

Shock Response and Acoustic Radiation Analysis

Summary

Accurate numerical modeling of the shock response of marine structures is of considerable importance in their design since the cost associated with physical testing is often prohibitive. Along with the shock response calibration, designers often have to grapple with opposing factors while trying to optimize performance during operating conditions. Abaqus allows for the analysis of both the structural integrity and acoustic radiation in such cases.

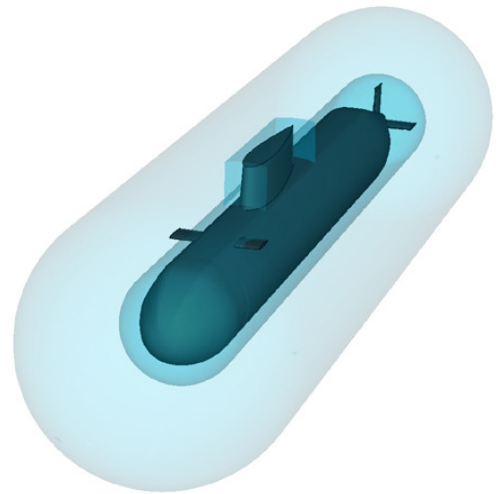
In this technology brief two related but distinct analyses are examined. First, the shock response of an example structure due to a shock event is considered. Second, the steady-state acoustic field established due to machinery-induced vibrations within and around the structure is estimated.

Background

Most naval organizations require some form of shock survival assessment to be performed on marine structures before they are commissioned. The response of concern is the behavior of the structure when exposed to a nearby noncontact underwater explosion (UNDEX). Both the low-frequency hull “whipping” modes and the high-frequency structural displacements are of interest. The shock response analysis can be performed either at the whole-ship level or for an individual mounted piece of equipment.

The current design practice is to carry out experimental testing as well as numerical simulations. The costs associated with experimental testing are high, and in some cases designers are compelled to rely solely on numerical predictions. In practice, numerical analysis presents a significant challenge in terms of accurately representing the governing physics, modeling the structure in sufficient detail, and completing the analysis in a reasonable amount of time. In all these areas Abaqus offers superior techniques and features that provide timely, robust, and reliable solutions.

Besides shock survivability, another important consideration in submarine design is stealth. Since their inception, submarines have been deployed in strategic situations where susceptibility to detection is equated with reduced effectiveness of the vessel. Various acoustic treatments are used to reduce the target strength and acoustic signature of a submarine. Surface ships may also be subject to stringent radiated sound requirements. In addition, ship-



Key Abaqus Features and Benefits

- A cohesive framework to create and manage analyses within Abaqus/CAE
- Model development tools within Abaqus/CAE
- Analysis capabilities specific to structural acoustics
- Extensive results visualization within Abaqus/CAE including acoustic far-field visualization

board sonar equipment is sensitive to the boat’s self-generated noise as well as other factors such as turbulent flow around the boat, operating depth, and physical properties of the local region of water. To address these concerns, Abaqus provides fully coupled structural acoustic capabilities in the frequency domain that predict near and far-field sound pressure levels due to machinery-induced vibrations.

Finite Element Analysis Approach

The model discussed in this technology brief is based on specifications provided by the *Forschungsanstalt der Bundeswehr für Wasserschall und Geophysik (FWG)*, located in Kiel, Germany (Ref. 1). The model is known as the Benchmark Target Strength Simulation (BeTSSi) submarine. Although created for the purpose of verifying acoustic simulations, it has also been used for shock response in the current effort.

Geometry of the submarine

The model is significantly detailed and features a double-hull design with a long pressure hull aligned with the exterior hull. The model contains a bow comprising bulkheads, torpedo tubes, and a sonar chamber. The submarine is equipped with side fins and a sail structure. Some details of the boat are shown in Figure 1 through Figure 5. The structure is composed of a single material (steel) with isotropic elastic mechanical behavior, and the section thicknesses are position-dependent.

Important features of the submarine geometry are shown in Figure 4, Figure 5, and Figure 6.

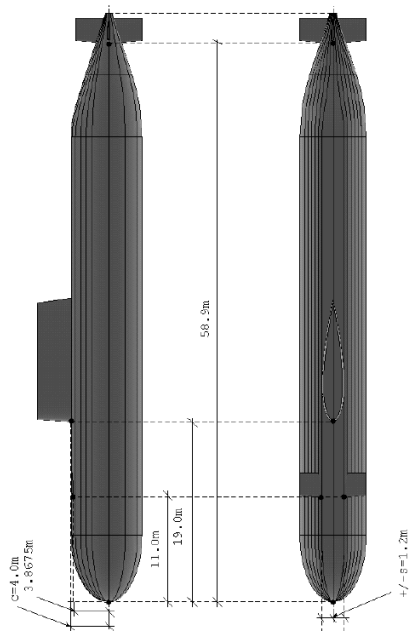


Figure 1: Longitudinal views of the BeTSSi model

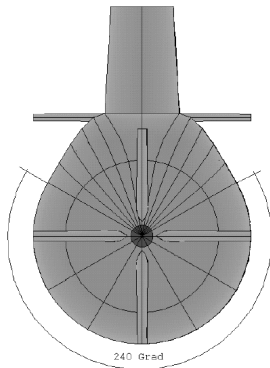


Figure 2: Back view of the submarine

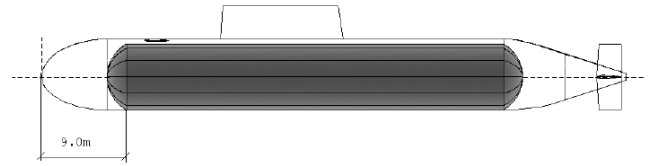


Figure 3: Location of pressure hull relative to structure

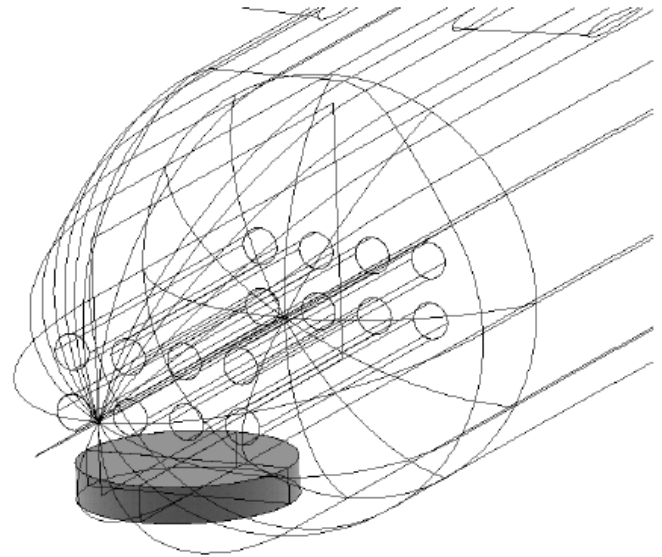


Figure 4: Sonar chamber

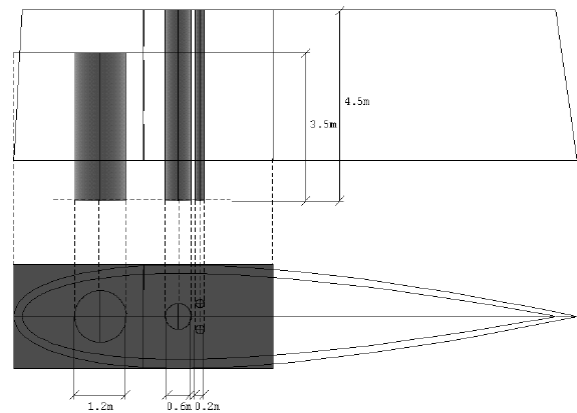


Figure 5: Details of the sail

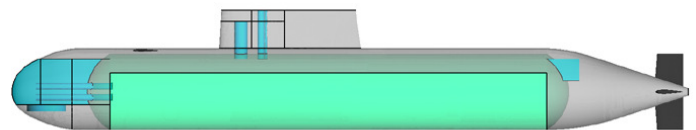


Figure 6: Abaqus/CAE submarine model

The model was created entirely within Abaqus/CAE and is shown in Figure 6. The lofting operation in Abaqus/CAE was used to merge the different cross-sections to form the exterior hull. The level of detail in the original FWG model was higher than that required for the current analyses and would, if left unaltered, lead to extremely fine meshes at multiple locations. To alleviate this situation, extensive use was made of the Virtual Topology feature in Abaqus/CAE, which allows the user to “defeature” desired regions in the geometry. Figure 7 shows the effect that virtual topology had on the exterior of the nose region.

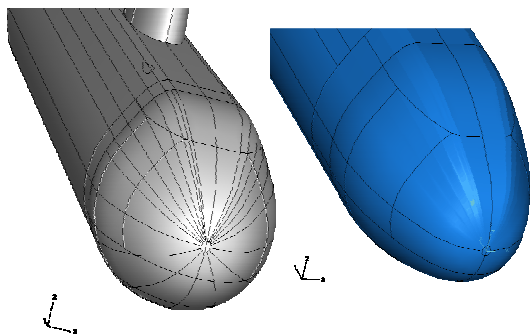


Figure 7: Nose region with full geometric detail on left and after using virtual topology on the right

Modeling the fluid around and inside the submarine

In these types of applications an important issue is the manner in which the surrounding infinite expanse of water is modeled. Traditionally, the approach was to use the Doubly Asymptotic Approximation (DAA), a boundary element formulation that does not require the creation of fluid meshes. Although the DAA was an indispensable tool in the past, it suffers from drawbacks such as inherent limits on accuracy and model size. In current years, with advanced computer resources becoming increasingly accessible, the use of the DAA may not be justifiable. Abaqus now provides a continuum-based fluid modeling approach that does not suffer from the limitations of the DAA formulation.

To study either shock or acoustic radiation, the structural model must be encapsulated in a fluid zone that mimics the acoustic behavior of the surrounding water; i.e., brings in incident acoustic energy, interacts with the structure, and absorbs scattered acoustic waves. The extent (size) and mesh density of this fluid zone depend on the application. In the case of acoustic radiation, we simply mesh the fluid zone with about 6–8 elements per wavelength (for low- to midfrequency problems), and the extent (or standoff distance) of the zone is set to about a third of the wavelength. If the analysis is a frequency sweep rather than a single frequency response, we must ensure that these requirements apply to the highest and lowest frequencies of interest, respectively. In cases where the

range of frequencies to be analyzed is broad, it may be advantageous to split a single sweep into multiple disjoint sweeps and use more refined meshes for the higher frequencies, allowing more economical analyses to be performed.

The meshing requirements become more complicated when a shock response analysis is required, since this type of problem is usually performed in the time domain and there may not be easily identifiable frequencies with which to design the mesh. In these cases a spectral decomposition technique may be used to identify the prominent frequencies in the shock amplitude; however, the appropriate selection of the mesh density and extent remains primarily a matter of user experience and judgment. Good comparisons between experiment and analysis have been observed to require anywhere from 10 to 25 elements per wavelength and an extent of about 1 to 5 wavelengths (Ref. 2), and similar mesh densities have been used in this example. Due to the large volume of the submarine and the need for high accuracy at the fluid-solid interface, the fluid zone was divided into two regions (Figure 8). The region immediately adjacent to the submarine (Layer 1) was created to follow the external contours of the boat and extended up to a distance of one wavelength away from the structural surface. From the exterior boundary of this region to the exterior boundary of the fluid zone, a second fluid region (Layer 2) was created with a coarser mesh, and this layer extends up to 6 wavelengths away from the structure.

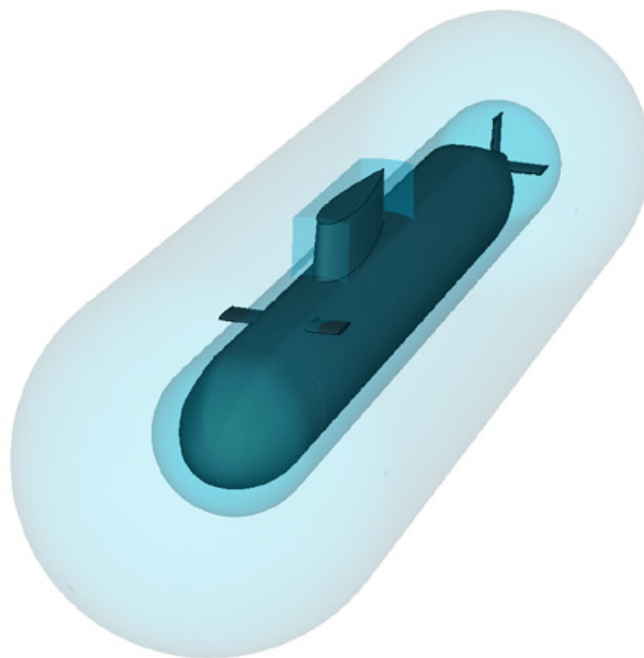


Figure 8: Exterior fluid is divided into two regions

Since the shock amplitude (Figure 9) has a prominent frequency of about 1200 Hz, these mesh densities correspond to about 10 elements per wavelength in Layer 1 and about 2 to 3 elements per wavelength in Layer 2 (Figure 10). Since the primary interest of the current analysis is the global displacement response of the structure, these densities are adequate. If the detailed response of a particular region of the structure is needed, a finer mesh may be required to capture the local behavior more accurately.

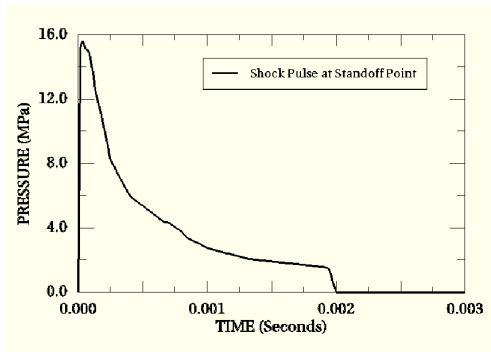


Figure 9: The shock pressure amplitude

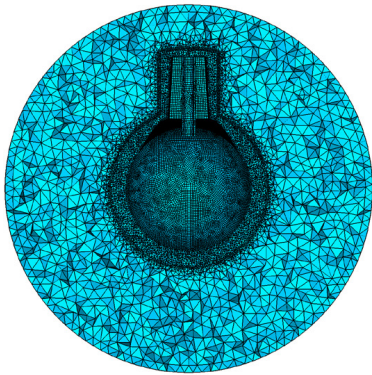


Figure 10: Typical mesh densities used in Layer 1 and Layer 2

Typically analysts are in possession only of the structural geometry (sometimes only the structural mesh) and must employ potentially time-consuming mesh generation techniques to create the fluid zone. In these cases the Boolean operation in Abaqus/CAE provides a simple and efficient alternative. For both the models discussed here, the shell-to-solid feature was first used to create a solid (cavity-free) part that had the same boundary as the exterior hull. Next, a region of fluid with a boundary matching that of the desired fluid zone was created, also as a “solid” part. The Boolean subtraction feature was then used to subtract the volume of the “solid” submarine from that of the “solid” fluid region, the remainder being the required fluid zone surrounding the structure. The structure was meshed with quadrilateral shells and the fluid with acoustic tetrahedra. All elements were first-order.

In the case of the radiation analysis, internal fluid volumes were also created such that they would be enclosed in the various compartments in the submarine. It is quite typical for certain regions inside the submarine to be flooded during operation. It has been observed that the results (both shock and radiation) may show significant dependence on the existence of interior water (Ref. 2). Hence, interior water was included in the radiation model; and the Abaqus/CAE Boolean feature facilitated this modeling as well. Internal water was placed in all bow compartments, in the aft section, and between the pressure hull and exterior hull. The sail was not flooded. All flooding was complete in the sense that no flooded compartment possessed a water-air interface. Consequently, the effects of sloshing were not included.

Coupling the structural and acoustic fields

To account properly for the presence of the fluid in the model, the displacement field in the structure must be coupled with the pressure field in the fluid. Abaqus offers a simple surface-based coupling constraint wherein it automatically generates the fluid-solid coupling after the user has identified the surfaces to be “tied.” The fluid and solid meshes need not be conforming, which is of great help to the analyst. The shock model had two coupling constraints imposed. The first was the solid-fluid coupling between the submarine and the immediately adjacent layer of fluid (Layer 1). The second was the fluid-fluid coupling between the finely meshed Layer 1 and the coarsely meshed Layer 2. Both couplings were nonconforming.

The radiation model has multiple solid-fluid constraints imposed since the water in each compartment is coupled to the compartment walls. A single surface was created for each enclosed fluid volume, but the compartment walls were discretized such that each side constituted a unique surface.

Loading of the submarine

The effect of the UNDEX event is transferred to the structure by means of the incident wave loading feature. Abaqus offers both a scattered wave formulation, which is typically employed when the structural behavior is the sole interest and the fluid behavior is linear, and a total wave formulation, which becomes necessary if cavitation is of concern or if the exact pressures in the fluid are needed. Both formulations allow for the initialization of the incident wave at the fluid-solid interface. The user identifies the location of the charge and the location of the standoff point (the point that the shock front has reached at the onset of the analysis; i.e., typically the point on the submarine closest to the charge). A pressure or acoustic particle acceleration history is specified at the standoff point, and a choice is made between a planar and spherical wavefront. Abaqus then automatically calculates the spatial and temporal distribution of the load and applies it accordingly. In addition, Abaqus also provides bubble

formulations wherein the pressure amplitude is calculated automatically from the physical properties of the charge. For the current application the shock amplitude used was the same as that used in the experimental study by Kwon and Fox, the results of which have been successfully reproduced by Abaqus/Explicit (Ref. 2). The standoff point is located on the starboard (-3 axis direction as shown in Figure 8) side of the submarine, approximately midway along the length and the height. The source point is also located on the -3 axis, 22.5 m away from the surface of the submarine. A spherical wavefront is used together with the scattered wave formulation, neglecting the effect of cavitation.

In the case of the radiation analysis the loading is a concentrated unit load (representing engine-induced vibration) applied at the tail end of the submarine.

Modeling the effect of an infinite amount of surrounding water

The absorbing (or nonreflecting) boundary condition was applied via a surface impedance. The surface impedances are local, and several types (differing absorptions or differing geometries) of impedances can be used simultaneously. The cylindrical portion of the boundary aligned with the submarine received a cylindrical impedance (asymptotically exact if the wavefront is cylindrical), whereas the two end caps were given spherical impedances (exact for spherical wavefronts).

In addition to the surface impedance approach, Abaqus provides acoustic infinite elements that can be used as nonreflecting surfaces. These elements have a variable (1 through 9) order of interpolation in the infinite direction and can be used to reduce the size of the fluid zone due to their higher-order accuracy.

For steady-state dynamic analyses the use of acoustic infinite elements provides the ability to visualize the acoustic far field. For example, Figure 11 (Ref. 2) shows the acoustic pressure on an imaginary spherical surface 50 m away from the tail of the submarine in a model that contains no interior water.

While not used in the analyses discussed in this technology brief, this capability is useful when the analyst is interested in pressures in the outer fluid medium at locations fairly distant from the submarine where there is no fluid mesh present.

Model size and execution

The shock response model has approximately 10 million degrees of freedom and was run using Abaqus/Explicit for a step time of 10 ms, which is sufficiently long to establish peak velocity at the standoff point. The analysis was run using double precision, as is typically the case with shock analyses. Besides a small amount of numerical damping, no additional damping was added to the model.

The radiation analysis was run using Abaqus/Standard and performs a frequency sweep at 10 distinct frequencies between 100 Hz and 300 Hz. At each frequency the results are the fluid and structural response to a concentrated unit load, applied as described earlier. The model used has approximately 1.8 million degrees of freedom.

Results and Conclusions

First we examine the results of the 10 ms shock response analysis. Figure 12 shows the position of the shock front at the end of 10 ms. The shock has been scattered from the starboard side, while the fluid in the vicinity of the port side has also experienced the passage of the shock front. The contours of the shock front are not altered by the presence of the terminating fluid boundary. This indicates that the fluid zone is sufficiently large, so there are no significant spurious reflections from the boundary. Since the effect of hydrostatic pressure is neglected and there are no constraints on the motion of the submarine, we see high tensile (negative) pressures in the vicinity of the boat (blue). If these negative pressures are of concern, we should include the cavitation effect in the model. In practice, cavitation may not be as significant an effect in the case of submarines (if they are at a sufficient depth where high hydrostatic pressure never allows the overall pressure to become negative) but usually cannot be neglected when analyzing surface ships. In this case we must use the total wave formulation as well as ensure that the fluid zone is large enough to encompass the entire potentially cavitating region.

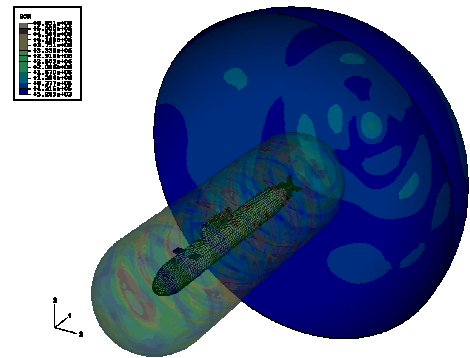


Figure 11: Acoustic infinite elements provide far-field pressure visualization via interpolation

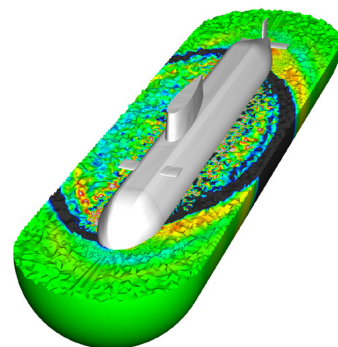


Figure 12: Acoustic pressure in the outer water, 10 ms.

Figure 13 shows the athwartship velocity experienced by the standoff point and the point directly opposite on the port side. We see a large spike in the standoff velocity, typical of a shock response. We also see the lag in the response of the portside point whose initial velocity gradient is not as sharp as that of the standoff point.

Figure 14 and Figure 15 show the Mises stress distribution on the external surface of the submarine and in the internal compartments, respectively. Stresses are notably lower in the areas where the hulls overlap, as is expected due to the enhanced thickness there.

The results of the acoustic radiation analysis are examined next. Figure 16, Figure 17, and Figure 18 show the magnitude of the acoustic pressure in the exterior fluid at 100 Hz, 211 Hz, and 300 Hz excitation frequencies, respectively. As the frequency increases, the response tends to become localized around the driven region at the tail.

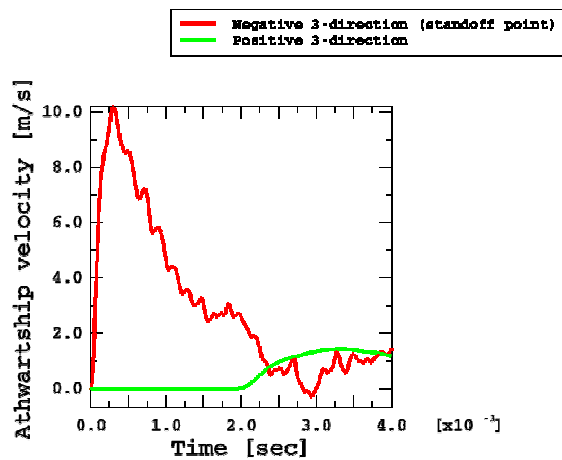


Figure 13: Velocity history at standoff point and point on hull opposite to standoff point

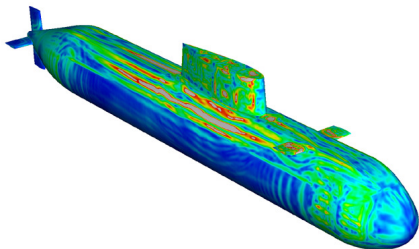


Figure 14: Mises stress distribution on the exterior surface of the submarine after 10 ms

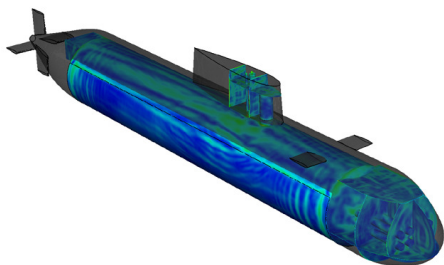


Figure 15: Mises stress distribution in the internal structures of the submarine after 10 ms

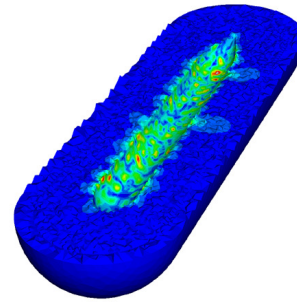


Figure 16: Acoustic pressure in outer water at 100 Hz excitation

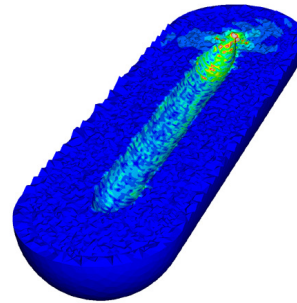


Figure 17: Acoustic pressure distribution at 211 Hz excitation

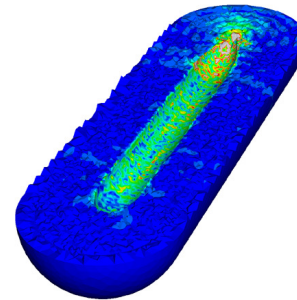


Figure 18: Acoustic pressure distribution at 300 Hz excitation

Figure 19 shows the pressure contours in the internal water at 211 Hz excitation frequency. The shaded patch on the port side of the boat represents the region that is common to the exterior hull and the pressure hull. We see that there is a pressure build-up in the narrow gap where the two hulls begin to separate.

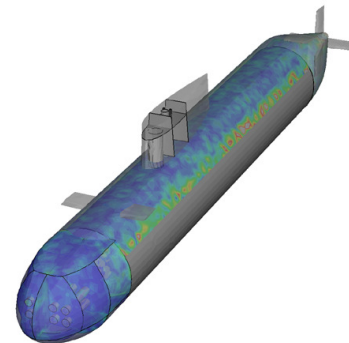


Figure 19: Acoustic pressure distribution in inner water at 211 Hz excitation

Figure 20 shows the pressure distribution in the water in the bow compartments at 100 Hz excitation frequency, and Figure 21 shows the Mises stress in the bow compartments at the same frequency.

Typically the vibrations experienced by the sonar assembly are of interest. Figure 22 and Figure 23 show the variation of the real and imaginary components of the normal displacement experienced at the front and bottom of the sonar assembly.

Abaqus provides a comprehensive and robust capability for shock response and acoustic radiation analyses of naval structures. The existing capabilities as well as upcoming developments establish Abaqus as an attractive solution tool for these classes of problems.

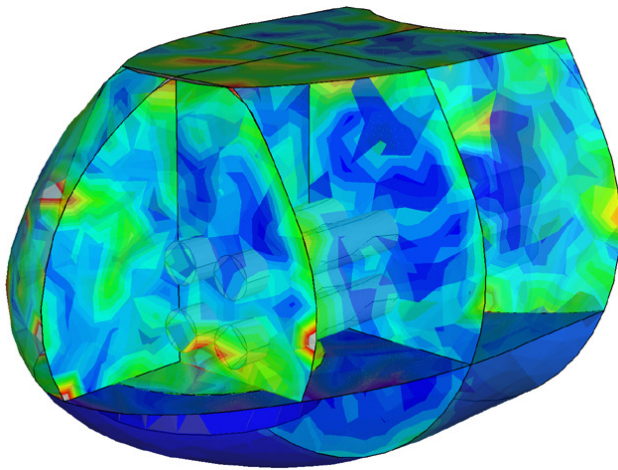


Figure 20: Acoustic pressure distribution inside the bow region at 100 Hz excitation

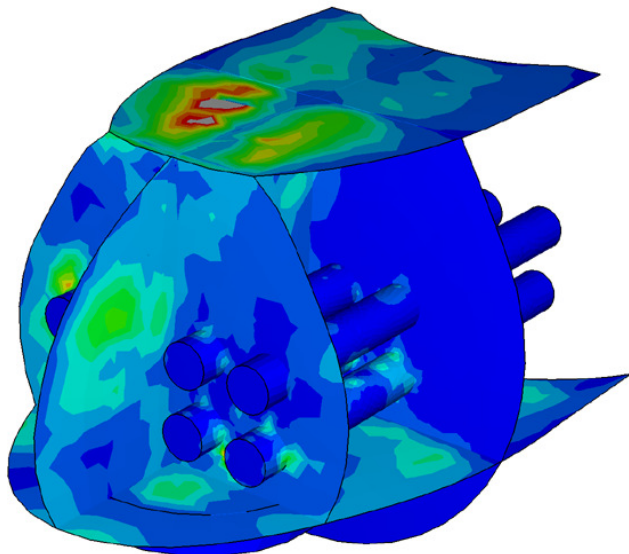


Figure 21: Mises stress distribution in the bow compartment at 100 Hz excitation

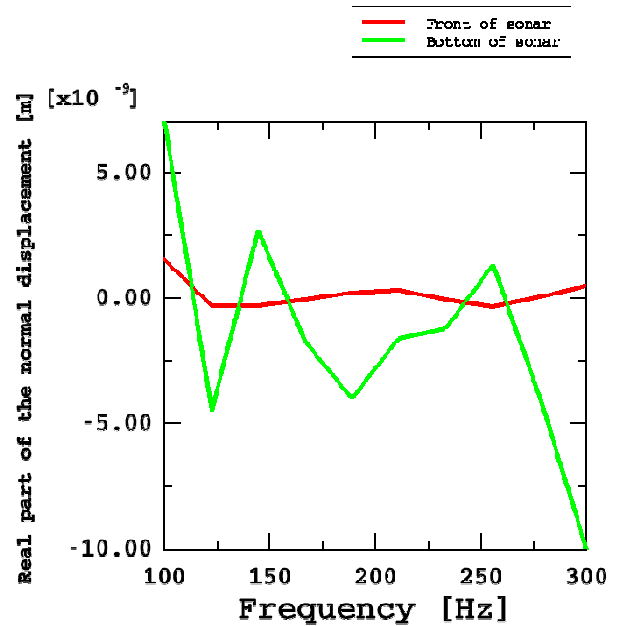


Figure 22: Variation of real part of normal displacement on sonar

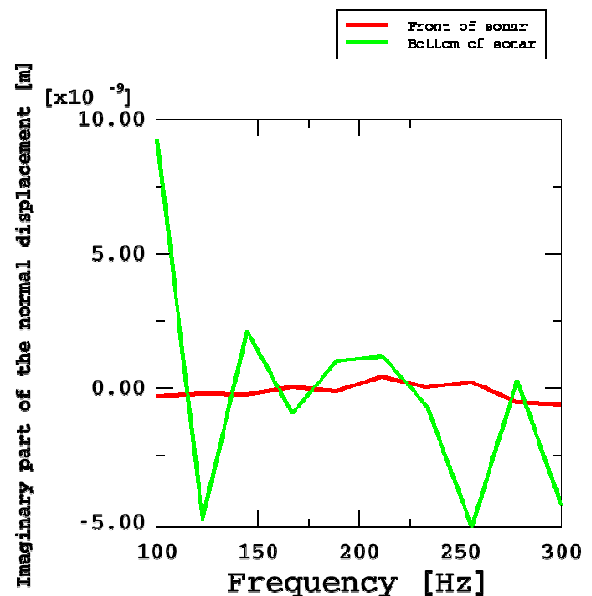


Figure 23: Variation of imaginary part of normal displacement on sonar

References

1. Schneider, H. G., Ch. Fiedler, "Benchmark Target Strength Simulation Workshop" Conference Proceedings UDT EUROPE 2003, Malmo, Sweden, June 2003.
2. D'Souza, K., C. Ianculescu, J. Cipolla, "A Unified Approach to Finite Element Modeling of Shock Response and Acoustic Radiation of a Submarine," 74th Shock and Vibration Symposium, San Diego, October 2003.

Abaqus References

For additional information on the capabilities and techniques outlined above, see the following references to the 6.13 Abaqus documentation:

- Analysis User's Guide
 - "Acoustic, shock, and coupled acoustic-structural analysis," Section 6.10.1
- Example Problems Guide
 - "Response of a submerged cylinder to an underwater explosion shock wave," Section 9.1.3
- Benchmarks Guide
 - "Underwater shock analysis," Section 1.14

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