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USE OF HYDROELASTIC ANALYSIS FOR VERIFICATION OF TOWED EQUIPMENT FOR ACQUISITION OF SEISMIC DATA

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ABSTRACT

This paper presents how analysis can be used in the design and the design verification process for towed equipment. Analysis of a seismic gun array has been carried out and points out the challenges that need to be addressed in order to obtain an assessment of the system. It is shown how analysis should be carried out to obtain proper design verification. Applicable rules and design criteria are presented and discussed. The work shows the importance of carrying out a coupled hydroelastic analysis of towed equipment. The strong effect of waves and currents to positioning of equipment is shown.

INTRODUCTION

The seismic acquisition industry has in general been driven by geophysicists. The mechanical parts used to fulfil the specifications of the geophysicists have, according to the authors impressions mainly been pushed forward by empirical data and trial and error. The complexity and demands on seismic acquisition systems are growing both from customers and governmental organizations. Customers generally want more accurate results whereas governments are being more and more concerned with environmental implications. This means more work need to be carried out during the design phase of such equipment.

This paper presents how the design and the design verification process for towed equipment has been carried out and points out the challenges that need to be addressed in order to obtain an assessment of the system. A literature search revealed little with regard to the design criteria for such equipment. This shows a need for a method to identify and assess these technical challenges. These challenges addressed in this study are:

-Equipment deployment and retrieval
-Strength and capacity where both accidental loads and fatigue is of large importance.
-Behaviour of the system in sea.

Figure 1 shows an outline of a typical marine seismic data acquisition system.

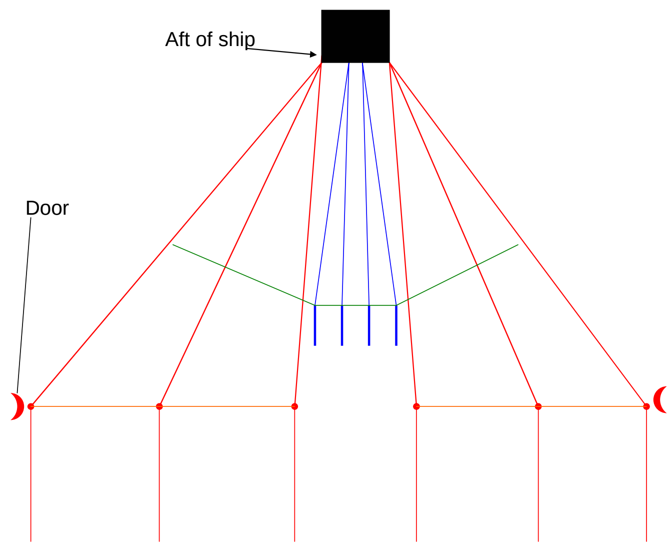

Figure 1 Outline of typical marine seismic acquisition system. The source system is seen in blue and the streamer system is seen in red.

The system consists of several components including towcables, air guns, hydrophone streamer system including equipment to spread the system in the horizontal direction. Define a coordinate system where the *x*- axis points backwards from the tow vessel and the *z*- axis is vertical. To spread the equipment in the transverse (*y*-) directions, "doors" (e.g. Barovanes seen in Figure 2.) attached to the outermost hydrophone streamer cable to spread properly in the *y*-direction.

A seismic system's acoustic signature depends on various parameters of the air gun part of the system. There are typically between 10 and 50 guns or gun clusters in a towed configuration. The signature depends on size of each gun as well as the arrangement. A gun configuration is chosen to achieve a good acoustic signature. However, the actual gun arrangement in sea may deviate from the nominal position due to waves, currents and forward velocity, hence both static and dynamic motions of the equipment in current and waves need qualitative assessment. Recently analytic tools have become available, and they can be used to calculate the hydroelastic response of the towed coupled system. One of these is the AquaSim program (Berstad et. al. 2004).

This paper also presents a case study. The simulation results are shown and discussed and the governing physical relations are presented.

Figure 2 A concept for "door" on a seismic survey system. The "Barovan" (Baro 2008)

The source system seen in Figure 1 consists of 4 gun arrays. A typical gun array is seen in Figure 3. In Figure 3, the handling system for such arrays is also seen.

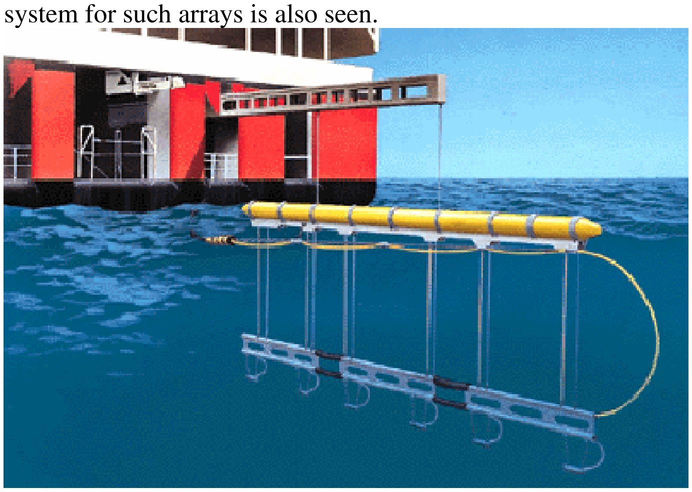

Figure 3 Gun array (Baro 2008)

The gun array seen in Figure 3 typically consists of 6 guns or gun clusters. The guns hang below the float in Figure 3. A typical gun is seen in Figure 4.

Figure 4 Gun hanging in chains in array (Bolt 2008)

An alternative gun configuration with 2 guns in a cluster is seen in Figure 5.

Figure 5 Gun cluster. 2 guns side by side. (Bolt 2008)

Figure 6 shows a seismic vessel passing fishing vessels (FOE 2008).

Figure 6 Seismic vessel meeting fishing vessels.

As seen from Figure 7, a gun array consists of series of flexible lines connecting rigid components. This means that the system will deform when towed and when exposed to wave action.

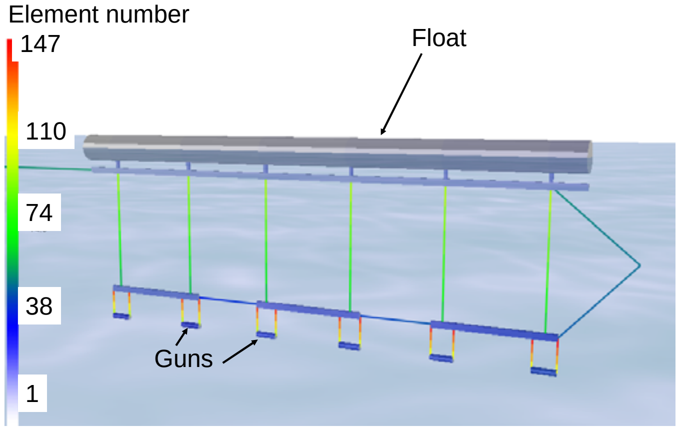

Figure 7 FE model of gun array

The colours in Figure 7 show the element number of the elements in the model, 213 in total. Float , beams and guns are modelled with beam elements to include rotational stiffness. This means 6 degrees of freedom (DOF's) for each of the 2 nodes on the element. Lines are modelled with bar elements, each having 3 DOF's on each node, only translational DOF's.

Because the gun array geometry will change, there is a need for a coupled analysis where both the hydrodynamic loading and the structural response are calculated in the time domain for a given environmental condition (waves, current and wind) as well as the forward velocity of the vessel.

Design criteria were derived from the Offshore and Aquaculture industry. For environmental loads NS 3490-4 (2002) (wind) and DNV-OS-E301(2004) were used as a basis. For capacity checks, the NORSOK (1998) and NS 3472 (2001) were relevant for steel structure, supplemented by DNV Class Note 30.1(2004) and DNV RP 202 (2000) for buckling, DNV Class Note 30.7 (2003), DNV RP 203 (2001) and IIW(1997) for fatigue. For making a testing program, DNV-OS-C401 (2004) would be resorted to. For the ropes and chains, DNV-OS-E301(2004) was applicable both for loads and capacity. In addition, NS 9415 for the Aquaculture industry can be resorted to.

The model shown in Figure 7 is the case study. When this system is towed at a velocity of 6 knots, it will deform as seen in Figure 8.

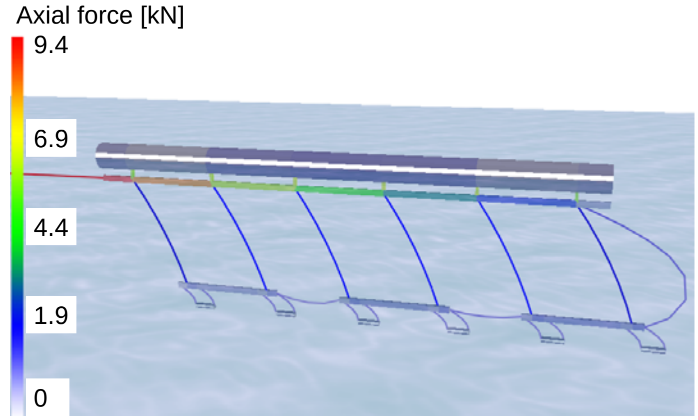

Figure 8 Source system towed at 6 knots forward velocity

From this preliminary analysis, it was apparent that coupled analysis was needed to obtain the response of this system being exposed to nonlinear load effects and a hydroelastic response pattern. The challenge was to cover all design sensitive interactions between tow ropes, floats and guns. AquaSim (Aquastructures 2006a-b, Berstad et al 2004) is used as the tool for the analysis. This is described in the next section. From this analysis tool, the relevant response parameters such as stress level and motions could be derived from time domain simulation. The analysis tool has been developed through many years of research and verification testing with the bases founded through PhD studies at NTNU. The program was developed because of a need for an analysis tool that was able to incorporate several individual floating objects integrated in one numerical model. To the best of our knowledge, no other analysis tools are available to carry out this type of coupled analysis. Hence the project did not compare results to other tools This paper focuses on the challenges regarding the analysis and design verification, and how analysis can be utilized to minimize the uncertainties in a design verification process.

THEORETICAL BASIS FOR AQUASIM

The AquaSim program is based on the finite element method. It utilizes beam and shell elements with rotational DOF's, as well as membrane elements and bar elements with translatory DOF's only. Geometric nonlinearities are accounted for in all element types, so the program handles large structural deformations. The program is based on time domain simulation, where it is iterated to equilibrium at each time instant. Both static and dynamic time domain simulations may be carried out. Features such as buoys, weights, hinges and springs are included in the program.

The basic idea of the FE analysis program is to establish equilibrium between external loads acting on the structure at a given time instant, and internal reaction forces.

$$\sum F = \mathbf{R}_{ext} + \mathbf{R}_{int} = 0 \qquad (1)$$

where R_{ext} is the total of the external static forces acting on the structure at a given time instant, and R_{int} is the internal forces. The structure is discretized to a finite number of degrees of freedom (DOF's). Equation 1 is then discretized as

$$F^{idof} = \mathbf{R}_{ext}{}^{idof} + \mathbf{R}_{int}{}^{idof} = 0, \quad idof = 1, N_{dof} \qquad (2)$$

where N_{dof} is the discrete number of DOF's the structure has been discretized into. The current element program deals with strongly nonlinear behaviour both in loads and structural response. In order to establish equilibrium, the tangential stiffness method is used. External loads are incremented to find the state of equilibrium. Having established equilibrium in time step ***i-1***, the condition for displacement ***r***, step ***i***, is predicted as

$$\Delta\mathbf{R}^{i}(\mathbf{r}_{i-1}) = \mathbf{R}_{ext}{}^{i}(\mathbf{r}_{i-1}) + \mathbf{R}_{int}{}^{i-1}(\mathbf{r}_{i-1}) = \mathbf{K}_{t}^{i-1}\Delta\mathbf{r} \qquad (3)$$

where K_t^{i-1} is the tangential stiffness matrix at configuration ***i-1***. The external load is calculated based on the configuration of the structure at ***i-1***. This gives a prediction for a new set of displacements ***(j=1)***. Based on Equation 3, a prediction for the total displacement $r_{(j=1)}$, is found as

$$\overline{\mathbf{r}}_{j=1} = \mathbf{r}_{i-1} + \Delta\mathbf{r} \qquad (4)$$

Based on this estimate for new displacements, both external and internal forces are derived based on the new structural geometry, and the residual force is put into the equation of equilibrium as follows

$$\Delta\mathbf{R}(\overline{\mathbf{r}}_{j}) = \mathbf{R}_{ext}{}^{i}(\overline{\mathbf{r}}_{j}) + \mathbf{R}_{int}{}^{i}(\overline{\mathbf{r}}_{j}) = \mathbf{K}_{t}{}^{i}\Delta\mathbf{r} \qquad (5)$$

Note that both the external and internal forces will vary for each iteration due to the strong hydroelastic nature of the fluid structure interaction. Equation 5 is solved for the displacement Δr. Incrementing ***j*** with one, the total displacement is now updated as

$$\overline{\mathbf{r}}_{j} = \overline{\mathbf{r}}_{j-1} + \Delta\mathbf{r} \qquad (6)$$

Now if Δr, found from Equation 6, is larger than the tolerated error in the displacements, Equation 4 is updated ***(j = j+1)*** and Equation 5 is solved based on the new prediction for displacements, this is repeated until Δr is smaller than a tolerated error, then

$$\mathbf{r}_{i} = \overline{\mathbf{r}}_{j} \qquad (7)$$

i is increased with one, and Equation 4 is carried out for the new load increment.

At the default configuration, the program sequence proceeds as follows: Static analysis is used to establish static equilibrium including buoyancy. Secondly, current loads are applied, and wind and wave loads added. (Still static analysis.) Then dynamic analysis commence. Waves are introduced with the first wave used to build up the wave amplitude. Both regular waves and irregular waves may be simulated. Waves are assumed to be sufficiently described by linear wave theory. Inertia and damping are accounted for in the wave analysis, meaning that mass and damping are accounted for in the equations of equilibrium. The Newmark-Beta scheme is applied for the dynamic time domain simulation (e.g. Langen and Sigbjørnson 1979). Note that the foregoing equations imply using the Euler angles for rotations. This is just a simplification for easy typing. For rotational DOF´s AquaSim uses a tensor formulation for the rotations as outlined in e.g. Eggen (2000). His work follows Argyris, J. H. (1985), Crisfield. M. A. (1990) and Rankin C. C. and F. A. Brogan. (1986).

Wave loads may be derived using the Morison formulae (Morison et al 1950) or using diffraction theory.

The diffraction theory used in AquaSim is a form of "strip theory" (e.g. Salvesen et al 1970), but in this case hull forces are derived by direct pressure integration over the mean hull surface. Diffraction loads may be applied to beams or bars. In this case linearized values for diffraction, added mass and damping are derived at the mean wetted position. Added mass and damping are linearized at the peak period in the wave spectrum . The Froude Kriloff part of the hydrodynamic pressure is applied at the actual location of the component. Wave interaction between separate components is not accounted for.

When the Morison formula is used, the cross flow principle is applied for beams and bars (see e.g. Faltinsen 1990). This load term is quadratic with respect to the relative velocity between the undisturbed fluid and the structure, both the mass of the structure as well as added mass in the cross sectional plane is accounted for. Due to the large deflections occurring, the added mass is nonlinear.

The above presented algorithm represents a practical approach to simulate this type of integrated structures, given the size of the structures and current computer capabilities.

ANALYSIS PROGRAM VERIFICATION

Prior to this work Aquasim was used for verification and analysis on a wide range of computational cases where results have been compared to handbook formula or other programs, (Aquastructures 2006a). Model tank testing conducted and compared to analyses (Berstad et al 2004). The program has been compared to accidents where the capsize origins were known (Aquastructures 2003 and 2005). In addition, experience has been obtained during several years of use for calculation of the structural integrity of fish farm systems in Norway. These systems in general consist of moorings, stiff structure and nets responding to wave and current in a strongly hydroelastic manner.

We present a case study here.

The case study describes the analysis needed to be carried out to find the appropriate design values for strength and displacement.

CASE STUDY

The case study presents an analysis intended to find the loads on and an assessment of the structural capacity of the various components.

In a simplified manner, the load components can be viewed as:

-Forward motion. From this load, a constant drag force is acting on the system.

-Wave loads. Wave loads depend on the wave amplitudes and periods when the survey is conducted. The waves can be identified by a spectral formulation of waves within sea states which can be identified by a scatter diagram.

-Gun shots. The gun shots introduce impulse shock loads in the gun array. This can more or less be considered independent of the two other loads. In this case study this latter component is not considered, but need to be included in the design verification work.

The most common way to design components in equipment for seismic operations is to calculate the static response of the system, and then apply an experienced based dynamic safety factor. However, as outlined above, the goal in this study is to use direct dynamic and hydroelastic calculations to find explicit design loads for limit state conditions. This approach is consistent with that used in other sectors of the offshore industry as well as other maritime industries such as the fish farming industry.

The effects of waves were examined using the gun array shown in Figure 7 and Figure 8. Here, the nominal depth at gun level is 6 meters with the beam located 1 meter above the guns mean position. A forward velocity of 2.5 m/s is used as nominal towing velocity. Towing at this velocity gives a tensile force in the tow cable of 9.6 kN.

Figure 9 shows a time instant in the analysis with the gun array towed in waves. The simulated wave condition is a design wave with wave height 3.8 meters, wave period, 5 seconds and the wave direction is 45 degrees relative to a backwards pointing x- axis. This design wave represents the worst wave to occur in spectral with a significant wave height, hs of 2 m. The relation between hs and hmax has been found from NS 9415 (2003).

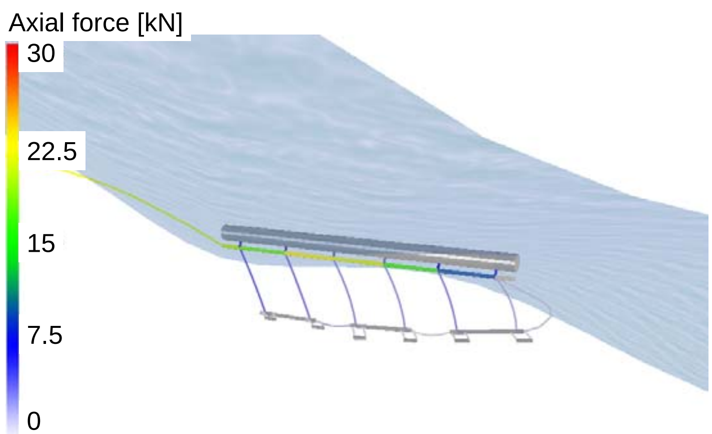

Figure 9 Gun array towed in waves. Array under wave crest.

As shown in Figure 9, the maximum axial forces due to the wave condition seen in Figure 9 are approximately 3 times the nominal wave free value. This corresponds well with the experience based dynamic factors used in the industry which typically ranging from 4-6.

Figure 10 shows the same as Figure 9 but for a different time step in the analysis.

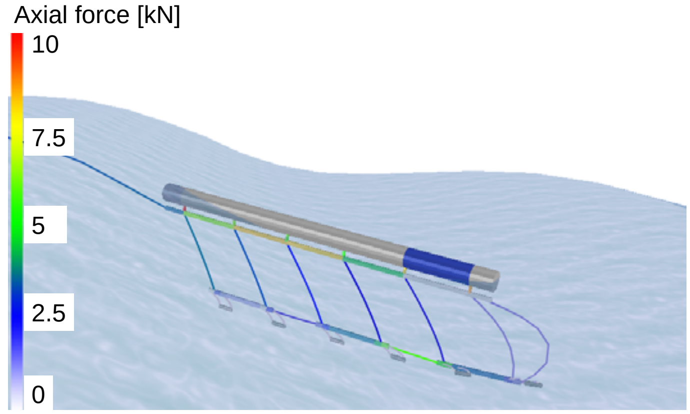

Figure 10 Gun array towed in waves. Array under wave through.

As seen from Figure 10 the forces in the tow cable is in this case very low. This means that the waves introduce large time variations in the loads meaning fatigue need to be assessed properly.

In order to meet the design criteria, analysis of towed equipment in wave need to be carried out for a range of environmental conditions and combinations of vessel velocities reflecting the actual design specifications. There is a constant push to operate the equipment in rough conditions in order to obtain return of investment. This means higher loads on the equipment and thus a higher degree of fatigue on critical components.

COMMENTS ON ANALYSIS PROGRAM

The AquaSim analysis program is currently used on a windows platform and can be run both on lap top computers and servers. The system may also be compiled for other platforms. Carrying out static analysis (without waves) the computation time is typically less than one minute for models with approximately 1000 DOF's. The analysis time for dynamic analysis with waves is typically 30 minutes for a design wave running 3 full wave cycles (relevant for the case study). Running irregular seas, the analysis time is approximately 30 minutes per 10 wave cycles (less time per cycle as each wave in general is smaller).

The time needed for analysis depend strongly on the convergence properties of the model. The more viscous the deformations gets, the harder it gests to obtain convergence and the more time is needed to obtain it.

The program has been used for models with up to 5000 elements with approximately 20,000 DOF,s. The analysis time does not only depend on number of DOF,s but also the sparseness of the stiffness matrix. This means that models with long cables in general uses less time in the analysis than models with fish nets.

Time increment need to be chosen appropriate, not to short such that one run into problems with numerical resonance, and not to long such that convergence is not achieved. The parameters in the Newmark-Beta method may be adjusted. Usually the Newmark-Beta parameters are chosen to give the method of constant average acceleration which is stable and have no numerical damping. As an alternative some numerical damping may be introduced by changing the parameters slightly. This may improve the convergence.

Element meshing is important for stability and convergence, as is added mass. Mass is more stable than added mass as the latter usually changes as the geometry change.

For elements in the splash zone where buoyancy of elements is accounted for, one usually accounts for in and out of water effects such that buoyancy is 0 when the element is fully submerged of fully above the water line. This may reduce the convergence rate or lead to non-convergence.

In general, AquaSim have shown excellent convergence and stability properties compared to similar tools used by the authors. Analysis has been carried out for a large amount of different cases where some are reported in Berstad et al. (2005a, 2005b, 2007)

CONCLUSIONS

This paper explains how analysis may be applied to investigate response of towed equipment exposed to waves and current forces.

The AquaSim analysis program proved very useful for this case study. In particular its capability to account for fluid structure interaction proved suitable for this case study with its hydroelastic response. This versatility was expected due to previous use for a wide range of offshore structures with a hydroelastic response pattern.

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