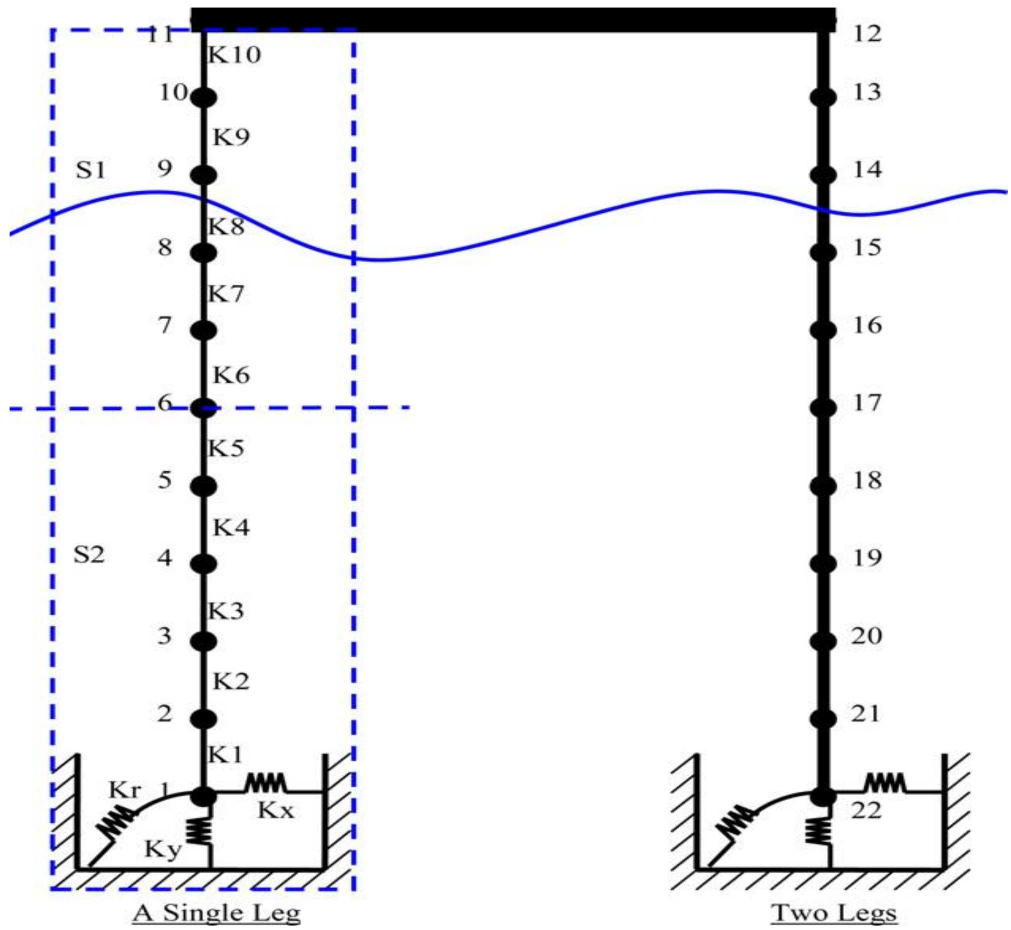


Figure 19: Numerical model of jacket platform

Dynamic analysis in time domain

For wave force evaluation on jacket, Morison's equation is applied knowingly that the diameters of the leg members are considerably smaller than the wavelength [82]. At a node under the water, the total wave force is obtained by adding the distributed wave forces on the beam structure via Gauss integration formula (5 points per element). Drag forces and mass of water must be added in the case of unsteady flow, given that the relative velocity changes intermittently between the structure and the surrounding water. Thus, the modified Morison's equation for wave force per unit length is [68]:

$$dF_j = C_d \frac{\rho A}{2} (U_j - \dot{u}) |U_j - \dot{u}| + C_m \rho V \dot{U}_j - (C_m - 1) \rho V \ddot{u}$$

where *Cd* and *Cm* are drag coefficient and inertia coefficient respectively. *Uj* and *Üj* are, respectively, the velocity and the acceleration of water particle. ů and ü are, respectively, the velocity and the acceleration of structural response. *A* is the area per unit length, while *V* is the volume of the wet structure per unit length.

For jacket platform, the displacement of the structure is negligible, thus the kinematics of water can be determined at non-deformed position of structure. In addition to linearized Morison's force and neglecting the wave load in splash zone, with applying the least square method to the distributed drag force, the wave force per unit length becomes:

$$dF_j = C_d \frac{\rho A}{2} \left[\left(\sqrt{\frac{8}{\pi}} \sigma_{U_j} \right) U_j - \left(2\sqrt{\frac{2}{\pi}} \sigma_{U_j} \right) \dot{u} \right] + C_m \rho V \dot{U}_j - (C_m - 1) \rho V \ddot{u}$$

where σ_{uj} is the standard deviation of *Uj*.

Note that the added mass of water and hydrodynamic effects caused by drag forces are included in the coefficients *Cm* and *Cd* respectively. Additionally, linear wave concept and empirical wave spectrum are utilized to simulate arbitrary wave situations in order to arise water particle kinematics. The velocity and the acceleration of water particle fluctuating respect to the distance from the free water surface are expressed:

$$U_j(t) = \sqrt{2} \sum_{i=1}^{N} [S_{\eta\eta}(\omega_i) \Delta\omega]^{1/2} \omega_i \frac{\cosh[\kappa_i (z_j + d)]}{\sinh(\kappa_i d)} \cos(\kappa_i x_j - \omega_i t + \xi_i)$$

$$\dot{U}_j(t) = \sqrt{2} \sum_{i=1}^{N} [S_{\eta\eta}(\omega_i) \Delta\omega]^{1/2} \omega_i^2 \frac{\cosh[\kappa_i (z_j + d)]}{\sinh(\kappa_i d)} \sin(\kappa_i x_j - \omega_i t + \xi_i)$$

Where ($\omega_i^2 = g\kappa_i \tanh \kappa_i d$) is dispersal relation, κ_i is wave number related with ω_i, $S_{\eta\eta}(\omega_i)$ is one-sided power spectral density of wave height, *N* is the number of the data points,

z_j is the vertical coordinate of node j (assuming the coordinate system is placed on the free water surface), $\omega_i = i\Delta\omega$ is the frequency of the ith wave component, x_j is the coordinate along wave direction, and ξ_i is statistically independent random phase angle uniformly distributed between 0 and 2π.

Making a note of not using the input (wave loading) in the projected identification strategies since it is dependent on the output. Hence, the simulation of kinematics of water particle is founded on deterministic spectral amplitude and is suitable in the forward analysis to calculate dynamic response as simulated measurements. Besides, Rayleigh damping matrix is applied in the numerical model with the Rayleigh damping coefficients α, β in which they are valued by cracking two equations concerning the damping ratios for two specific modes.

Finally, re-representing equation of motion for dynamic analysis by:

$$\mathbf{M}\ddot{\mathbf{u}}(\mathbf{t}) + \mathbf{C}\dot{\mathbf{u}}(\mathbf{t}) + \mathbf{K}\mathbf{u}(\mathbf{t}) = \mathbf{P}(\mathbf{t})$$

The added mass and drag induced damping are in the mass matrix **M** and damping matrix **C** respectively. **K** is the global stiffness matrix and **P** is the effective wave force.

Dynamic analysis in frequency domain

Equation of motion for structural analysis can be converted into frequency domain by Fourier transform resulting in the following equation [68]:

$$\left(\mathbf{M} + \frac{\mathbf{C}}{i\omega} - \frac{\mathbf{K}}{\omega^2}\right)\hat{\ddot{\mathbf{u}}}(i\omega) = \hat{\mathbf{P}}(i\omega)$$

where ω is circular frequency (rad / s) and over hat symbol "ˆ" designates Fourier transform. Then, structural response vector in frequency domain can be calculated as:

$$\hat{\ddot{\mathbf{u}}}(i\omega) = \mathbf{G}(i\omega)\,\hat{\mathbf{P}}(i\omega)$$

where **G** (*i*ω) is frequency response matrix. Consequently, spectral density matrix of structural response designed for spectral analysis can be attained by the following equation:

$$\mathbf{S}_{\ddot{\mathbf{u}}}(i\omega) = \mathbf{G}\,(i\omega)\,\mathbf{S}_{\mathbf{p}}(i\omega)\,\mathbf{G}^{T}\,(-i\omega)$$

Proposed identification strategies

Sub-structural identification is a strategy to reduce the size of the system instead of struggling with the quasi-impossible detection interpretation in big structures. This strategy is also called divide-and-conquer strategy. As an advantage, this method simplifies the condition by subtracting the complex connections from the sub-structure like the connection leg-hull. Figure 20 illustrates the sub-divisions of the single leg of the structure in the figure above into two divisions: S1 represents the top-half of the leg, S2 represents the bottom-half of the leg with the spudcan fixity. Note that analysis in two-dimensional frame is more efficient than three-dimensional model [68].
As for the selection of the direction of the leg, it is done according to the corresponding measurement plane. Whereas parameters in the other plane are to be documented. As for similar procedure in the new plane, the selection is repeated. Also, damping coefficients (α, β) are considered as unknown parameters in the identification procedure besides the main unknown parameters like stiffness and spudcan fixity.

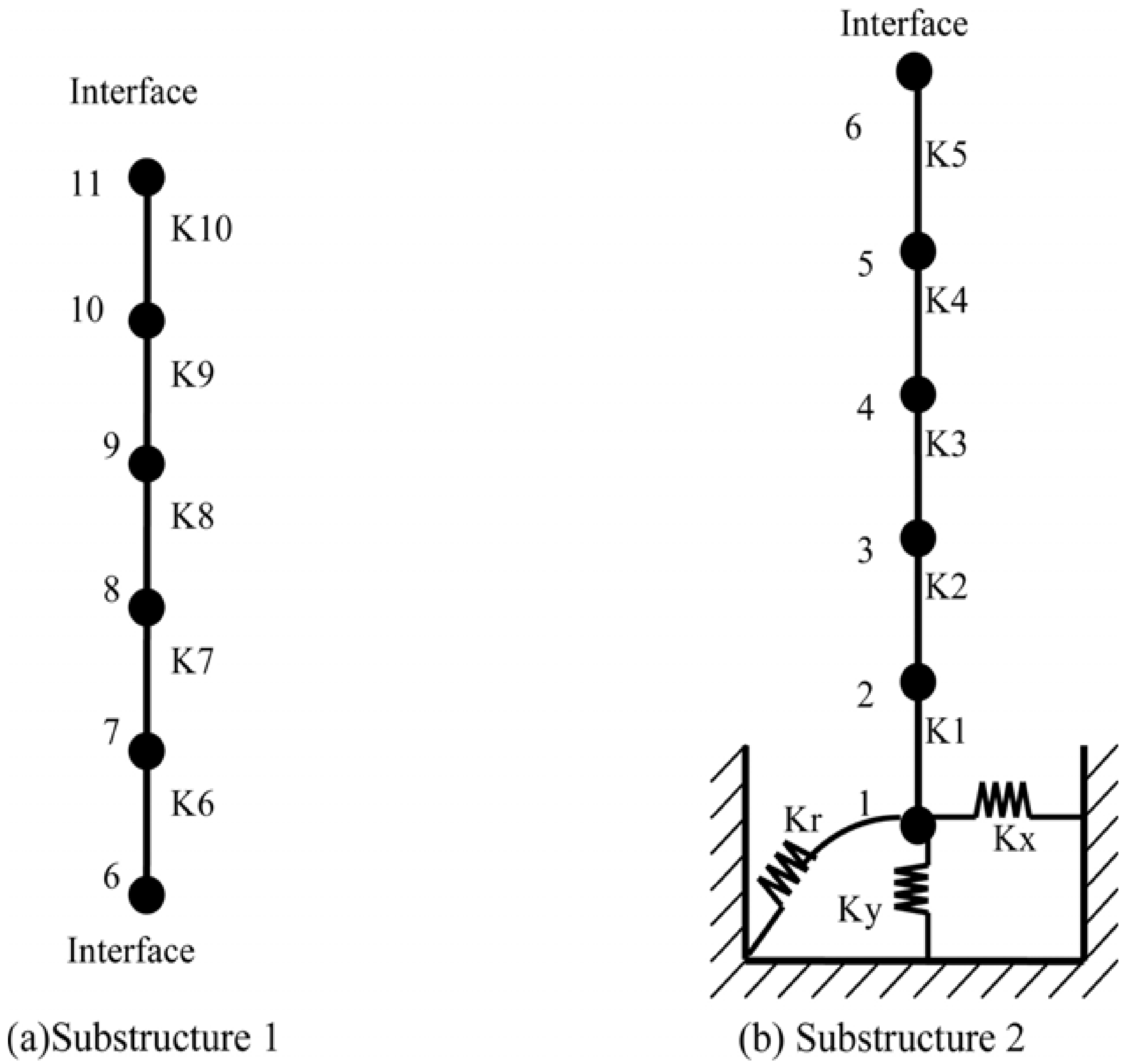


Figure 20: Sub-divided structure of jacket model.

Time domain structural identification generally necessitates in known initial conditions. This necessity is rather not genuine for offshore structures exposed continuously to wave loading. A practice is planned herein to pact with unknown initial conditions. Practically, wave forces are problematic to evaluate or to forecast precisely. Therefore, only outputs are preferred. Consequently, a corrective predictor algorithm is assumed to confront this obstacle in time domain. Accordingly, spectral analysis is bringing into play the solution of the dynamic system through unknown initial situations and arbitrary excitations. However, no technique existence in addressing the unknown wave loading in frequency domain. Thus, unknown wave loading in frequency domain identification could be seized by eliminating it. However, the natural frequencies of the sub-divided structures are more considerable than the entire structure. Thus, a frequency range has been carefully chosen mainly to contain the natural frequencies of the sub-divided structures. Therefore, the dynamic response is mainly provoked by the frequency with higher excitations on the hull, thus, it might be beneficial to add an extra force to generate bigger dynamic response. As for the equation of motion for sub-divided structure, it can be derived [68]:

$$[\,\mathbf{M}_{rj}\ \ \mathbf{M}_{rr}\,]\begin{Bmatrix}\ddot{\mathbf{u}}_j\\ \ddot{\mathbf{u}}_r\end{Bmatrix}+[\,\mathbf{C}_{rj}\ \ \mathbf{C}_{rr}\,]\begin{Bmatrix}\dot{\mathbf{u}}_j\\ \dot{\mathbf{u}}_r\end{Bmatrix}+[\,\mathbf{K}_{rj}\ \ \mathbf{K}_{rr}\,]\begin{Bmatrix}\mathbf{u}_j\\ \mathbf{u}_r\end{Bmatrix}=\mathbf{P}_r$$

Where r expresses the degrees of freedom in the sub-divided structure, while j denotes for degrees of freedom of the exterior of the sub-divided structure.

<u>Sub-divided structural identification strategy in time domain</u>

Figure 21 represents the summery of the flowchart of the sub-divided structure identification approach in time domain. Since the variation in stiffness values effects the dynamic response of the structure, a helpful indicator as the sum of squared errors lead the search with Generic algorithm for the unknown parameters. The indicator SSE is done between the simulated and measured time histories of the structure response. As a start, the model requires estimation of the unknown initial conditions passing by SSE. Accelerations from accelerometers for dynamic response are calculated and then velocities and displacements are estimated. Continuously, output-only algorithm predicts and corrects the estimated parameters Newmark’s constant-average acceleration approach. Note that the numerical study demonstrates that the identification of Cd is accurate, and no existing influence on stiffness by the estimated wave spectrum. After putting together and comparing the simulating and measured data in time domain, a filter window is used to find the response of the structure in a defined range of frequency that encloses the chosen natural frequencies of the sub-divided structures [68].

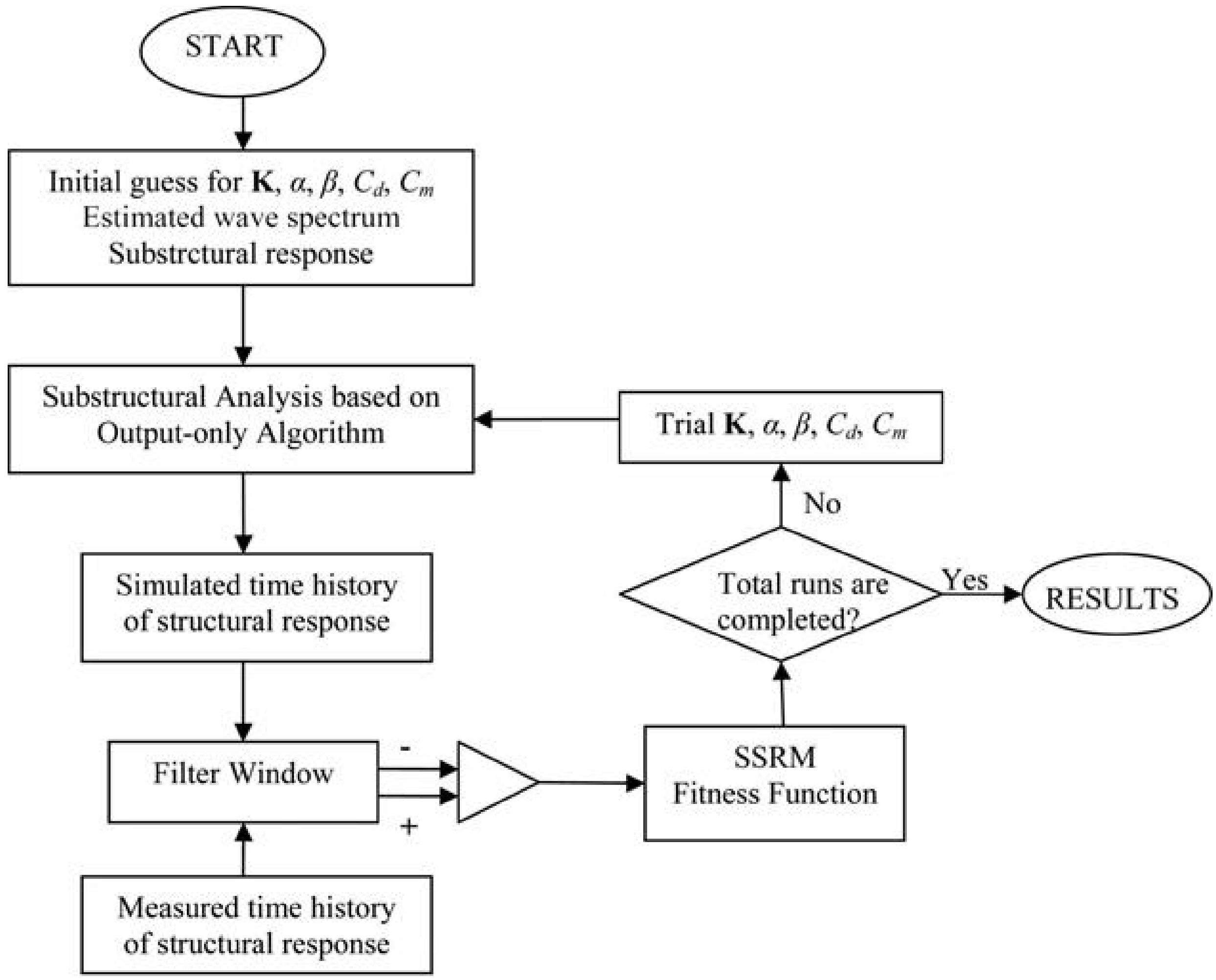


Figure 21: Flowchart of sub-divided structure identification strategy in time domain.

Sub-divided structure Identification Strategy in Frequency Domain

Figure 22 represents the summery of the flowchart of the sub-divided structure identification approach in frequency domain. In frequency domain, acceleration measurements are only requisite. On the other hand, the frequency range is selected to contain the chosen natural frequencies of the sub-divided structures without the domineering wave frequency. Thus, no need to measure the wave force. Nevertheless, in frequency domain approach, the measurements must be converted into power spectral density measures (PSD) [68].

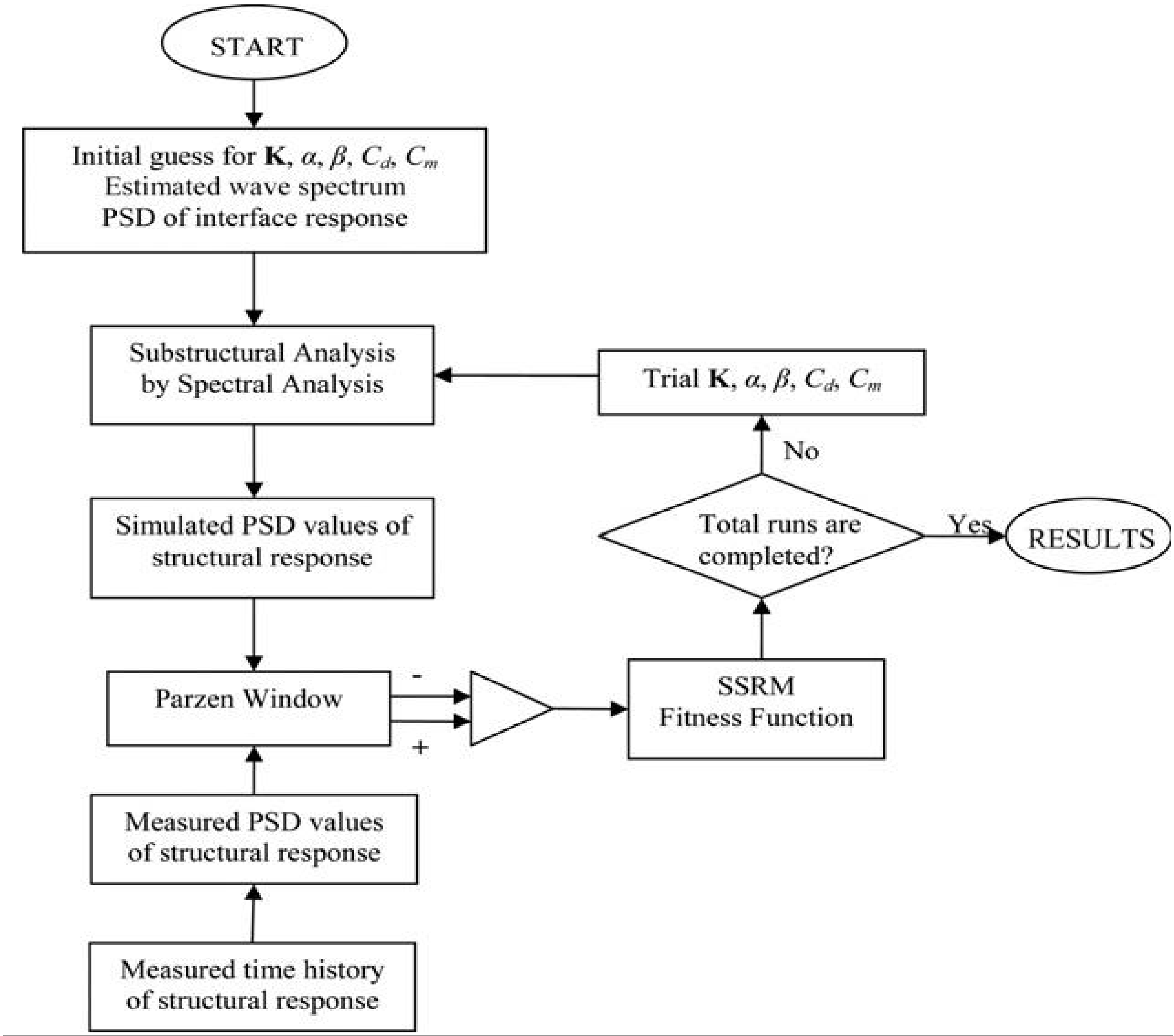


Figure 22: Flowchart of sub-divided structure identification strategy in frequency domain.

With the help of FFT, data in time domain are converted to PSD. Hence, the simulated data accelerations from PSD are compared to the measured data in the selected frequency range after smoothing the noise with Parzen window. As for time domain, also frequency domain uses the SSRM to improve the efficiency [68].

Numerical simulation study

For numerical model of jack-up platform, the stiffness properties needed to calculate springs values are [68]:

The Spudcan diameter B, the Poisson's ration of soil υ, the shear modulus for vertical, horizontal and rotational loadings $G_{(x,y,r)}$.

$$\begin{Bmatrix} K_x \\ K_y \\ K_r \end{Bmatrix} = \begin{Bmatrix} \dfrac{16 G_x B (1-\nu)}{(7-8\nu)} \\ \dfrac{2 G_y B}{(1-\nu)} \\ \dfrac{G_r B^3}{3(1-\nu)} \end{Bmatrix}$$

In addition, structures properties with external conditions are needed to conclude modeling, and they are summarized in the following:

- Mass, length, area and second moment of area of the hull
- Mass, length, area and second moment of area, equivalent diameter and area, and young modulus for each leg.
- Mass with surrounded water and stiffnesses for vertical, horizontal and rotational for each spudcan.
- Water depth, wave height (peak wave period in storm, enhanced wave factor), hydrodynamic factors, damping factor (3%) .

Apart from modeling, usually, the measurements to identify the sub-divided structure of jack-up model are certainly corrupted by noise. Thus, a white Gaussian noise vector is introduced to every numerical analysis in order to circumvent the exact same outline of noise. The definition of noise is denoted as:

$$Noise = w \times RMS_{(Clean\ Signal)} \times Noise\ Level$$

Where RMS is the root mean square and w is the standard random Gaussian variable.

Another important clarification in the numerical study is the sensitivity of the structure response to the stiffness variation [92]. This latter sensitivity affects the fitness function.

As an example, in S1 substructure, the rotational acceleration shows additional sensitivity respect to linear accelerations to the variation in leg stiffness. This concludes that rotational accelerations of interior nodes are rather preferable to be involved in the fitness function. On the other hand, in S2 substructure, the rotational and horizontal responses regarding spudcan stiffness are more sensitive to leg stiffness variation, whereas vertical and horizontal responses show additional sensitivity to spudcan stiffness change. As a deduction to S2 case, it is preferable to involve in the fitness function a mixed group of parameters like: horizontal accelerations of interior nodes without considering the prior node, plus two sets of rotational and vertical accelerations at both the third and fifth nodes.

An examination check is carried out to identify stiffness values with two noise percentages (5% and 10%) with ten tests for each proposed noise. The results are provided in relations to the ratios between the identified mean parameters and the precise values in both time domain and frequency domain as shown in Figures 23-24.

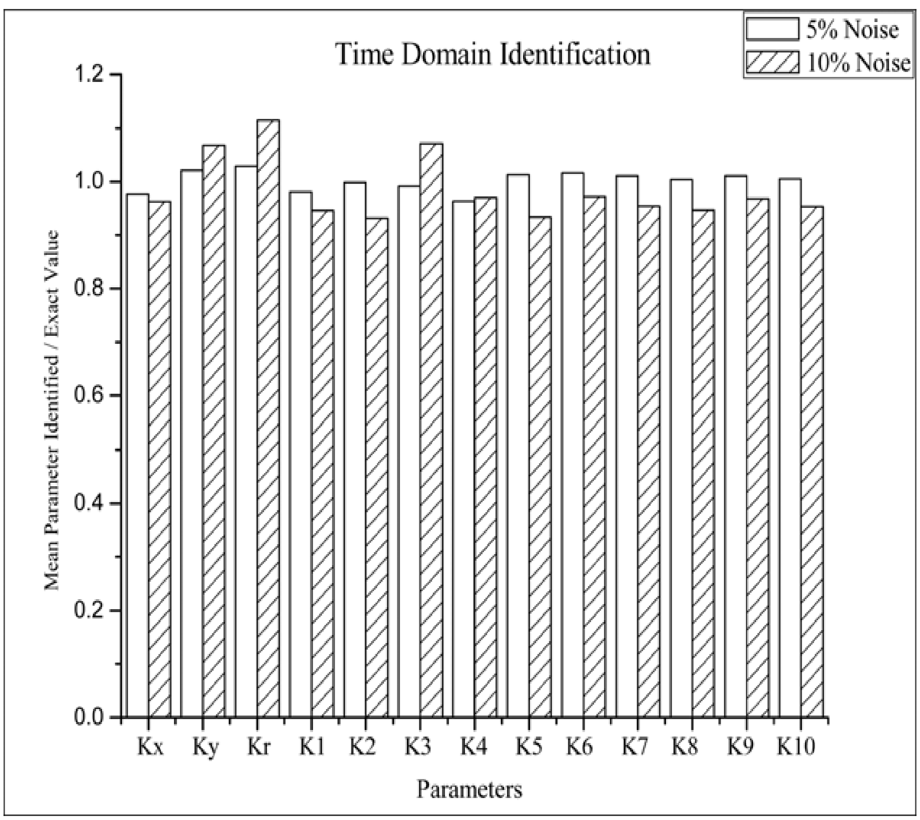


Figure 23:Time domain identification results in numerical study.

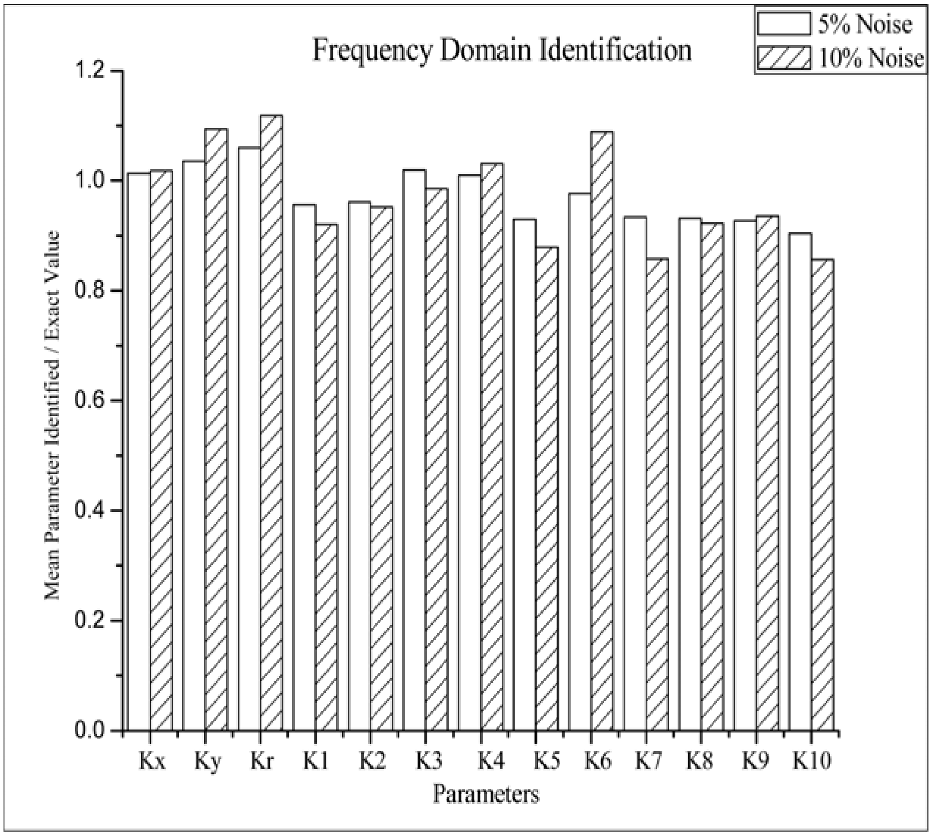


Figure 24: Frequency domain identification results in numerical study.

As a result, the errors in time domain for 10% noise is equal to 8% while, for the 5% noise is around 4%. Instead, compared to frequency domain, the errors are respectively 15% and 10%. This leads to a general conclusion, that the time domain approach is better than frequency domain. In addition, only the amplitudes of the spectral are used in frequency domain, and for further explanation, converting frequency data to time domain creates more computational errors [68].

5.4. EVALUATION PHASE

The evaluation phase consists of three parts: damage evaluation, Identification of acceptance criteria and the required corrective actions needed.

Damage evaluation

Damage evaluation involves an assessment of the processed data to be able to justify the concerning motives in mind.

As introduced in earlier sections, damage detection based on vibration is parted into four levels, where [2]:

- Level 1: Determination that damage is present in the structure
- Level 2: Level 1 plus determination of the geometric location of the damage
- Level 3: Level 2 plus quantification of the severity of the damage
- Level 4: Level 3 plus prediction of the remaining service life of the structure

Typically, a quantifiable valuation is achieved with models neglecting noises from signals. Table 13 cites some familiar model techniques with their advantages and disadvantages [69] [70] [71].

FLS is a method with no adoption of the binary value instead it makes decision grounded on full detailed knowledge [69] [71]. In contrast, AIS model depends on human immune system based on memory capacity and learning skills to expand its detection. Thus, it requires a complete training of the model and existing scenarios in order to provide, in the future analysis, a quick answer to recognizable situations. Comparing FLS and AIS models in detecting damage on operational jackets, it is remarked that both have high success grade even with the presence of environmental noises.

ANN as named is dependent on artificial neurons to transmit information. It is activated with the increase of weight that respectively induces a rise in the signal intensity. Mathematical functions simulate the activation process afterwards the other functions calculate the real output [72].

Statistical damage process compares the mean values and the standard deviation values between the variation of the statistical distribution of the collected data. Thus, a sign of change in these factors will lead to a failure in SHM system detection [71].

Table 13: Damage detection models

Model	Positive aspects	Negative aspects
Fuzzy Logic System (FLS)	- Relatively high success rate - Computationally lower cost than AIS - Efficient	- Lower success rate than AIS - Need rule development
Artificial Immune System (AIS)	- High success rate - High efficiency - Efficient - Noise immunity	- Detailed training of the model - Computationally higher cost than FLS
Artificial Neural Network	- High success rate - Efficient	- Long training time needed
Statistical	- High success rate - Slow	- Requires a large amount of data - Not suitable for rare anomalies

<u>Remaining estimation of acceptance criteria</u>

After the assessment of the damage for monitored structures on the jacket, a definite estimation needs to be done according to the guidelines selected.

<u>Correctives actions / mitigating measures</u>

Results from damage evaluation are subjected, if necessary, to corrective actions that can modify methods or actions, or even taking decisions in decommissioning a structure. Example on mitigation measures done to a fatigue crack according to NORSOK N-006 [16]:

- reduction in loadings (substitute members, eliminate inactive conductors, appurtenances, marine growth)
- reduction in stress level by strengthening (put new members, clamps)
- reduction in stress concentrations (by internal grouting of tubular joint)
- improvement in fatigue capacity by correcting methods.
- make in-service inspections controls in a way cracks are detected before they are within the wall thickness and in such a way they can be confiscated by grind repair methodology.

6. CONCLUSION

After defining SHM methods and their performances in different fields, and specially in offshore platforms, a detailed description of phases is introduced to identify the steps required to assess the state of the structure. Planning SHM system acquires motivation establishment based on history and specified objectives with identification of failure modes. Afterward, data normalization is a valuable step in data collection phase to be applied in order to reduce noise for better processing phase. The latter comes in transforming the signal into damage identification. Usually, the most used method is FFT. At last, damage evaluation phase involves an assessment of the processed data to be able to justify the concerning motives in mind and estimating the remaining operational lifetime of the structure.

Bring to a close a briefing into the comparison made in this thesis, local damage technique based on non-destructive techniques is effective in localizing the damage only on the component examined but rather expensive while global damage pinpoints any damage on the structure with the help of additional analyses. Nevertheless, it is noted that global technique is frequently associated with local damage techniques. Along damage identification methods, numerous failures modes and their parameters are compared. It is concluded that crack propagation triggered by fatigue failure is the most common parameter affecting the structure integrity of the jacket platform. On the other hand, sensors selection and their characteristics plays an important role in detecting damage. Thus, they are dependent on types of failure modes chosen to be spotted and assessed. As proven, crack detection is preferably executed by AET sensing. The latter is more efficient in detecting crack than corrosion. While electrical gauges and piezoelectric are applied to strain detection. In addition, most of the data processing techniques are relevant to modal analysis application. The dynamic characteristics are the best fitting parameters for damage detection, but in case of noise, acoustic fingerprinting method is best fitting.

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MARIEBELLE GHSOUB

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