Quality Control of PipeLay and Riser Dynamic Analysis

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***Abstract**: The increasing frequency in the use of Engineering Criticality Assessments (ECA) to determine weld quality in the installation of offshore pipelines and risers has put an increased focus on the importance of accurate predictions in dynamic stresses during installation and service. Over-predictions impose constrains to the installation campaign with high cost and safety implications. The response predictions of a pipe profile suspended from a vessel in random sea state with environmental loading and interaction with the seabed is a complex nonlinear problem. From a dynamic structural in place perspective the pipe catenary presents a near continuous spectrum of frequencies and modes of vibration. This has important dynamic numerical and structural relevance, implying excellent resonance transmissibility for any input forcing oscillation frequency. The numerical work used to represent the physical structural system present a tendency to amplify its response. It is well diffuse in the analytical community that common dynamic software present unreasonable high dynamic amplification factors. This work proposes an Abaqus based approach to calibrate appropriate damping. It is clear that the generalized effective parasite forces acting in phase with the velocity of the structure is key to the ultimate response in the dynamic analysis. When a simple cantilever beam is left oscillating to rest after an initial deflection in water or air medium, many of the software would over predict the total number of oscillations. When a pipe was dropped to rest on the seabed many software unrealistically counted several bounces indicating not accurate pipe soil dynamic interaction set up. The methodologies and "tools" set forth in this work are extendable to a variety of mechanical subsea components. The predictions reflected a rigorous process involving several iterations to validate predictions with numerical work reflecting a true of depiction of pipe response. This paper suggests essential quality control methods, used to debug dynamic lay predictions with a view to increasing Project offshore workability and ultimately Project profitability. This is greatly needed to make deep water and offshore oil and gas cost competitive with lower cost onshore reserves.*

***Keywords**: Design Optimization, Dynamics, Experimental Verification, Low-Cycle Fatigue, Multi-Body Dynamics, Damping, Soil-Structure Interaction, Vibration, Riser, Pipeline.*

1. Introduction

The use of Engineering Criticality Assessments (ECA's) to qualify acceptable defects in a welded facility can result in lower fabrication and installation cost for the project compared to empirical "workmanship" acceptance criteria. This accurate method demand correct prediction of dynamic (fatigue) stresses during facility installation and service. Offshore construction and installation of a pipeline (or Deepwater riser) requires the pipe to be retained at the surface by a large vessel. The suspend pipe can be laid to the seabed following the path of either "S-Lay" or "J-Lay" configuration. The "S" configuration resulting in a "over bend" curvature over a series of rollers on the installation vessel to control to the profile (hence strain) to a downward trajectory where after it progresses to the seabed where it goes into the sag bend common with the "J" lay configuration. The sag bend curvature leading to the touchdown of the pipeline on the seabed is controlled by the axial horizontal tension applied by the installation vessel and for slender pipe where stiffness is negligible compared to the suspended weight, is usually approximated using a classical catenary formula. Where an ECA is used, a key requirement is that the dynamic load exposure of a given section of pipe at sea is limited in time window in order to not accrue fatigue damage that impacts the integrity of the facility during its design life. The motions of the vessel impose pipeline oscillations that relate to safe sea state allowable during construction. Key parameters are the location of the pipeline departure with respect the vessel center of motion as well as the pipe interaction with the highly specialized handling equipment. Of similar nature is the riser design where the pipe structure is permanently connected to a floater. In this circumstance the riser structure must withstand the floater imposed dynamic motion for the entire life of the system in accumulation to the other environmental loading demands. The installation of a pipeline may entail the installation of inline structures or end fittings that create additional load conditions experienced by the pipe as it is laid. This increases the complexity of the dynamic model and increasing the need for quality assurance/control methods to guarantee a realistic "experience" is predicted. The offshore oil and gas industry demand for bespoke dynamic analysis for each pipeline/riser installation has led to software applications specific to the industry developed for the purpose of making the complex analytical process as simple as possible to maximize its utility for average Users. The industry specific software use routines that facilitate convergence and User satisfaction, at the expense of some simplicity and may not accurately predict the true outcome.

Notwithstanding, any design software, in any industry, that; consistently predicts a conservative outcome, always errors on the side of safety, that does not result in an uneconomic outcome for the Project on which it engaged, will be embraced by the Project Manager and the industry at large.

This paper present means to use the Abaqus suite of software to provide quality assurance and quality control of dynamic analysis of offshore pipelines and risers, to ensure a valid and most cost efficient design is realized by a Project.

In the case of offshore pipeline and riser installation over-predictions impose operational weather constraints on the installation campaign with high cost and safety implications associated with the increased length of the offshore campaign. This work proposes an Abaqus based approach to verify appropriate damping and discusses modeling routines and output post-processing methods that should be used to assure the quality of the results of a dynamic analysis of pipeline or riser system.

2. Analysis

Global and local models are used for the design of pipeline and riser installation. Global models include end constraints and the entire pipe profile including any given inline or end structures. The level of complexity of the global model is limited by time (cost) devoted to the effort and the desired specificity of the model output.

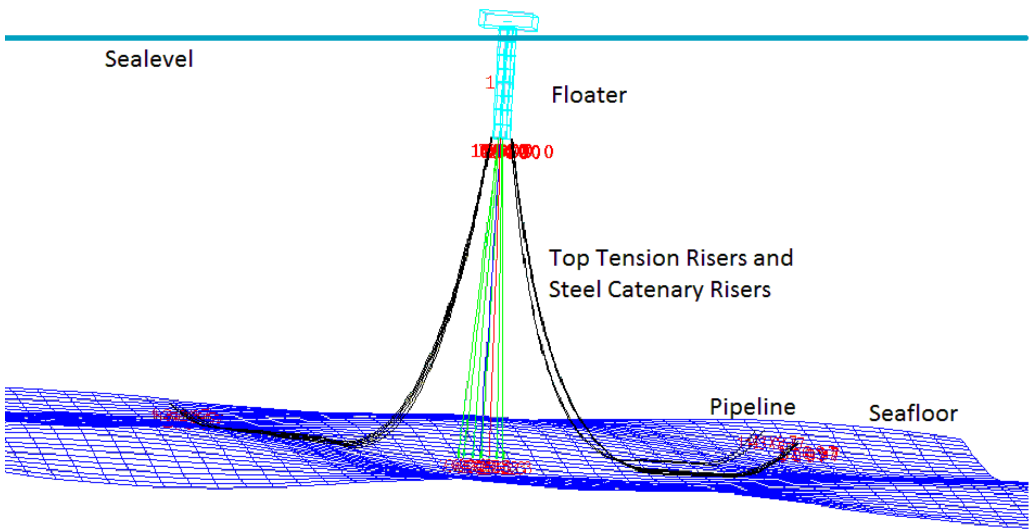

Figure 1. Riser Global Model (Abaqus/CAE+Abaqus/AQUA)

Modeling experience dictates the approach and procedures for an efficient simulation of pipeline and riser systems. Experienced analyst understands where increased detail (computational) effort yields no material change in the model results. In any case the quality of a global model can be validated by sensitivity checks involving permutations in input ranges, model element sizes and time steps. Dedicated models can be built to specifically study a part of the system to analyze a single component once the loading/motions of the component have been obtained from a vetted global model. The objective of this work is to focus more on the global time domain dynamic analysis of a pipeline/riser structure from surface to seabed. The pipe structure system presents numerous other design complexities that are not specifically addressed in this paper, such as vortex induced vibration, resonance by slugging to name a few. The model must address many loading mechanisms: environmental loading (waves and currents), driving motions and related loads imparted by the vessel/floater suspending the structure in combination with the buoyancy, drag and inertial forces over the length of the pipe structure from the seabed to surface.

Establishing the environmental and vessel/floater motion input is a blend of deterministic and stochastic loading conditions. These conditions often occur simultaneously and for a new design or a proven design in a new location, are mainly forecasts. A time domain dynamic analysis is conducted utilizing nonlinear finite element solver. The challenges of the structural problem solved by the finite element approach are multiple for these models. Firstly, unlike most structural problems where the loads are applied in the un-deflected configuration, risers and pipeline models must capture the consequences on loading due to the large deflection and deformations and multi-step sequences of boundary conditions. Combination of tension and bending, torsion. Non correlated, torsional, axial, flexural stiffness, compression behavior and inertial property of the deforming body (rigid pipe, pipe-in-pipe structures, flexible pipe, umbilical, cable). With the pipe sizes and unit weights of pipe in deepwater, the behavior of the pipe becomes less impacted by it stiffness and approaches the behavior of an un-stiffened chord in suspension. A Global Riser or Pipeline Installation Model offers more clarity and reference in regard to the spatial azimuthal distribution or riser, pipeline and barge or floater structure. The more carefully the model is prepared the more useful to identify clashing and other interference problem between the structures as well as coupling of loading conditions. For example, as in following figure the coupled model of an over bend stinger structure supporting rollers interacting with the pipeline.

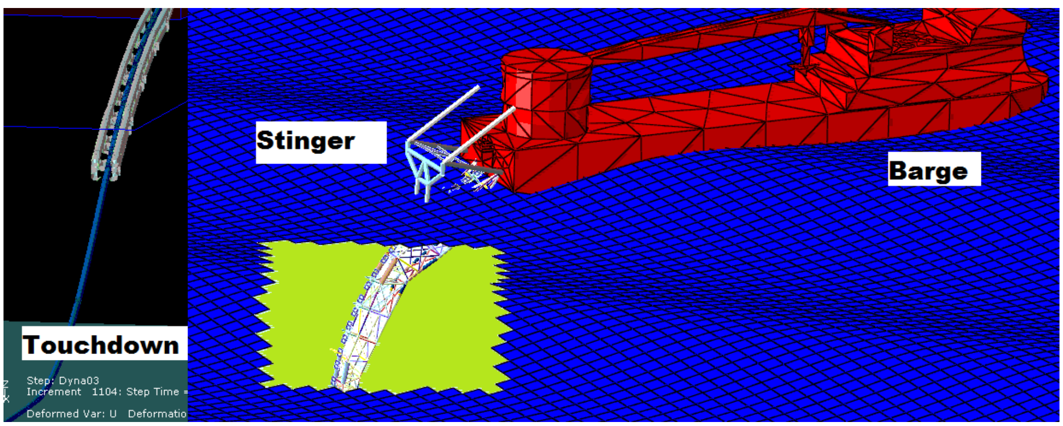

Figure 2 Pipeline Installation Global Model (Abaqus/CAE+Abaqus/AQUA)

These structural systems and their interaction with the environment and seafloor involves the modelling of several sources of irregularities ranging the digital terrain topography, manufacturing out of straightens, presence of ancillary structures such as pipeline terminations, valves, bending restrictor and multi-tube arrangements.

3. Quality assurance of Dynamic Amplification

During the Project engineering, global dynamic analysis will be used to predict the dynamic stresses (or structural metric) in excess of the static analysis. This will be done for the installation phase and the in-situ life of facility. The ratio between static and dynamic stresses is known as the "dynamic amplification factor" (DAF). The DAF is often used in the ECA to factor various loading scenarios/cases as opposed to completing specific dynamic analysis for the spectrum of load conditions modeled in a stochastic fatigue analysis. Experience and many Codes recognize a DAF of the order of 1.2 as the most likely to be seen during installation operations in conditions likely to be engaged by a prudent pipe lay contractor or the Insurance Underwriters Warranty Surveyor.

A project analysis that predicts an installation DAF exceeding these levels will likely dictate permissible installation weather conditions that have negative cost and/or schedule impacts to the Project. This papers considers how the results of a dynamic analysis can be interrogated for errors before engaging in an independent review with a more thorough modeling of the system using Abaqus.

In the writers' experience, where excessively high DAF predictions were discovered by this means of interrogation, the predictions were subsequently confirmed invalid by subsequent analysis using Abaqus software to provide dynamic predictions in line with experience. The sequence of verification steps is outlined in the following sections and involves clarifications on kinematic analysis, input and signal validation, understanding of modelling limitations, soil behavior, modal analysis, resonance and energy balance approaches, continuity of derivatives and calibration of damping with repeatable tests.

4. Loci analysis kinematic amplification (quasi-static analysis)

The dynamic amplification factor is a ratio of the time history maximum of a given selected structural quantity with respect to its value in static conditions. To validate a dynamic amplification, the first step is to assure the kinematic analysis of pipeline (quasi-static excursion) is quantified. There are instances as in figure 2 where the transformation of an input orbital motion pattern at the structure support, when projected kinematically (quasi-statically) at different location of the structure can have natural amplification. The example in the figure shows a driving motion in the form of an orbital vessel excursion "A" in surge or heave direction and its influence into a mid-point location motion "B" and "C" in two different profiles of a structure. For the structure configuration of B, the motion is amplified for the structure configuration of C, the motion is reduced. Plotting the quasi-static range of motion along the structure confirms the response of the exciting motion of the of the structure, absent the effects of any damping or inertial response on the motion. If the range of motion at a given point on the structure is significantly different and/or trends differently in a dynamic analysis compared to that of the quasi-static result, there is cause to believe dynamic model has inherent inaccuracy and should be further interrogated.

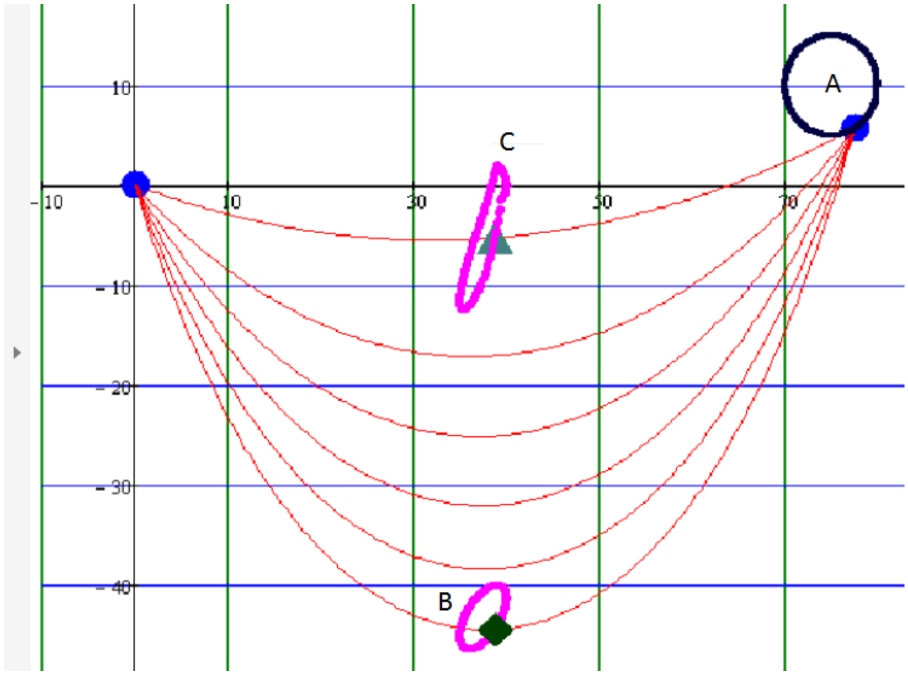

Figure 3 Quasi-static Analysis (Abaqus/Standard)

5. Input validation

How loads and driving motion is input is material to the quality of the results in a dynamic analysis.

The dynamic model of a suspended pipe must address force acting on the body as it moves. These forces vary depending upon the boundary conditions and damping force predictions used. Assuming a simple cyclic motion model, with time the dynamic forces on the body will produce a cyclical response. It is important realistic motion is vetted by experience personnel. Signal and statistical analysis need to be performed where time domain external input is used to characterize the motion of the vessel or the floater. Quality of the piecewise interpolation will significantly affect the desired results. Transient management is required when considering the transition to every boundary component and inertial forces. Initial transitory effects in dynamic could produce non physics, impossible frequencies. Damping alone is incapable to reduce the big-bang transitory which takes some time to relinquish. Amplitude and a study of time forces application require attention to assure the inertial body is merged in a dynamic field gently enough to minimize as possible inertial over-reactions. Amplitude curves and initial condition correctly orchestrated can minimize the transitory upset. The movement of suspended pipe touching down on the seabed results in a continuum of motion and forces with no sudden changes in movement or instantaneous load. In the choice of modelling care needs to be included in selecting installation versus in place modelling. Installation modelling begins with a straight pipe and several static steps are created to develop the body into a pre-stressed configuration that will then behave dynamically. There are different methods such as pick up from bottom or drop into configuration etc. Boundaries should be as possible replaced with actual modelling for example modelling pipeline and riser or a considerable extra length of pipe upstream installation touch down.

The numerical methods use to generate inputs (such as the six-degrees of motion input) need to address the non-commutative relationship of motions such that error in special positioning is not introduced. Pitch, Roll and Yaw are a non-commutative group and time need to be spent on conventions awareness to assure spatial positioning is represented with fidelity. An input selection before analyzing a problem is in many instances a pondered choice.

In summary attention shall be given to vetting of input motions, statistic quality of signal, management of transients, installation versus in place analysis, limitation of boundaries effects and awareness 3D motions and conventions.

6. Modelling

Using a finite element model to predict the forces and resulting motions necessitate segmenting the body in to discrete elements and evaluating the forces and motions in discrete time steps. The time step can result in “snap shot” changes. The segmentation of the body can result in sudden changes in shape. An example of this double complexity is that of modeling a rocking chair motion in time. A coarse segment model will result in a bumpy/jerky output motions similar to rocking on spokes of a wheel, not the continuous smooth motion of a rim. The segmentation of the pipe in space and its motion in time steps makes it very difficult to simulate the continuous reaction forces of the seabed. Contact conditions can result in negative damping (equating to the introduction of energy into a closed system) *(Hilber, 1977)* in many commercially available software. The running of the dynamic model with time results in the accumulation of numerical errors, some of which result in inconsistent behavior. Ignoring convergence tolerances can result in erroneous findings. General nonlinear dynamic analysis in Abaqus/Standard uses implicit time integration to calculate the dynamic response of a system. In Finite Element Modeling beside mesh quality metrics such as Warpage, Aspect Ratio, time discretization influences the long term results of time domain integration. In other words, it is fairly possible to model faithfully short term time domain performance. The longer the analysis time lapses the more challenging to match closely experimental results. This is because errors become more visible with time. Matching exactly is not the aim in general of the approach. The goal of most modelling is capturing a plausible behavior of the system. Accurate resolution of very high-frequency vibrations is usually not of interest in these applications. After a set of carefully planned loading steps the pipe is connected to the motion of the floater. The dynamic boundary condition can be applied simulating the offset and dynamic motion of the vessel. The Fortran subroutine DISP is used to achieve this input or a set of harmonic amplitude curves. Most material models that describe mechanical behavior are available for use in a dynamic analysis with Rate-dependent material properties for advanced applications. These also allow for further calibration with the introduction of Rayleigh damping.

7. Pipe Soil Interaction

A time plot of the acceleration of the forcing signal versus response acceleration at the touch down will manifest considerable numerical noise acceleration in the absence of correctly modeled damping. Soil is best modelled with Eulerian approach when considerable interaction and displacement occurs such as at the touchdown of the pipe on a soft seafloor. In global modelling parameters calibrated with experiments and Eulerian approach can be translated in Lagrangian taking great care to introduce attuned damping. The accuracy of the pipe lay dynamic model is very dependent upon the correct assessment of reaction forces with the seabed.

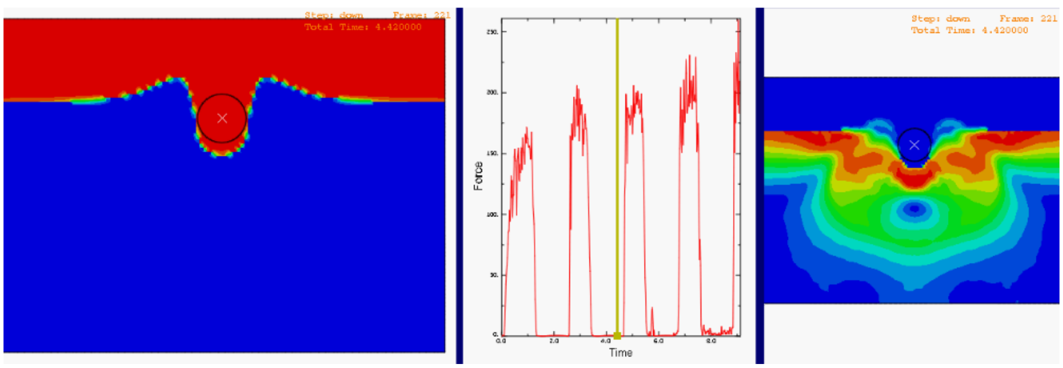

Figure 4 Pipe Soil Interaction Abaqus/Explicit (Eulerian approach)

This must consider the damping and the energy dissipation of the interaction. The first step to validate the soil stiffness model to confirm the embedding of self-weight with that which is typically witnessed. This for long undisturbed segment of pipes. The second validation is to confirm the trend of increased soil embedment where shear gradients arising from the sag bend curvature dissipate gradually from touchdown. The third validation is to build a simple model with the same general soil parameters setting and simulating the dropping a small segment of pipe free-falling a short distance say 1m. If rebound inconsistent with the soil condition occurs, this means the soil model is not valid. Such a generic model can be readily developed using Abaqus with the necessary parameters and then scaled to suit any given pipe configuration soil condition and be readily used as a tool to validate soil responses predicted by other software. A common fault found in many industry specific applications (with limited soil parameters input availability) is too much elasticity and too little damping. Any mistakes in assessing soil response and damping is exaggerated by the presence of in line structures. The model results, in the vicinity of the structure, can be validating using a similar approach to those described above.

8. Derivatives Continuity

Post processing of the analysis output can provide an assessment of the quality of the analysis results. The output data should be processed precisely with attention to significant digits as the response motions to be assessed are typically inches on typical model lengths of over a mile. The response output being validated should be plotted as a function of space across the pipe profile as well as in function of time. Comparing a string of values of adjacent nodes in at fixed point of time (spatial) allows relative change in the properties of the profile along its length to be assessed and confirmed as reasonable. The response property differentials between changes should be smooth and continuous, consistent with the actual structure and loading condition. Post processing the output signal with FFT (Fast Fourier Transform) tools in relation to the input signal allows discerning realistic responses from inaccurate ones. In this class of problems input signal are six different time domain histories of the floater or barge as sufficient length in window sampling time to project all the maximum interaction of all different signals is required. Unlike most industry specific software used to perform dynamic analysis, Abaqus allows many different output variables (including energies) across every position of the pipe mesh as well as the time discretization of a dynamic simulation. Each absolute variable can be numerically post-processed in relation to its gradients both in time and space.

The ability to interrogate signal differentials at higher orders using the output of Abaqus makes it easier to vet the results. However, this can be done with additional post-processing efforts for industry specific software. In the writer's experience dealing with false predictions of extreme DAF, the diagram of key macroscopic variable such as shear force or contact force with seabed presented several anomalies and too numerous discontinuities. The table below indicates typical cross-sectional macroscopic variables that can be derived subsequently from the node position.

Table 1

Relation to Displacement, Deflections actual profile	
Slope, Angle, Spatial Heading	GRADIENT
Curvature	GRADIENT
Bending Moment	Strain History or simple Constant for Elastic Field
Sectional Shear	GRADIENT
Distributed Load, Contact Load	GRADIENT

In summary this section recommends a careful review of the output thru instruments of mathematical analysis. These methods have proven to have found inconsistency in many simplified software's products and works. Fidelity of derivatives is a tool that can unmask with brilliancy numerical output products.

9. Modal analysis

The excitation of the body at or near one of its natural frequencies can cause a buildup in motion. The long freely suspended slender body has many modes of motion resulting in a quasi-continuous spectrum of frequencies. Modal analysis of the suspended pipe shows it has modes which differ by as little as 0.1 seconds in the first few hundreds modes, as such almost any excitation frequency could result in some harmonic behavior. Typical response analysis of a structure presents spectrum that have clearly separated frequencies and modes. Only forcing frequencies in close proximity with a natural harmonic will produce excitation transmissibility. The catenary structure present very close resonant frequencies and hence is both structurally and numerically susceptible of excitation in the absence of damping. This excellent resonance transmissibility for any input forcing oscillation frequency allows energy from the surface floater or barge to be transferred and accumulated with ease in other part of the pipeline catenary. In other simple terms whatever is your exciting source of motion to the system the system will find a couple of modes with a close enough frequency to become resonant energy accumulator. There is an important consideration: this is true in air and can easily be tested using a string model. This response is dramatically affected by the generalized damping. A structural system suspended in water experiences significant fluid drag and fluid inertia forces which impede both resonance transmissibility and dynamic amplification. Calibration of these sources of damping is paramount to getting a valid dynamic model. Calibration of the damping model can be done using generic structural models of pipe that can be readily scaled for any pipeline/riser analysis.

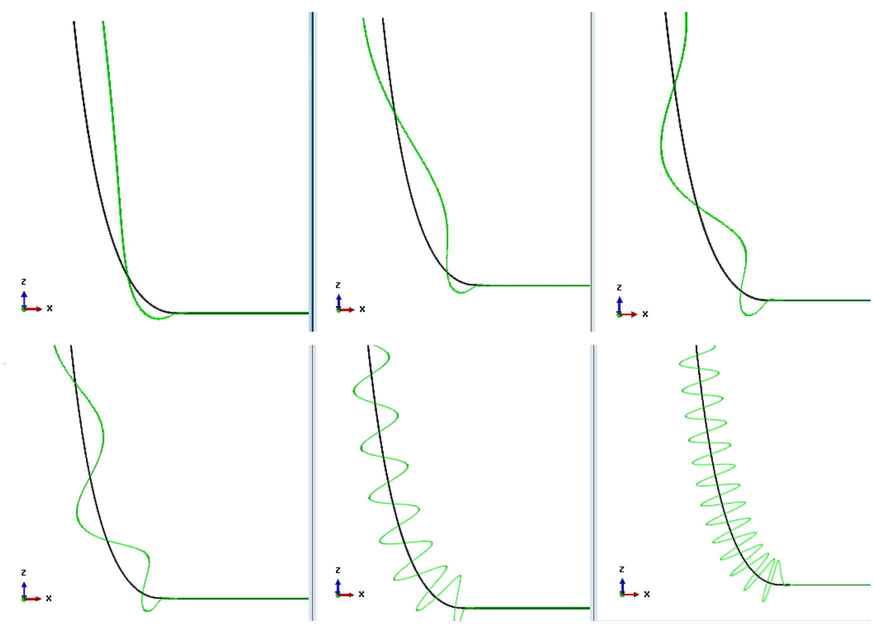

Figure 5 In Plane flexural modes (Abaqus/Standard)

Figure 5 illustrates some typical mode shapes of the tensioned catenary from the elementary to the more numerous in wavelengths. A selection is made of the one in the main plane of bending of the catenary profile.

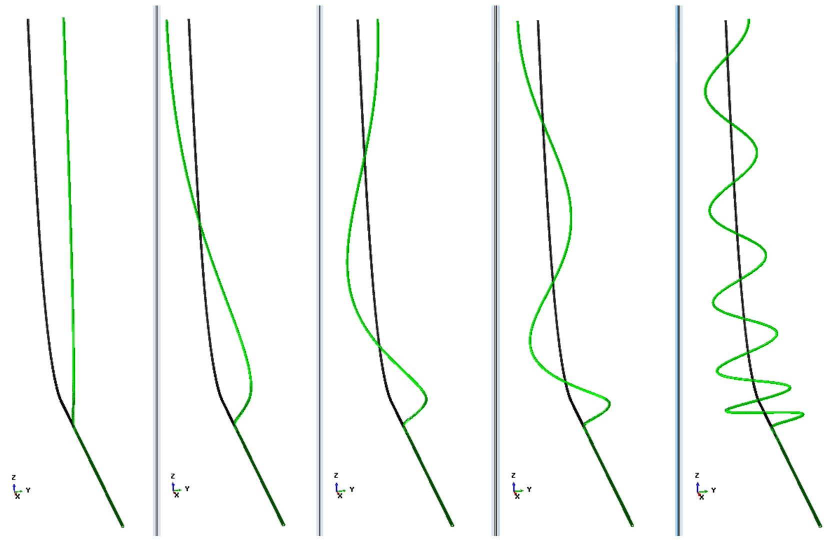

Figure 6 Out of Plane flexural modes (Abaqus/Standard)

Figure 6 illustrates some typical mode shapes of the tensioned catenary from the elementary to the more numerous in wavelengths. A selection is made of the one perpendicular to the plane of bending of the catenary profile. In summary a key step in the understanding of a dynamic time simulation is to enquire the modal behavior, energy sources, transmissibility across the structure, resonance, distributed and local dissipation

10. Validation Tests

The accuracy of the pipe lay dynamic model depends upon the proper assessment and application of damping forces over the full spectrum of the motion simulated.

A practical mechanical model is to simulate the restoration of a deflected pipe to its unloaded position. A proposed benchmark in this discussion is to rank the damping to the time to rest in air and water of a simple cantilever beam left oscillating after an initial deflection.

In one Project where excessive DAF was predicted the analyst was asked to use the same damping model parameters the predict the restoring motion time plot of a deflected fixed simple cantilever beam, in essence a classic ‘tuning fork’ analysis. The errant model predicted 80% of the full deflection after 1-hour in air and 20% of deflection after 5 minutes in water. It was recognized the result greatly over stated the time required for the motion to decay, indicating the model grossly underestimate the damping effects of air and water. Numerical models that fail to abide by first principals will be prone to infidelity.

Calibration of damping is needed to accurately predict energy transmissibility and dissipation. The calibrated model will satisfy system energy balance. First principals dictate that parasite drag forces act in phase with the velocity of the structure. These drag forces affect the response of the structure and any error in these drag force predictions will be compounded. The variable that most affect these effects are the molecular friction of the fluid often simplified as viscosity that is highly variable in temperature and also in pressure. With pressures ranging to hundreds of bars in deep water cold temperature viscous parasite forces are considerable and will inhibit large modal shape of deformation to be activate.

An experiment was conducted using a small steel [4.7ft 5/32 in. diameter] pendulum beam with precise properties and a small 3.78 ounces' lead oval mass. This was deflected to rest in air and in a 4ft deep water tank filled at 2 different levels. It can be seen from the following figures how the inertial and drag presence of the water dissipates the simple pendulum beam energy motion.

Figure 7 Flexural Pendulum in water tank arrangement

It can be seen from the following how the presence of the fluid inertia and drag dissipates the motion effect. The counting in table 2 and figures 8, 9 illustrates the matching with the Abaqus software.

Table 2 Observed Pendulum Experiment: Motion To Rest

Test	Cycle Count	Time [s]	Tank
1a	107	240	Air
1b	109	244.5	
2a	97	217	Water Half Filled
2b	96	214	
3a	19	42	Water Full
3b	18	40.25	

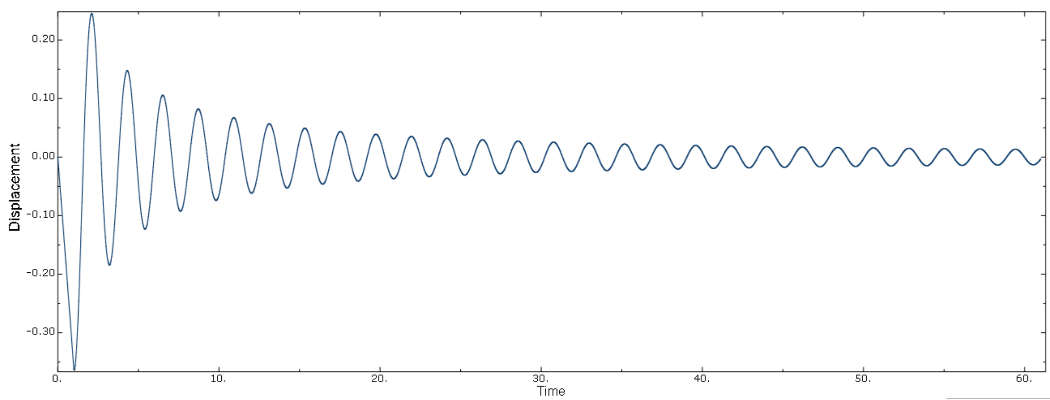

Figure 8 Abaqus Simulation Pendulum [displacement=m] decay in water [Time=s]

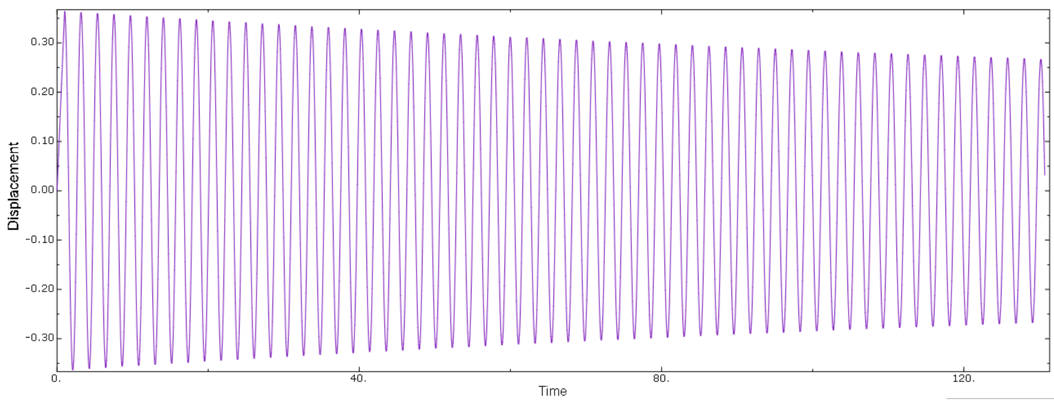

Figure 9 Abaqus Simulation Pendulum [displacement=m] decay in air [Time=s]

11. Conclusion and Recommendations

The increased use sophisticated dynamic models with the goal of achieving the best possible Project solution must be done with the understanding that models are complex. It is unreasonable to expect that modeling of complex systems can be practicably done to absolute precision. It is reasonable to expect that any dynamic model produces results which are consistent with real experience and observations in nature. In the offshore construction industry, the use of complex dynamic models with the goal of improving the Project outcome can have the opposite effect if false predictions result in suboptimum decision making. The above discussion outline methodologies and analytical tools that can be used to vet the results of dynamic models on any software platform.

The Abaqus platform is easily configured to provide outputs that be readily vetted for accuracy. The platform can be used to build generic models to verify the damping models produced by other software platforms.

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