Mooring system monitoring of offshore renewable energy floating platforms

I. Touzon

Tecnalia R&I - Department of Mechanical Engineering, University of the Basque Country UPV/EHU, Bilbao, Spain

A. Garcia-Corcuera

Zunibal, Bilbao, Spain

V. Nava & R. Rodriguez

Tecnalia R&I – BCAM, Bilbao, Spain

B. de Miguel

Oceantec Energias Marinas, Bilbao, Spain

ABSTRACT: An appropriate schedule of the operations for the maintenance (both long and short term) of offshore renewable energy devices can be a crucial key factor for assessing the economic viability of marine energy projects. Moreover, floating devices suffer from a higher uncertainty in the determination of loads and failure occurrence. For these reasons, in this work a methodology based on global positioning system (G.P.S.) signals for mooring integrity monitoring is introduced. Indeed, besides the already widely used automatic identification systems (A.I.S.), which provides alerts for drifting devices, it is proposed here a more advanced methodology enabling the detection of line failures or simply broadcast alerts if the device position reaches a contour line, previously calculated and provided by the floater and mooring designers. Different position monitoring strategies and contour line will serve to identify when a simple visual inspection is required, a mooring line is broken or whether the device is freely drifting away or not, to plan maintenance operations.

1 INTRODUCTION

Offshore renewable energy devices supported by floating structures are currently attracting a significant academic research and the first demonstration and precommercial power plants have already been designed or even installed. Floating wave energy conversion community is seeking a promising concept with some demonstration projects ongoing. Technology demonstration projects are intended to achieve relatively high technology readiness levels (TRLs) to start commercialization. For example, a reduced power demonstration device based on the Oceantec MARMOK-A technology (Oceantec, 2010) has been installed off the Basque Country coast, with the additional research support of the H2020 OPERA project (OPERA-H2020, 2016), or the CorPower Wave Energy Converter (WEC) (CorPower, 2016) and the WaveBoost project (CorPower, 2016). In relation with floating offshore wind energy projects (Carbon-Trust, 2018), the most relevant project is the Hywind Scotland pilot park (Hywind-Scotland, 2018), already in the precommercial phase whilst other promising floating platforms are under technological development, such as Nautilus FS (Nautilus-FS, 2017) or Olav Olsen (Olsen, 2017) semisubmersibles, whose small prototypes are being currently tested within the frame of the H2020 Lifes50+ project (Lifes50+H2020, 2016).

All the mentioned technologies are in a techno-logical competition to demonstrate competitive Lev-elized Costs of Energy (LCOE) and gain trust of in-vestors and utilities. The costs of O&M, estimated at 16% for floating offshore wind turbines (FOWTs) (Carbon-Trust, 2015) and at 40% for WECs (IEA-OES, 2015), together with the lack of real field experience make necessary appropriate monitoring systems so that major incidents are avoided.

There are several mooring failures documented from the traditional offshore industry (Gordon, Brown, & Allen, 2014), such as the Oil & Gas industry, which demonstrates that a rapid detection of mooring system failures may avoid major consequences, both economic and environmental.

Different mooring system monitoring methods are already developed (Gordon, Brown, & Allen, 2014) (Noble-Denton-Europe, 2006) (ABS-Consulting-Inc., 2015) based on load cells, sonars, inclinometers or GPS. Most of them are in-tended to take either a direct or indirect tension measures.

Response learning systems (RLS), as introduced in (Noble-Denton-Europe, 2006), are based on GPS signals fed back with environmental monitoring and adjusted with mathematical models of the moored floating structure. In this paper a similar approach is applied, however, the lack of environmental monitoring makes sometimes difficult to get a good estimate of how harsh the current environmental condition is. A simplified procedure is therefore introduced, based on the design worst case scenario horizontal displacement contours (DC). DCs are built up with the mean displacement of the structure subjected to the harshest environmental condition at all directions under different mooring failures which are to be considered as reference to decide whether a failure has been found or an inspection is recommended.

Since the base data consist of mean displacements, static characterization of the definitive mooring system is sufficient to provide feasible results. Thus, decisions about alerts are to be taken based on different mean positions to filter out dynamic motions of the floating structure.

2 NUMERICAL MODEL

The numerical model developed for the present work is based on the mooring system of the MARMOK-A WEC, already installed off the coast of the Basque Country by Oceantec Energías Marinas (Oceantec, 2010) (OPERA-H2020, 2016). It is primarily made of four-line catenary mooring system with a square cell close to the mean water level, which joins the catenary lines with the WEC through four polyester lines, as represented in Figure 1.

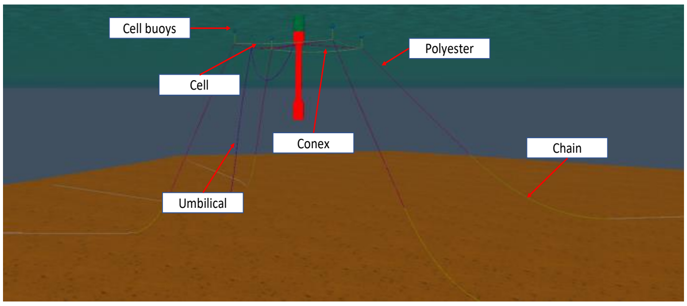


Figure 1 MARMOK-A mooring system schematic

The mooring system is made of five main components:

- Chain: Four chain sections to moor the device through its own weight. Anchored in the seabed and joint to the polyester section (yellow)
- Poly: Four polyester sections to raise up the chain tension, joining the cell and catenary lines (purple)
- Conex: Four polyester sections joining the WEC to the cell (purple)
- Cell: Four steel wire sections to make up the cell (green)
- Cell buoys: Four buoys to support the weight of the mooring system (blue points at the mean water surface level)

It has been built up on the commercial software Or-caflex (Orcina, 2018). In the numerical model the WEC has been modeled as made up of Morison buoys previously calibrated with tank testing. Sensitivity analysis has been performed with time domain simulations subject to the design environmental conditions, and a maximum element size of 5m in the catenary lines and of 1,8m in the polyester sections have been obtained. The characterization of the mooring system has been carried out by computing the statics of the WEC and mooring system at different horizontal displacements (of up to 100% the water depth) and 36 directions (with a 10º step), obtaining the horizontal force on the WEC for all of them. Therefore, a given mean horizontal force will have its corresponding horizontal DC, as represented in Figure 2.

3 DISPLACEMENT CONTOURS

To have an alert broadcasting system, independent from any environmental monitoring data, the design horizontal contours are computed. The horizontal contour is considered here as the structure will be performing its motions around its mean horizontal position. The alert broadcast system here presented is to be based on 1hour mean positions, this time aver-aging is set for rapid detection in case major failures occur. As recommended in (DNVGL, 2018) the mooring system shall be designed to withstand loads, in the ultimate limit state (ULS), induced by the 100-year return period (RP) sea state and mean wind speed and 10-year RP mean current speed, with the corresponding safety coefficients. In accidental limit states (ALS) same environmental conditions are recommended by DNVGL standards (DNVGL, 2018), reducing the safety coefficient.

Computed contours represent examples with representative mean forces of mean positions of the floating structure supposing mean environmental loads at each direction, provided by the mean current, wind and wave drift forces, all of them aligned so that the largest mean offset of the structure is considered.

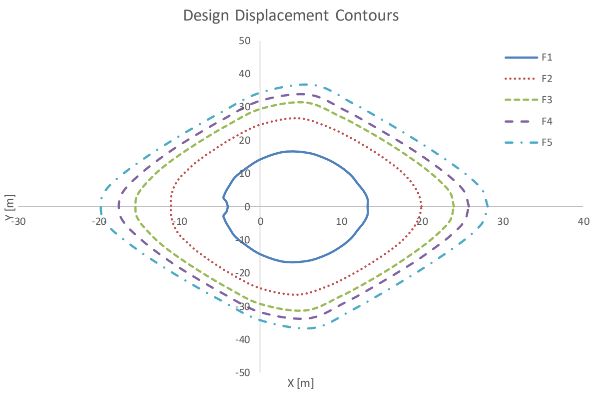


Figure 2 Horizontal displacement contours for five mean representative forces (intact mooring system)

After the design process of the mooring system is carried out, the worst-case environmental condition is identified for the ultimate limit state (ULS) of the mooring line tension. The corresponding mean force is therefore applied to obtain the ‘design displacement contours’ (DDC) with intact mooring system, similarly to what is introduced in Figure 2 for representative mean forces. It defines the mean position at which the WEC is subjected to its design loads, implying a risk for its structural integrity.

The main purpose of the alert broadcast system is to ensure that the WEC is placed in a safe position and, in case a mooring failure occurs, broadcast an alert indicating the type of failure.

If DCs are computed similarly to the DDC but with a predefined failure, the maximum mean displacement subject to the same ULS environmental conditions will be obtained. The herein presented methodology consists in deciding whether a failure occurred or not based on the mean position of the WEC, comparing intact and damaged mooring mean displacement contours.

In the case study presented here two types of failure have been modelled:

- Break of a Conex line
- Break of a catenary line (either the ‘poly’ or the ‘chain’)

If equivalent characterization is carried out with each of the introduced failures equivalent DC examples with representative mean forces are obtained as shown in **¡Error! No se encuentra el origen de la referencia.**.

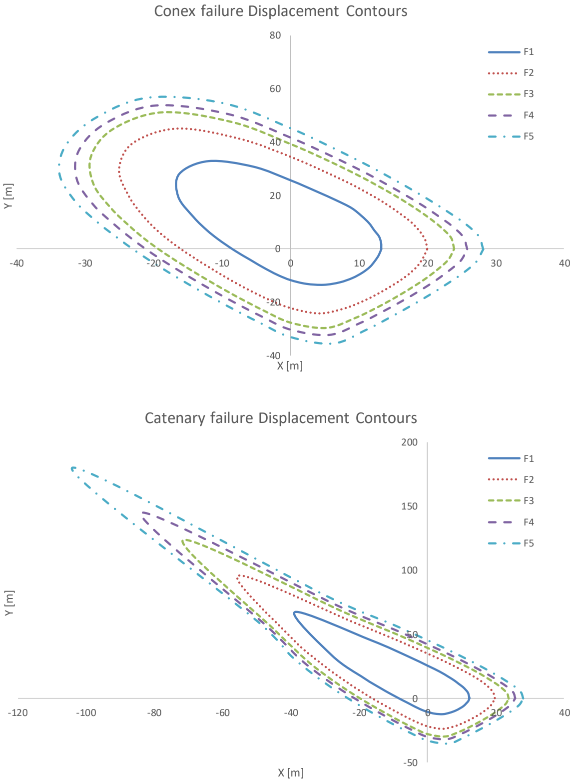


Figure 3 Conex 2 (top) and catenary 2 (bottom) failure con-tours subject to different mean loads

Although the contours have been built at all directions, the mooring system with each failure is unbalanced when the structure is close to its absolute origin, therefore it will tend to take a mean position in the direction of the missing component, making the failure identification easier. To verify this effect several fully non-linear time domain simulations have been carried out, considering a conex failure and a catenary failure, as shown in Figure 4 and Figure 5 respectively. The environmental conditions have been those of the recommended return periods in [15], and introduced in section 3.1. Carried out simulations consider waves, current and wind aligned at the same direction in each of them. The corresponding directions are specified in the legends in **¡Error! No se encuentra el origen de la referencia.** and **¡Error! No se encuentra el origen de la referencia.**.

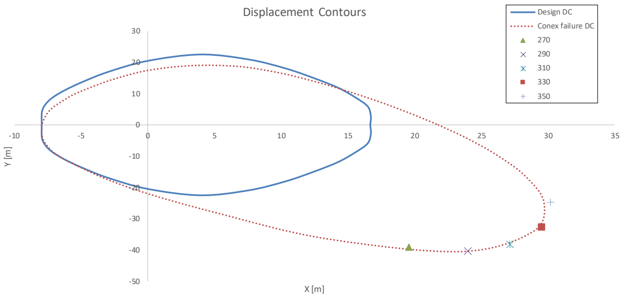


Figure 4 Verification of mean position of time domain simula-tions vs predefined conex 4 failure DC, at five directions

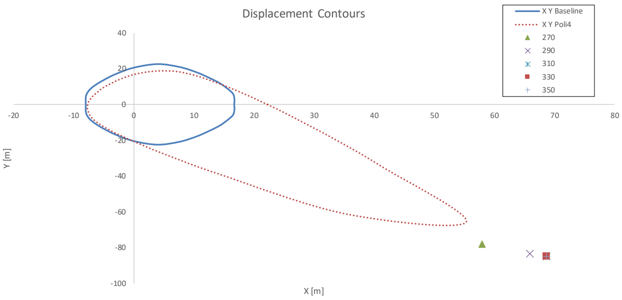


Figure 5 Verification of mean position of time domain simulations vs predefined catenary 4 failure DC, at five directions

It is shown that, due to the unbalance of the horizontal forces of the mooring system, the structure tends to take a mean position towards the direction of the missing line, even though the direction of environmental loads is at up to 45° with respect to the missing line.

3.1 *Failure detection methodology*

To broadcast alerts about mooring system integrity there must be a system to interpret if the actual mean position is correct or not. As already pointed out in this paper, to get an indication independent from the actual environmental condition, it is supposed that the mooring system is intact if its mean position is inside the DDC.

To identify a failure, its mean position should be outside the DDC and inside the DC of the corresponding failure. However, the mooring system has been designed to withstand all the variable loads at the DDC and in the rare case in which there is a stronger current than that of 10year return period a false alert could be generated. To avoid it, the DDC is complemented with the ‘total suspended length displacement contour’ (TSLDC), which supposes that at least one line is totally suspended at each position of the contour, both shown in Figure 6. Mean environmental loads have been computed subject to:

- Sea State:
    - Hs=9.56m
    - Tp=16s
- Current velocity:
    - Vc=0.571m/s
- Wind Velocity:

- Vw=29m/s

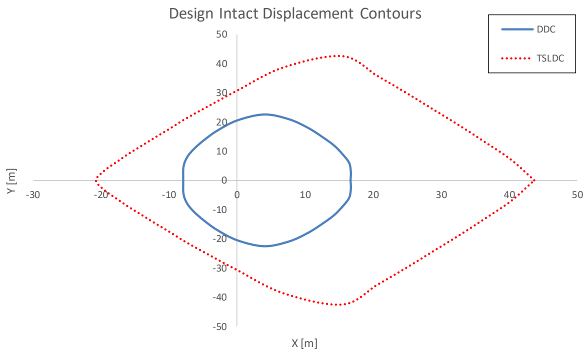


Figure 6 Design Intact DCs (DDC+TSLDC). To account for unusually large current velocities with small waves

The combination of the design intact DCs with the four conex failures results in low space to identify such failures as shown in Figure 7.

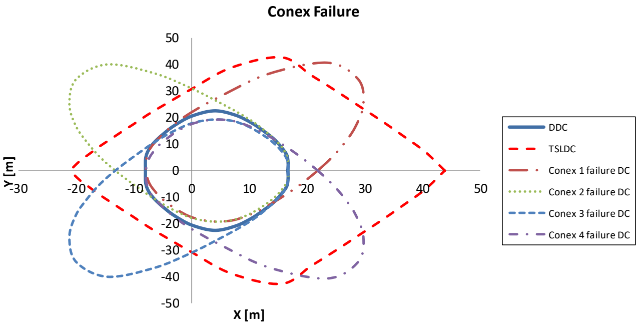


Figure 7 Conex failure DCs over intact design DCs

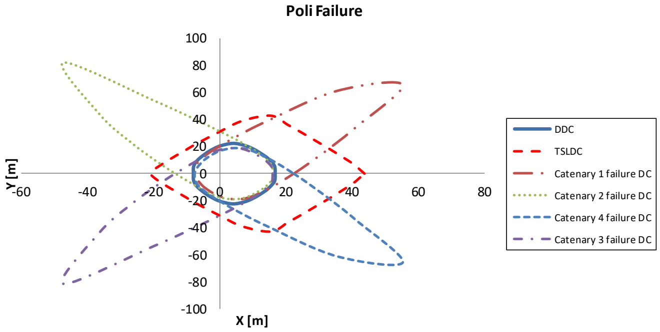


Figure 8 Catenary failure DCs over intact design DCs

The 1hour mean position has been selected as a reference time limit to detect a catenary line failure as well as the drifting away failure. It is therefore continuously monitored, and in case it is out of the DDC and inside the TSLDC then it could be due to a large current and cannot be interpreted as a system failure since it has yet capacity to withstand the mean environmental load, due to the safety factors.

As considered in (Puertos-del-estado, 2018) the Peak Over Threshold (POT) method takes the highest storm within five days since a defined threshold is exceeded. Therefore, here to identify a conex failure the 5days mean position should be outside the DDC and inside the corresponding conex failure DC. Alternatively, if the 1hour mean position is found in the gap between the TSLDC and its DC, then it is also identified.

In the other hand, a catenary mooring failure in order to be identified as soon as possible, the 1-hour mean position is always used. It is detected when the 1hour mean position is found outside the intact DCs, outside the conex failure DCs and inside the corresponding catenary failure DC, as represented in **¡Error! No se encuentra el origen de la referencia.**. Finally, when the 1hour mean position is found outside all the described DCs, it means that more than one catenary failure has occurred and it is considered that the device is freely drifting away.

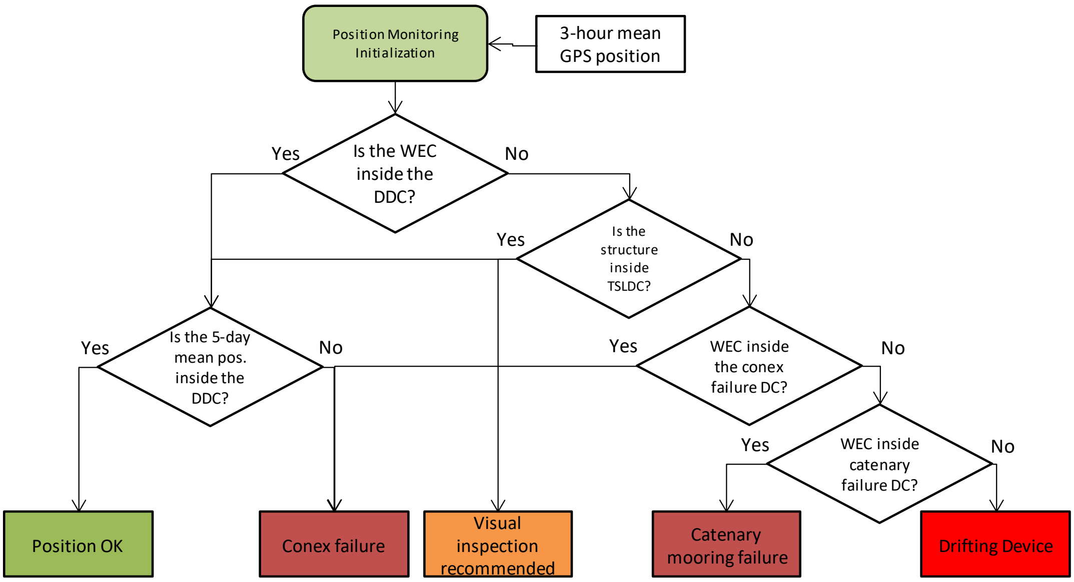


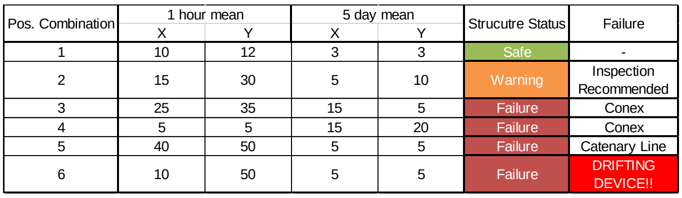
Figure 9 Alert broadcasting decision process

4 RESULTS AND DISCUSSION

According to the flowchart represented in Figure 9, there will be 5 possible status for the floating device:

1- Position OK
2- Visual Inspection recommendation
3- Conex Failure
4- Catenary Mooring Failure
5- Drifting Device

Table 1 Alert broadcast depending on structure mean positions



Pos. Combination	1 hour mean		5 day mean		Strucutre Status	Failure
	X	Y	X	Y		
1	10	12	3	3	Safe	-
2	15	30	5	10	Warning	Inspection Recommended
3	25	35	15	5	Failure	Conex
4	5	5	15	20	Failure	Conex
5	40	50	5	5	Failure	Catenary Line
6	10	50	5	5	Failure	DRIFTING DEVICE!!

These can be represented by several combinations of the considered mean positions of the structure. The most representative cases are shown in Table 1.

The lowest risk level is represented by the ‘Warning’ alert broadcast, represented in Figure 10 (1).

It just suggests the plant operator that, due to 1hour mean positions close to those for which the mooring has been designed for, it is recommended to carry out a general check on the device status as well as a visual inspection of the mooring system. Even though no major failures occurred a non-critical part may have failed, i.e. loss of a cell buoy that cannot be detected with present methodology, which could be replaced, avoiding further failures in the future.

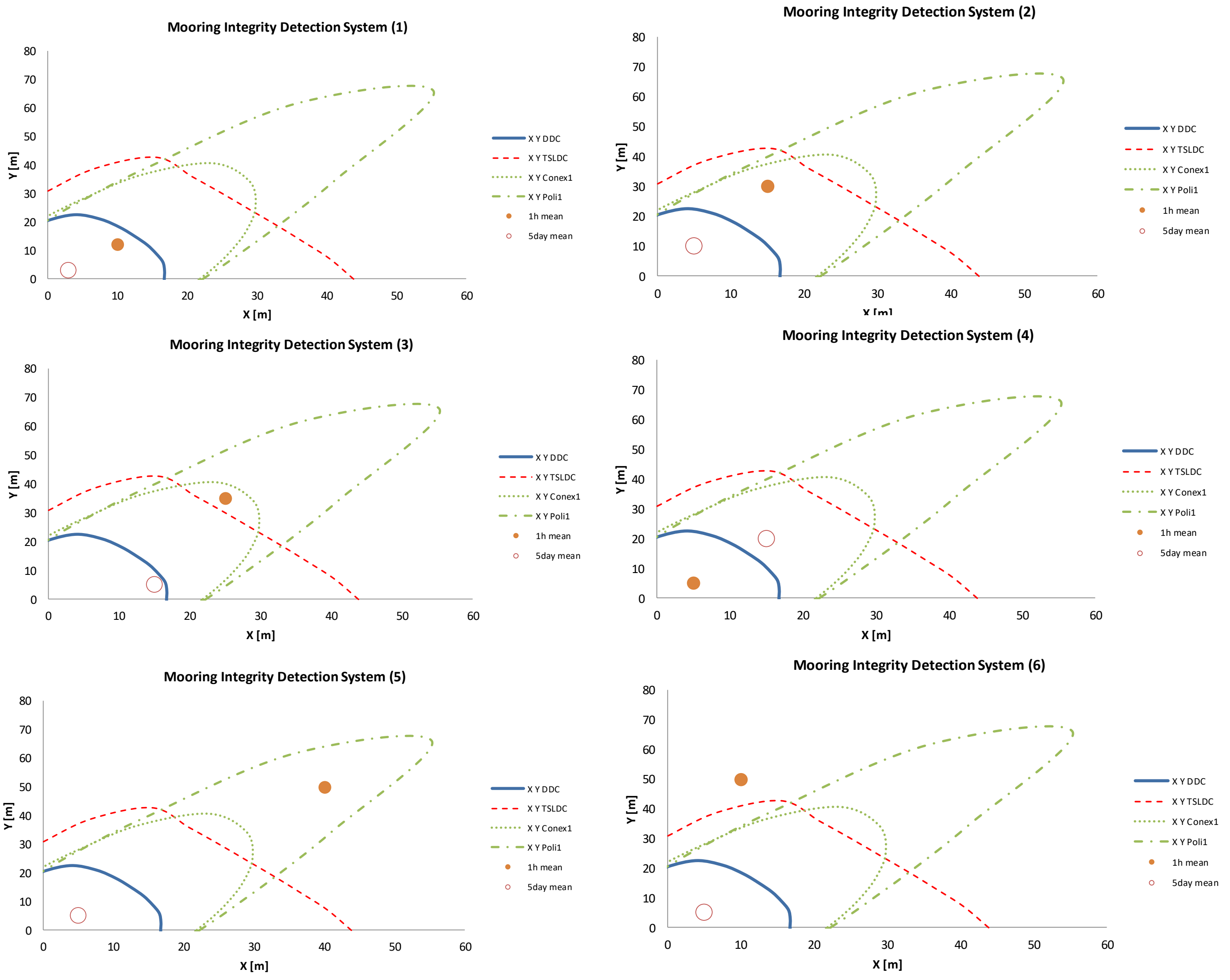


Figure 10 1hour and 5day position combinations according to Table 1 (from top left to bottom right – combinations 1 to 6)

A conex failure is the most difficult failure to be detected through the 1hour mean position since the area between the TSLDC and its failure DC is very limited, Figure 10 (3). Otherwise the 5day mean position is required, which will give the most feasible information, Figure 10 (4). Once a conex failed, the mean position of the device will point at the opposite direction of the failed lines, therefore, even if there is no a significant storm, it is expected that the failure will be clearly detected. A catenary failure, Figure 10 (5) is a critical aspect to be detected as fast as possible in order to plan its replacement as soon as possible. Similarly to what is done with the conex failure based on 5day mean, the catenary alert is broadcasted as soon as the 1 hour mean position is found as shown in Figure 10 (5). Finally, the most critical failure occurs when the device is out of all the introduced contours, Figure 10(6). Such failures occur when at least a catenary line and another component failed, i.e. another catenary or a conex. In this case the system interprets it as a catastrophic failure, broadcasting the ‘drifting away’ alert. Although two out of four catenaries may be yet in place, the standards (DNVGL, 2018) suggest designing against one accidental event instead of more, as here considered. Therefore, this alert suggests that all available contingency plans should be activated to mitigate a further risk increase.

It turns out that the most difficult failures to be detected are those of the leeward lines. The structure will take mean positions mainly in their direction, making the windward lines work, and keeping the structure within its DDC. However, even if further work should be carried out to enable its rapid detection, low currents, i.e. tidal currents, will easily move the device out of the DDC in the direction of a leeward line failure, suggesting at least a required visual inspection.

5 CONCLUSIONS

A methodology for mooring integrity indirect monitoring has been here introduced. It is based on mean position of the floating device, as carried out by RLS, with the difference that it does not need any environmental monitoring system. In exchange, an offline computation of the design displacement contours and those with the corresponding most relevant failures are required to be carried out with a numerical model. In this paper a case study based on the MARMOK-A reduced power device is presented. The proposed methodology is applied to broadcast alerts suggesting visual inspections to prevent further failures, connection lines failures (from the device to the mooring cell), catenary line failures and, drifting device. One hour and 5-day mean positions are applied to avoid false alerts based on rare events, i.e. unusually large current with no mooring failure, so that they can be distinguished from each other. The drawback of not enabling the detection of leeward lines is not yet solved, however, weak currents will make the device take positions pointing at the leeward failures and, probably, suggesting visual inspections.

ACKNOWLEDGEMENTS

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