Virtual Prototyping for Safer Product Development: integrated marine propulsion and steering system example

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Abstract

ZF Marine's POD Drive is an innovative marine integrated propulsion and steering system with increased performances compared to traditional shaftline systems in term of efficiency, manoeuvrability, ease of control and dimensions. The system comprises an inboard/outboard transmission and double motor electrical steering pod system equipped with counter-rotating propellers. An electronic control system manages one or more PODs and each of them rotates independently, depending on maneuver typology, speed and turning circle.
Due to their manoeuvring orbital functions¸ operating conditions and under hull position, underwater impact risk assessment is demanded as important safety design requirement.
To decode any potential impact scenario into its design specification is a technical challenge concerning the capability to predict structural consequences. A new design methodology, that incorporates statistical approaches to investigate non deterministic factors that affect design impact conditions (e.g. impact velocity and angle, debris mass and stiffness, etc.) and Virtual Prototyping tools is developed to increase safety reliability of the design choices respect to accidental underwater impacts. Sensitivity analyses, parametric numerical models with increasing complexity and different simulation methods are employed during design process to design different sacrificial components able to break or to shear below the hull for minimizing damage to POD system or to the primary boat structures. Complete 3D numerical simulations are performed through LS-DYNA and full scale experimental tests are carried out either to validate design process and numerical models or to compare numerical and experimental results.

Introduction

ZF Marine's POD Drive is an innovative marine integrated propulsion and steering system with increased performances compared to traditional shaftline systems in term of efficiency, manoeuvrability, ease of control and dimensions. The system comprises a an inboard/outboard transmission and a double motor electrical steering pod system equipped with counter-rotating propellers (cfr. Figure 1). Its rating is 882 kW at 2300 rpm. An electronic control system manages one or more PODs and each of them rotates independently, depending on manoeuvre typology, speed and turning circle.
Due to their manoeuvring orbital functions¸ operating conditions and under hull position, underwater impact risk assessment is demanded as important safety design requirement: any accidental underwater impact, either during navigation with floating obstacles or during mooring manoeuvres against underwater wharf parts, could have critical effects on ship structure if it is not considered. The main risk that should be avoided is a serious damage or a leak to the hull at

pod attachment zone. Decoding of any potential impact scenario into its design specification is a technical challenge concerning the capability to predict structural consequences. Impact speed, obstacle mass and stiffness, navigation conditions, etc., are crucial parameters for classifying design loads and requirements.

This kind of occurrence could be defined as an unwanted and unforeseen event with extreme conditions, high impact energies and potential elevated risks for crew and passengers. The prediction of the impact scenario is a qualitative, quantitative, time-sequence-based description of the probable incident, identifying key aspects that characterize the event and differentiate it from other possible situations. A new design methodology, that incorporates statistical approaches to investigate non deterministic factors that affect design impact conditions (e.g. impact velocity and angle, debris mass and stiffness, etc.) and Virtual Prototyping tools, as finite element method codes, is developed to increase safety and reliability of the design choices respect to accidental underwater impacts. This multi disciplinary and multi objective computer aided design procedure is managed by modeFRONTIER platform: it allows the organization of the software and permits the management of the entire investigation process comparing and combining different approaches to amplify their own capabilities for reliable predictions.

Complete 3D numerical simulations are performed through LS-DYNA to analyze phenomenon effects and system structural response using parametric numerical models with increasing complexity in different impact conditions. Simplified fem models are developed to design sacrificial components, as specific bolts, using LS-DYNA load impact results. Sensitivity analyses are employed during design process to highlight the correlations among the POD system dynamic response (accelerations, reaction force, breaking of sacrificial bolts,...) and the most important impact factors (velocity, masses, material properties, part geometries,..) assessed within the POD FE model. The sensitivity analyses have been carried out by coupling the LS-DYNA FE model into modeFRONTIER platform and taking advantage of its mathematical and statistical tools. Scope of the process is to design different sacrificial components able to break or to shear below the hull for minimizing damage to POD system or to the primary boat structures and to increase the global product safety.

Finally full scale experimental tests are carried out either to validate design process and numerical models or to compare numerical and experimental results.

Figure 1 – ZF Marine POD 4000 Series

Numerical models

The first numerical model is made to perform various preliminary analyses in order to understand the dynamic response of the principal structural elements of the POD subjected to underwater impact phenomena and to analyse the effects of different impact conditions.
For the preliminary analyses a full LS-DYNA 3D model is used, which has been explicitly created to represent the whole POD structure from the impacting nose to the boat frame connection elements (cfr. Figure 2), containing also the complete transmission system composed by different rotating elements that transfer, through the gears, the rotational speed from the engine shaft to the external shafts (cfr. Figure 3).

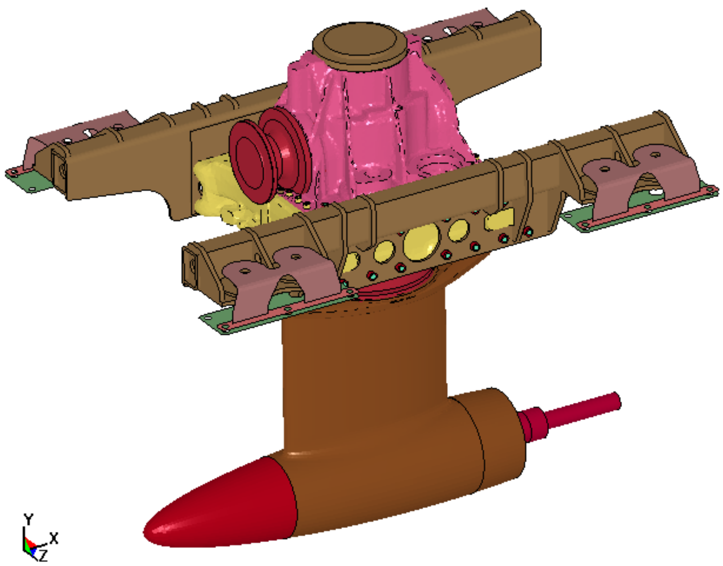

Figure 2 – Preliminary LS-DYNA 3D model

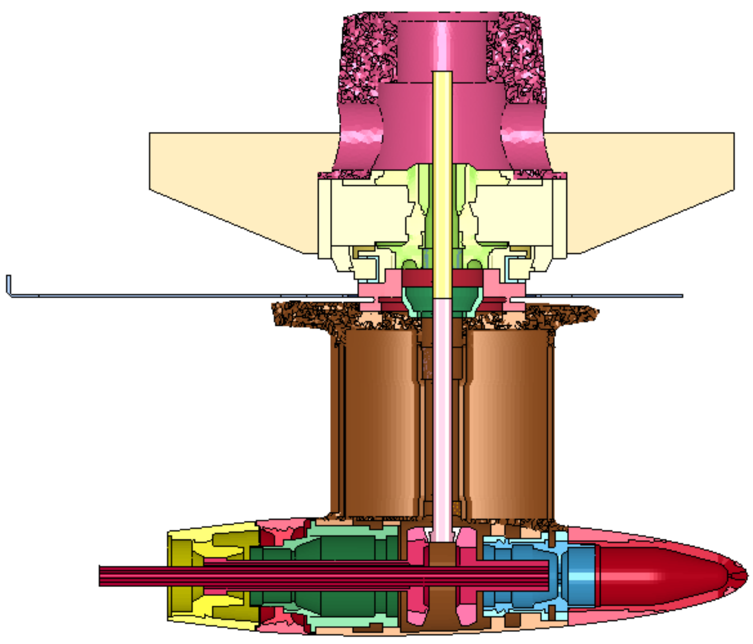

Figure 3 – Preliminary LS-DYNA 3D model – Internal transmission system elements

Simplified beam element models are created to investigate the effect on the whole system of specific principal element of the steering gear box. For example the bearing gap effects are analyzed respect to the horizontal and vertical reaction momentum (cfr. 1 and 2 reaction forces in Figure 4).

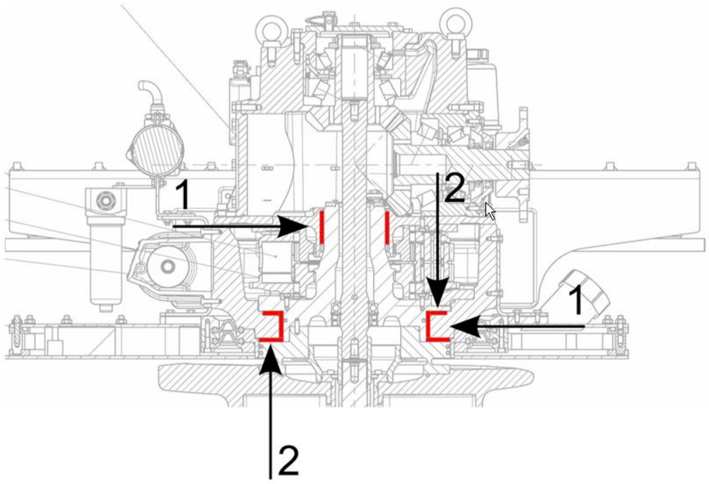

Figure 4 – POD System – Section view

Constructive tolerances, bearing gaps, mechanical flexibilities, inertia forces are some parameters considered to explore either system dynamic response behaviour or the simulation model accuracy using 3 simplified model different configuration (cfr. Figure 5): e.g. first configuration model is adopted for analyzing mutual effect of reaction bearing forces and steering gear box stiffness on global structure flexibility.

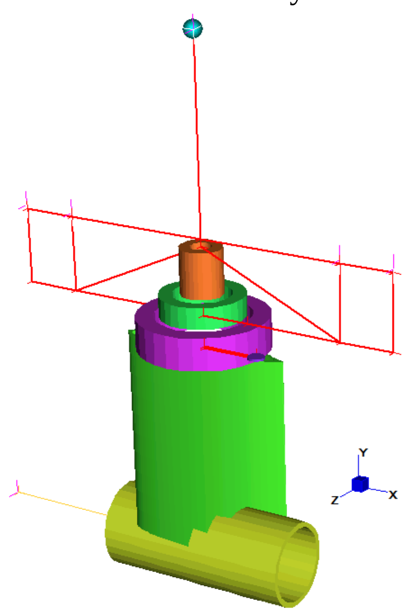

Figure 5 – First configuration of the simplified element model

A more detailed full LS-DYNA 3D model takes into account also other certain elements (e.g. different preloaded connection bolts between system parts, cfr. Figure 6) for a better numerical model representativeness.

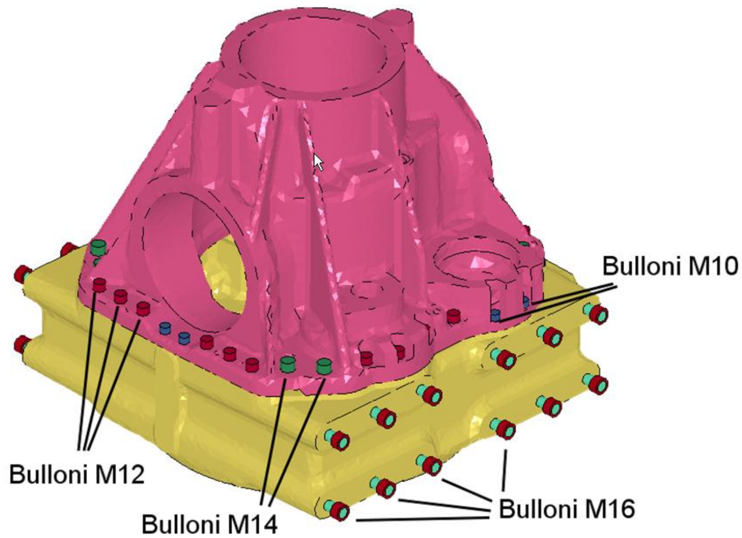

Figure 6 – Connection bolts models

A detailed LS-DYNA 3D model with increased complexity was employed either for underwater impact events or for full scale experimental test simulations [1]. Experiments are implemented placing POD system on a railway wagon through a special support designed to simulate the usual boat attachment and impacting it at different speeds against a steel portal frame designed specifically to perform all tests (cfr. Figure 7).

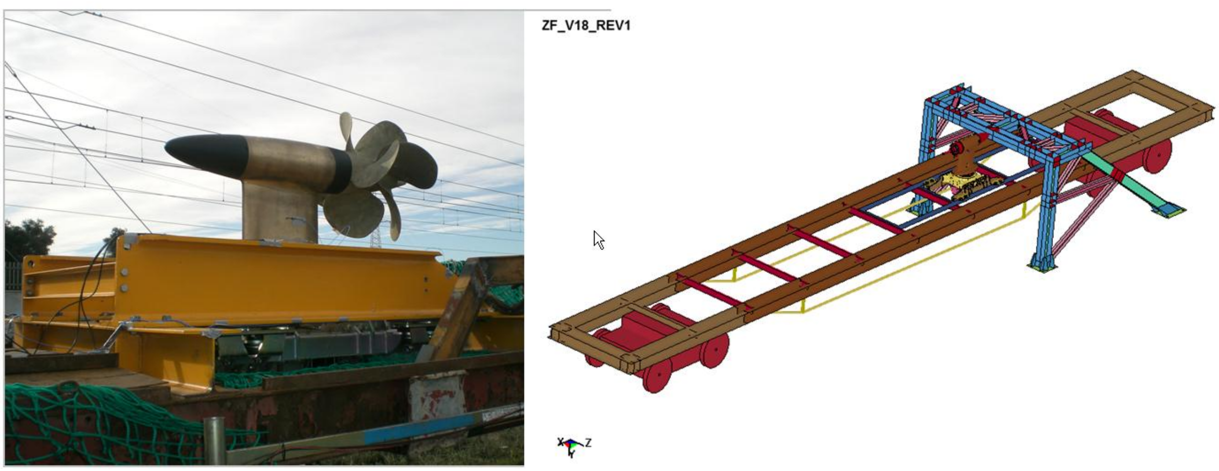

Figure 7 – Experimental set up and detailed numerical model

Procedure, Methods and Tools

All activities are developed in complete collaboration between and ZF Marine technical groups: specific technical competences and experiences are combined to maximize collaboration results.
In order to increase the safety of ZF products an innovative computer aided multidisciplinary procedure is developed taking advantage of statistical approaches (to investigate non deterministic factors that affect design impact conditions), numerical methods (to represent dynamic system behaviour with physics based simulations), experimental evidences (to validate numerical models and simulation results) and advanced tools for data mining (to perform

sensitivity analyses and correlations among the POD dynamic response and the most important parameters). The commercial multi disciplinary and multi objective optimization and design environment modeFRONTIER is adopted for the coupling of the different approaches and for processing data results. Moreover its specific features are exploited to perform sophisticated statistical survey, to adopt response surface methods, to execute multivariate analyses and to carry out data mining studies for multi criteria decision making.
First of all, a risk analysis able to identify potential underwater impact events and their specific concurrence probability is done. Four different floating movable obstacles (tree trunk, gas tank, oil barrel and standard container) at 3 diverse velocities and two impact velocities vectors against fixed concrete mooring wharf compiled event risk matrix.
A number of LS-DYNA simulations is run for correlating risk and impact effects. Moreover load predictions to define requirements for designing different solutions for the sacrificial element are extracted. This first round result indicated sacrificial bolt flange as more reliable solution than others considered. The following step of the design procedure can be easier described starting from the modeFRONTIER workflow (cfr. Figure 8).

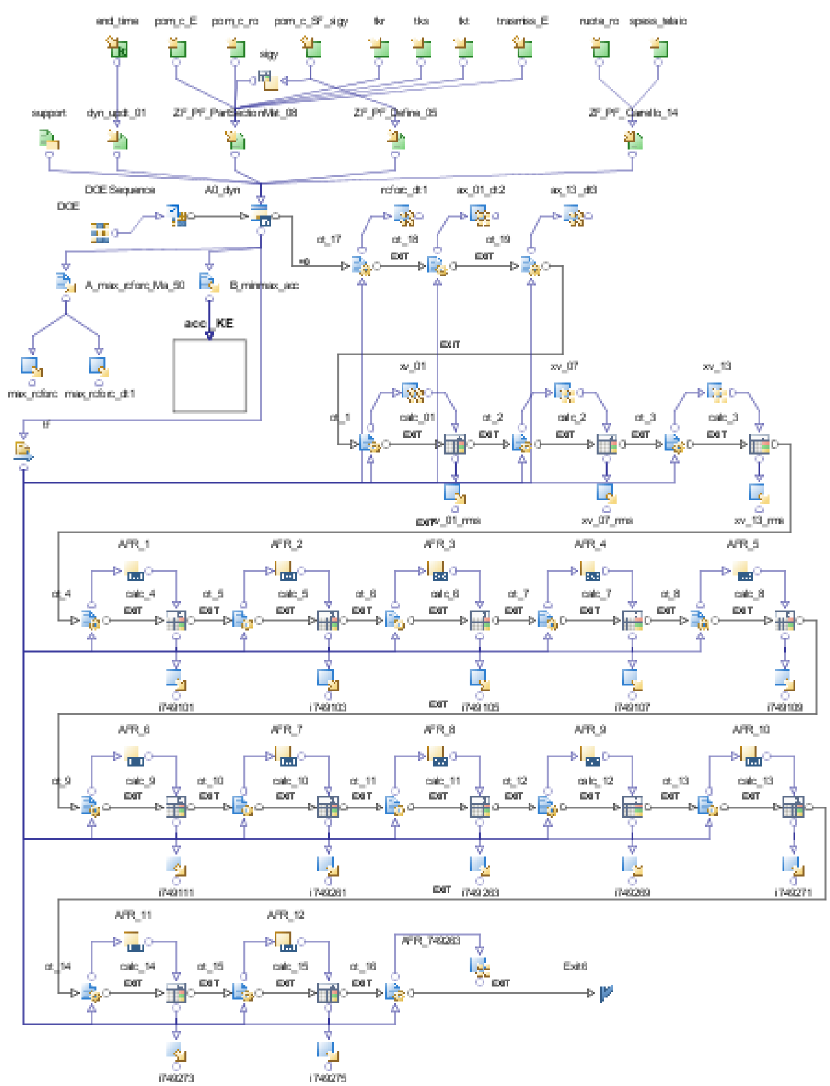

Figure 8 – modeFRONTIER workflow for ZF Marine's POD Drive design

The logic behind the workflow is to modify "with intent" suitable variable input parameters, the so-called "nodes", with the aim to evaluate how the system responds in terms of changes of the output variables. The background methodology, to decide how to modify input variable respect to the outputs, maximizes the knowledge gained from all data and relevant qualitative information to permit to understand which the most important design variables are, how to reduce the variables space and to eliminate redundant observations to reduce computational time and numerical simulation resources. These techniques allow to extract as much information as possible from a limited number of test runs. For POD design the chosen input variables are highlighted in Figure 9 and they refer either to design items (to explore meaningfully the design space) or to undeterministic parameters (to analyze effects depending on statistical factor); basically they refer to the material properties, bearing stiffness, and frame thickness, etc. Other no physical parameters (i.e. "trasmiss_E" in Figure 9) are entered to comprehend how the impact wave propagates through POD transmission system and influence the structural response.

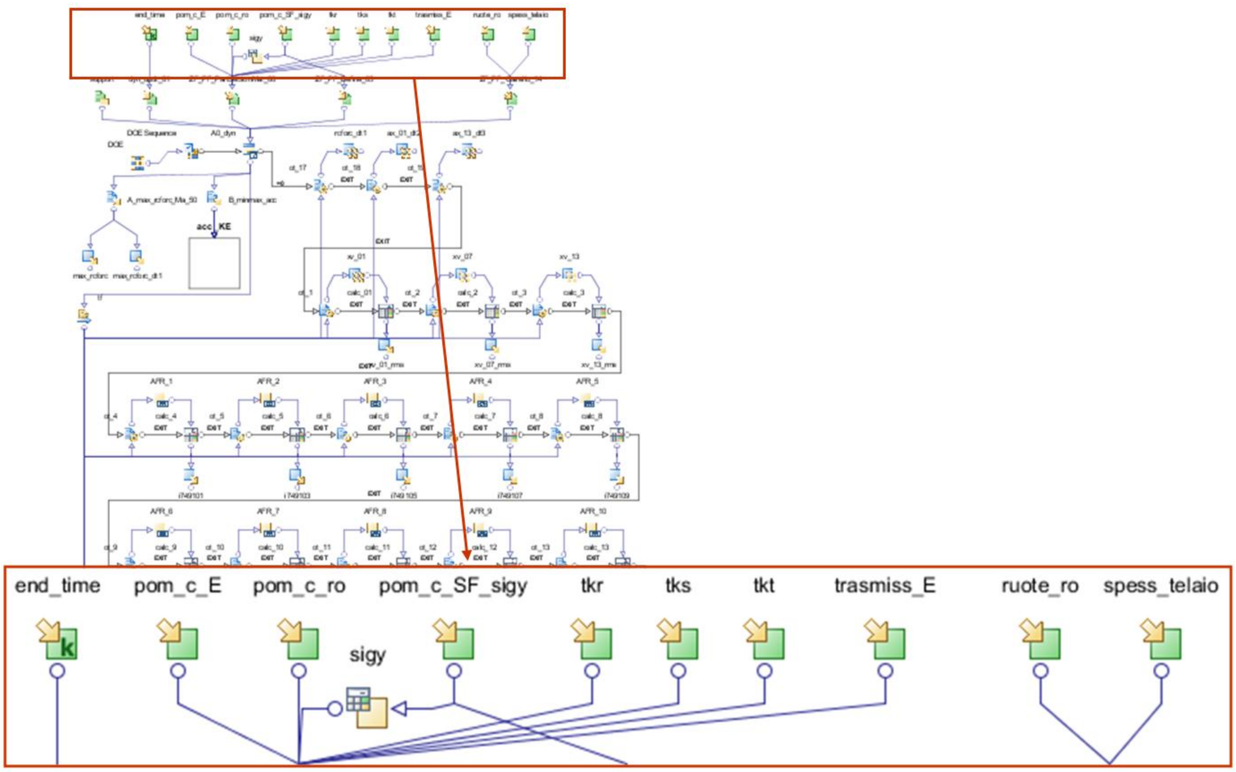

Figure 9 – modeFRONTIER workflow input parameters

LS-DYNA simulation model has been parameterized in respect of the input variables so that modeFRONTIER could automatically update the corresponding values, once the configurations to be investigated are established. The configurations to be evaluated (i.e. input values sorting) are stored into the DOE (Design Of Experiments) support file. The Reduced Factorial (RF) algorithm has been exploited to generate the DOE population, since it is able both to reduce the number of configurations and to preserve the data quality.

The POD dynamic response has been finally assessed by monitoring either scalar (99 values) or vectorial output quantities (7 vectors) according to the following collection:

- 78 accelerations (min, max in respect of fixed time frames) measured @ 11 accelerometers belonging to system;
- 4 kinetic energies (min, max) @ 2 different positions;

- 2 reaction forces (max value evaluated in respect of two different time frames) related to the impact force on the POD nose;
- 12 impulses of the axial resultant forces related to the sacrificial bolts;
- 3 nodes velocity RMSs (Root Mean Square of velocity) measured @ 3 accelerometers;
- 7 vectors with the aim to assess graphically the quantities trend.

The investigation of the impact phenomena within reduced time frames has been aimed to get values able to characterize the POD dynamic response in a more accurate way, since such values are strictly correlated with the POD local behaviour. The time frames have been chosen taking into account the sound wave propagation due to the POD impacts: being constant either the distance between impact point and accelerometers positions or the sound wave speed, it has been possible to evaluate results at different time frames (e.g. time needed by the sound wave to pass through the POD nose length, characteristic time to get broken the first sacrificial bolt, etc.) for a meaningful data mining. For any experiment a full 3D LS-DYNA simulation is performed using SMP solver (cfr. Figure 10).

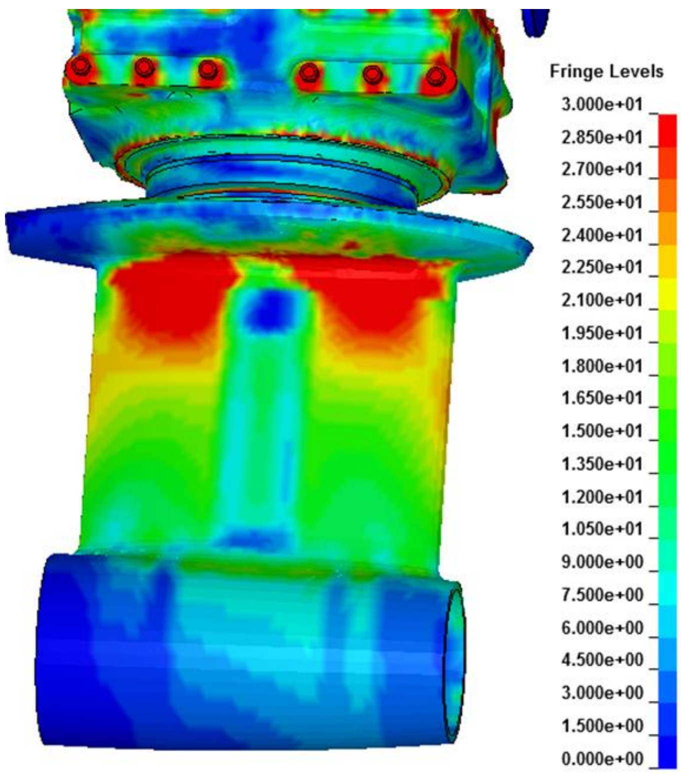

Figure 10 – 3D LS-DYNA simulation results - Von Mises stress results on POD principal parts

Results

First of all a sensitivity analysis has been built up according to the investigation of the relationships among the input and output variables. This task has been performed by exploiting suitable modeFRONTIER data mining tools, like correlation matrices, scatter charts, parallel axes charts. Such tools are able both to provide numerical values to quantify the correlation among variables and to realize how an input variables set influences a well established system. The input variables not affecting the output ones in a significant way can be dismissed in the following design steps. Moreover a comparison of the physical trends of the monitored quantities with the aim to get the absolute behaviour of the system performance permits the selection of the more appropriate design configurations. With the aim to extract the linear correlation between variables, a “Correlation Matrix” has been used: a value equal to +1 (-1) denotes a full direct (inverse) correlation, while a low absolute value means low correlation (cfr. Figure 11).

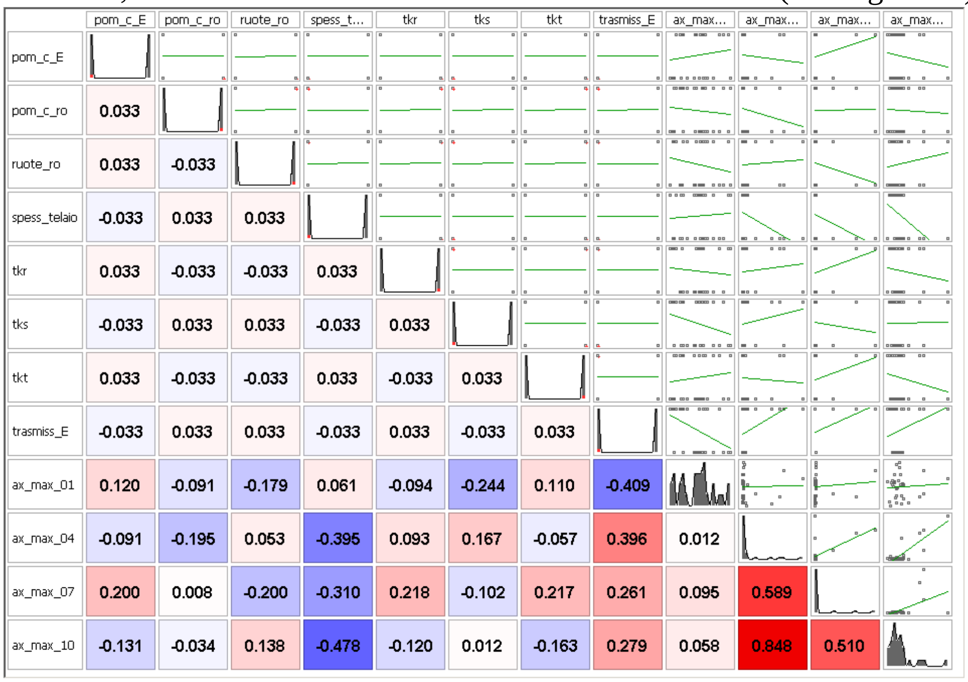

Figure 11 – modeFRONTIER Correlation Matrix

The correlation matrix analyses highlight not easily predictable correspondences and indicate where investigation should be focused on: e.g. the sorting of nose material young modulus and bearing translational stiffness values involve the formation of 3 clusters (i.e. three main groups in which all the solutions are included). This distribution takes into account the physical trend of POD impact reaction force: with the higher young modulus, just 2 force values are feasible (cfr. Figure 12) and 3 different curves families can be identified for every single design cluster (cfr. Figure 13).

With the aim to realize the dynamic behaviour of the sacrificial bolts and especially to identify the input variables affecting the bolt forces (cfr. Figure 14) for a reliable design of the system, considerations based on these kind of information are made.

The design process has defined the sacrificial bolt typology, number and position in order to be able to break following an expected serious impact with floating underwater obstacles or fixed concrete wharf to avoid serious damages or leaks to the boat hull at pod attachment zone.

Results from full scale experimental tests, carried out at different impact velocities against a steel portal frame designed specifically to represent the worst case scenario, demonstrate the high POD system safety level and validate the whole design process based on an innovative computer aided multidisciplinary procedure.

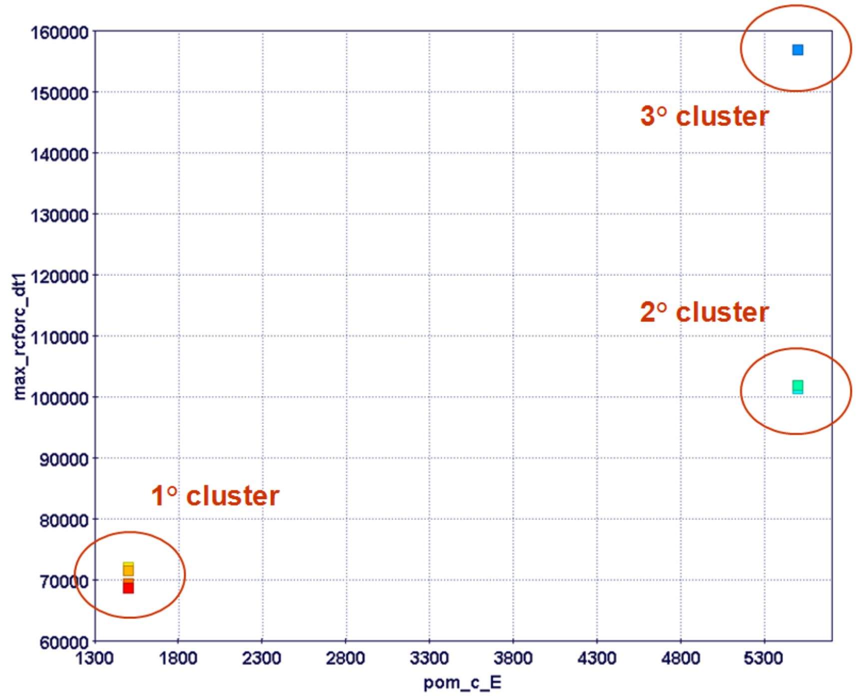

Figure 12 – Sensitivity Analysis: max impact force vs nose young modulus

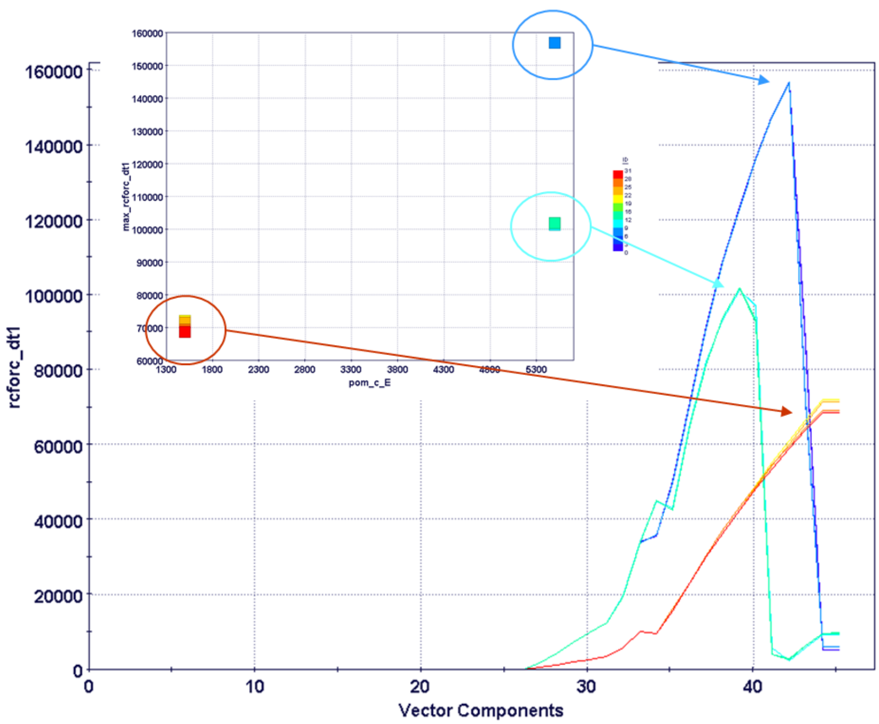

Figure 13 – Sensitivity Analysis: impact force vs nose young modulus

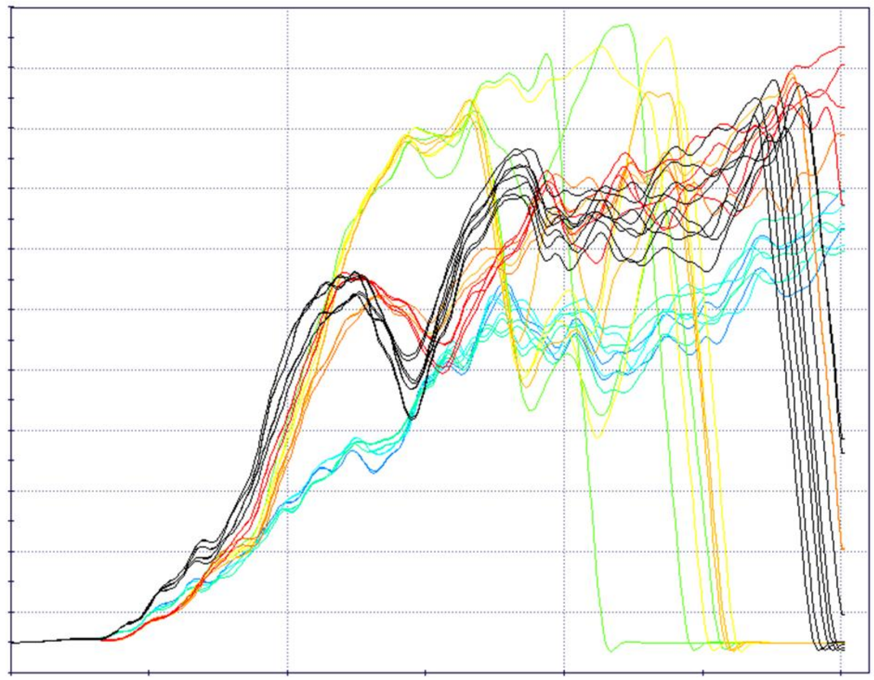

Figure 14 – Sensitivity Analysis: sacrificial bolt forces vs time

References

[1] – Numerical and experimental evaluation of structural impact behavior of large pod for nautical applications – G. Scarselli, P. Cavaliere, D. Sacchi, M. Perillo, V. Primavera – EnginSoft International Conference 2011