Modeling the Structural and Acoustic Behavior of a Sonar Dome with ABAQUS

Karl D'Souza[1], Subham Sett[1], Woo-jin Jung[2], Ku-kyun Shin[2], Young-hwan Lee[3]

1 ABAQUS, Inc.; 2 Agency for Defense Development (ADD), Korea; 3 ABAQUS Korea, Inc.

Abstract: In this paper, we discuss several topics relevant to naval sonar dome analysis. The sonar dome model is an active sonar array enclosed within a protective dome and mounted beneath a surface ship. The model includes water-flooded compartments inside the sonar dome, and uses two different approaches for the exterior fluid – either a fluid region with an absorbing boundary, or acoustic infinite elements. The model is first used for eigenvalue extraction up to several kilohertz. An oblique shock attack from an underwater explosion is treated next. The same model is then used to simulate acoustic radiation from the sonar dome into the external fluid. Finally, using the fluid-structure interaction (FSI) capabilities in ABAQUS, the stresses in the structure as well as acoustic radiation from the structure is examined when the system is under the influence of hydrodynamic loading caused by its motion through water at typical naval cruising speeds.

Keywords: Absorbing Boundary Conditions, Coupled structural-acoustics, Incident Wave Loads, Underwater Explosion, Wave Propagation, UNDEX, acoustic scattering, infinite elements, hydrodynamic loading.

Note: Due to the confidential nature of the work, this paper mainly focuses on the techniques that were used to conduct various types of analyses. Some details such as mesh sizes, material properties, and numerical values of results are not discussed.

1. Introduction

1.1 Background

Surface ship sonar systems are in a process of continual change and have steadily evolved by taking into consideration the changing needs of modern navies. Naval vessels are designed to function in varied conditions characterized by operating speeds, environment (open ocean or littoral), stealth requirements, etc. These conditions dictate the nature of the sensor system, its position on the vessel and its operational range. A sonar dome is designed to provide a quiet array space environment, and to maximize the performance of the array by reducing the effects of turbulence and protecting the sensitive interior equipment from wave slam, minor collisions, underwater explosions, etc. In the design of the sonar dome, both structural and acoustic considerations come into play. Typical structural constraints may include the deformation of the dome under steady external flow, and accelerations and damage under explosive loads. From an acoustic standpoint, the goal is to maximize the fidelity of the incoming sound by ensuring that the self-noise and flow-induced noise can be readily identified and minimized.

Early sonar domes were originally keel-mounted composite assemblies, but modern designs typically feature a bow-mounted high-performance lightweight shell, designed using the predictable structural and acoustic properties of advanced fibre composites. Current sonar dome developments bring additional benefits for strength and acoustic performance, extending the ability of the vessel to locate, evade, and engage hostile targets. Several enhancements such as carbon fibre composites, multi-axial non-crimped fabrics, external acoustic damping treatments, and internal acoustic palliatives are used to provide a harmonic balance between ship and array performance at higher cruising speeds and severe sea states.

In recent years, there has been an increasing use of computer simulations to aid in sonar dome design. Several customized computational tools offer specific sonar dome features such as slamming and manoeuvring loads. However the use of a general-purpose finite element solution such as ABAQUS can assist the analyst by providing a versatile set of capabilities that span more than what a customized code can deliver. In particular, ABAQUS may be used for the study of coupled fluid-solid modal behavior, acoustic scattering, shock response, and acoustic radiation, and is capable of analyzing problems in the time and as well as frequency domains.

1.2 Outline of paper

In the current paper, we describe the use of ABAQUS in performing the following analysis cases:

1. Structural strength analysis under cruising hydrodynamic loads (CFD + ABAQUS/Standard)
2. Coupled fluid-solid eigenfrequency extraction (ABAQUS/Standard)
3. Shock response (ABAQUS/Explicit)
4. Acoustic propagation (ABAQUS/Explicit)

2. Sonar Dome Model

The sonar dome model that we use for this analysis is shown below (see Figure 1). The sonar dome is an open ellipsoid-like shell divided by a baffle into a front (positive x-) and rear (negative x-) compartment. Both chambers are completely filled with water. The separate regions of internal water are allowed to communicate only through the baffle. The sonar array itself is located in the front chamber, suspended as if in contact with the rigid undersurface of the ship. A hemispherical region of exterior water (diameter equal to approximately thrice the sonar dome length) is also modeled. Typically, the size of the exterior acoustic fluid should be a third to a half of the largest wavelength of interest. The fluid element size was determined from a convergence study of the results of both shock and acoustic radiation analyses. It was found that acceptable results were obtained when the element size was about a tenth of the smallest wavelength analyzed. The sonar dome consists of several regions, each with its own material properties, which include metal plasticity as well as fiber-reinforced composites with viscoelasticity.

The effect of the exterior infinite fluid medium can be modeled in two separate ways in ABAQUS. In the first approach, we include a region of external fluid and use an absorbing boundary condition. As these boundary conditions are first-order accurate, it is usually required to place them some finite distance away from the structure. Alternatively, one could use acoustic infinite elements instead of absorbing boundary conditions. The disadvantage of using infinite elements is that they may contribute a significant number of additional degrees of freedom to the model. However, their advantage lies in their superior accuracy, allowing them to be located much closer to the structure than the absorbing boundary conditions. In certain cases, where the geometric complexity of the structural surface is minor (as in the present case, due to the smoothness of the sonar dome), they may be located directly on the structure, eliminating the need for a fluid domain altogether. Both approaches were used for this analysis. In Figure 1, we see the model using an absorbing boundary condition, where, on the exterior surface of the external fluid region, a spherical impedance condition is specified.

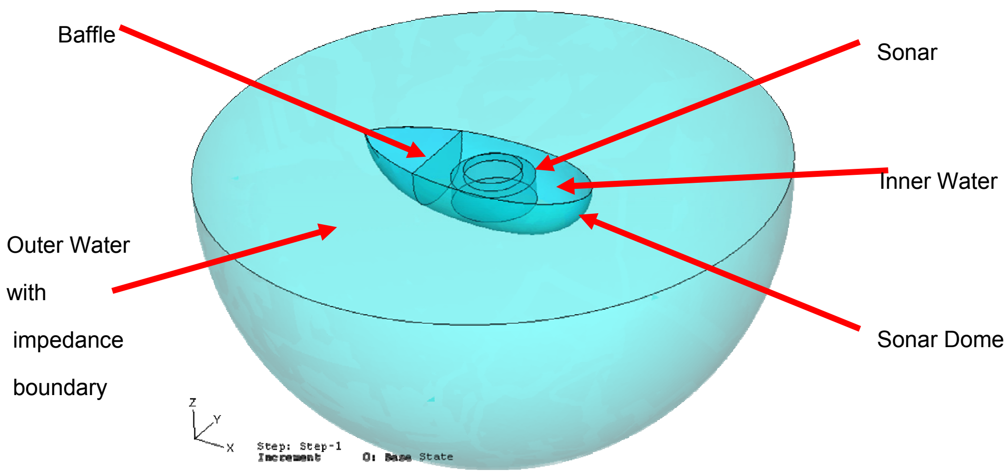

Figure 1. Sonar Dome model (with impedance) used for hydrodynamic load analysis

2.1 Structural Strength Analysis under Hydrodynamic Cruising Loads

The structural strength study begins with a CFD analysis to determine the hydrodynamic pressure on the exterior surface of the sonar dome. In this case, FLUENT was used for the CFD analysis. The CFD mesh used is shown in Figure 2. Note that in this case, due to bilateral symmetry, only half the sonar dome structure, and external fluid were modelled. As can be seen, a graded mesh was used, so that the mesh density is high near the structure and gets increasingly coarse as we move toward the boundaries. As it is expected that a greater fluid build-up occurs at the front of the sonar dome, the fluid domain extends further in the fore than in the aft direction.

ABAQUS/CAE was used to create a rectangular block of size 20m x 10m x 10m. Using the Merge/Cut feature in ABAQUS/CAE and the sonar dome geometry, a cut was introduced in the rectangular region representing the cavity containing the sonar dome. The fluid domain was then meshed with tetrahedra, and the meshed part was imported into FLUENT.

Various boundary conditions were used for the CFD analysis – inflow condition at the front; outflow from the far side (in Figure 2), the back, and the bottom; symmetry on the near side (in Figure 2); and wall conditions on the top and on the surface representing the sonar dome boundary. An LES turbulence model was used and CFD analyses were performed at various cruising speeds.

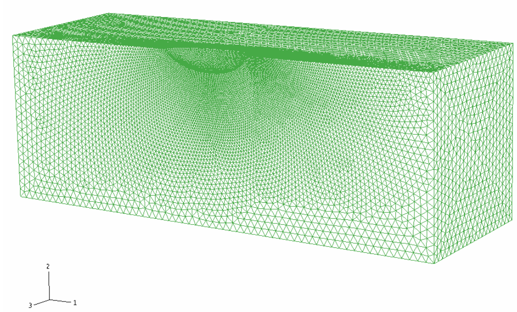

Figure 2. CFD mesh used for prediction of cruising hydrodynamic loads

In order to import the loads from the CFD analysis into ABAQUS, the co-simulation tool MpCCI was used. The steady state CFD solution provides both the pressure on the structural surface, as well as the fluid velocity around the structure. In general, acoustic wave propagation in a flowing medium differs from that in a stationary medium. The capability to include such a dependence of the acoustic wave propagation on flow velocity is included in ABAQUS from V6.6-1. However, in the present case, as the fluid velocity is much lower than the acoustic wave speed in water, such a dependence was neglected. In the case of fast-moving projectiles such as torpedoes, the deviation of acoustic propagation from that in a stationary medium is important and should be considered.

Figure 3 shows a vector plot of the velocity contours around the sonar dome at a cruising inflow speed. The stagnation of the velocity fore and aft of the structure is clearly visible. At such regions a compressive pressure is applied on the structure while at other regions where the flow speed is higher, we expect negative (tensile) pressures on the structure, in accordance with Bernoulli's principle.

Following completion of the CFD analysis, a static analysis was carried out in ABAQUS/Standard. The loads were obtained from the CFD analysis via MpCCI, which includes a mapping capability, thereby allowing dissimilar interface meshes on the structural and fluid sides. Both normal pressures as well as shear were applied. During the static analysis, the top edges of the sonar dome, baffle and sonar were constrained completely. Hydrostatic pressure was not applied as prior analyses had indicated that the effect of hydrostatic load at near-surface depths was insignificant.

It was noted that both the maximum displacements as well as the stresses in the structure were well within design limits. From this analysis, we conclude that the sonar dome design is robust under the specified cruising speeds.

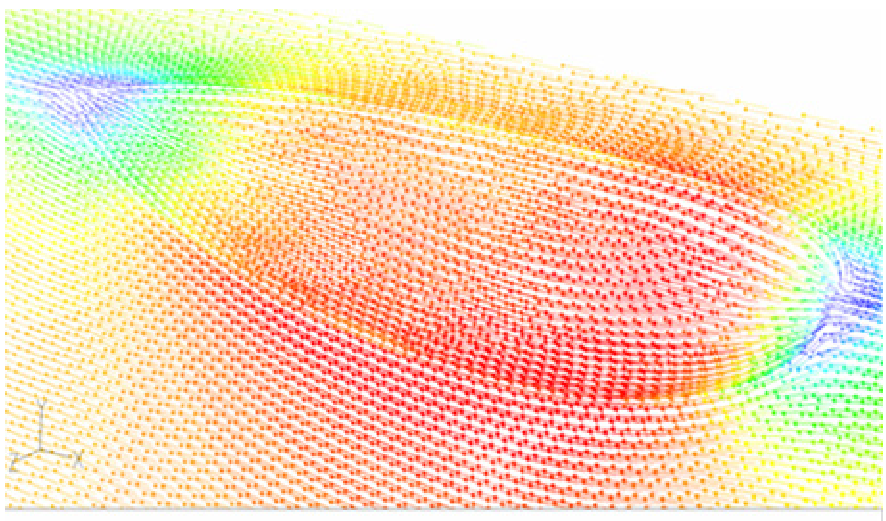

Figure 3. Fluid velocity vectors around the sonar dome at a specific cruising speed

2.2 Coupled fluid-solid eigenfrequency extraction

In this analysis, we examine the natural frequencies of the fluid-loaded sonar dome system. The model consists of the sonar dome with internal and external water, as in the previous case. The same spherical impedance is applied to the exterior surface of the external fluid. At low frequencies, the water is almost incompressible and thus primarily contributes inertia to the system – the 'added mass' effect. We observe this effect as a substantial drop in the natural frequencies. For comparison purposes, we also extract the natural frequencies of the system when the external fluid is absent – the 'dry modes' of the sonar dome. As can be seen in Table 1, there is a significant reduction in the natural frequencies when the external fluid is accounted for. This case was repeated using acoustic infinite elements placed directly on the sonar dome, and the results were in close agreement (maximum deviation of 11% for the first 8 modes) to those obtained using absorbing boundary conditions.

Mode	Excluding external fluid (Hz)	Including external fluid (Hz)
1	63.875	18.569
2	69.790	18.829
3	83.313	24.833
4	85.631	25.469
5	85.631	31.736
6	88.584	32.567
7	89.784	35.764
8	93.730	37.542

Table 1. Comparison of the effect of fluid loading on the first 8 modes of the sonar dome.

2.3 Shock response

Next, we analyze the shock response of the sonar dome. The shock is caused by the explosion of a depth charge some distance away far from sonar dome. Unlike the other cases, in this case we include a hull-like structure above the sonar dome. The model is shown in Figure 4. The hull is assumed rigid. The sonar dome and the external fluid are extended so as to be in contact with the hull. As we are interested in the early time response, and due to the higher frequency content of the shock pulse, we reduce the size of the external fluid domain. Due to the shape of the sonar dome, the fluid domain is constructed from a half-cylinder with two hemispherical end caps. A cylindrical impedance (absorbing) condition is specified on the cylindrical part of the surface, while spherical impedance conditions are used on the hemispherical parts of the surface.

An underwater explosion generates a gas bubble, containing the reaction products. This gas bubble oscillates radially and migrated towards the free surface. Due to this twofold motion, the loads on the structure vary in time, as both the bubble radius as well as its location alter the loading experienced by the structure. Such ‘bubble’ loading may be simulated in ABAQUS via the Geers-Hunter combined shock phase-bubble phase amplitude definition. For long duration analyses, it may be appropriate to include both the immediate shock loading as well as the subsequent bubble loads. However, in the present case, as we are primarily interested in the shock phase of the explosion, we use a simple pressure-time amplitude definition, specified at the standoff point, and assuming a fixed source. This assumption is justified since the acoustic wave speed in water is much larger than the bubble migration speed, so that during the course of the analysis, the bubble does not undergo noticeable movement.

The total wave formulation is used for this analysis. In this formulation, the pressure in the acoustic medium is the sum of the incident and scattered pressure. The total wave formulation is required if cavitation effects are to be considered. Typically, cavitation plays a significant role in the shock response of surface ships and neglecting its effects could lead to an underestimation of the structural response. However, in the present case, the rigid structure above the sonar dome obstructs the direct shock wave from reaching the free surface. Although reflections from the free surface in the vicinity of the structure and the resulting cavitation will eventually influence the structural loads, these effects will not alter the early time response, and were hence omitted from the current analysis.

The models used to study shock response were all initialized such that the analyses were begun at the time when the incident wave had already reached the fluid-structure interface. This initialization provides two cost benefits. First, although the loading is specified on the exterior boundary of the fluid domain, the analyst does not need to wait for wave to propagate towards the structure (an event which could consume substantial time in an explicit analysis). Second, if the incoming acoustic wave has to propagate through the fluid before reaching the structure, one has to ensure that a fine mesh is used throughout the fluid domain so as to maintain the resolution of the shock pulse; whereas, if the pulse is already at the fluid-structure interface at the onset of the analysis, it is possible to use a graded mesh – fine near the structure and coarser away from it, while still ensuring reasonable accuracy of the solution.

The results of these analyses with multiple attack scenarios identified regions on the dome that could potentially be compromised. Further analyses with appropriate mitigating measures in those regions (such as stiffeners or thicker sections) were also investigated. A comparison with experimental results is currently underway.

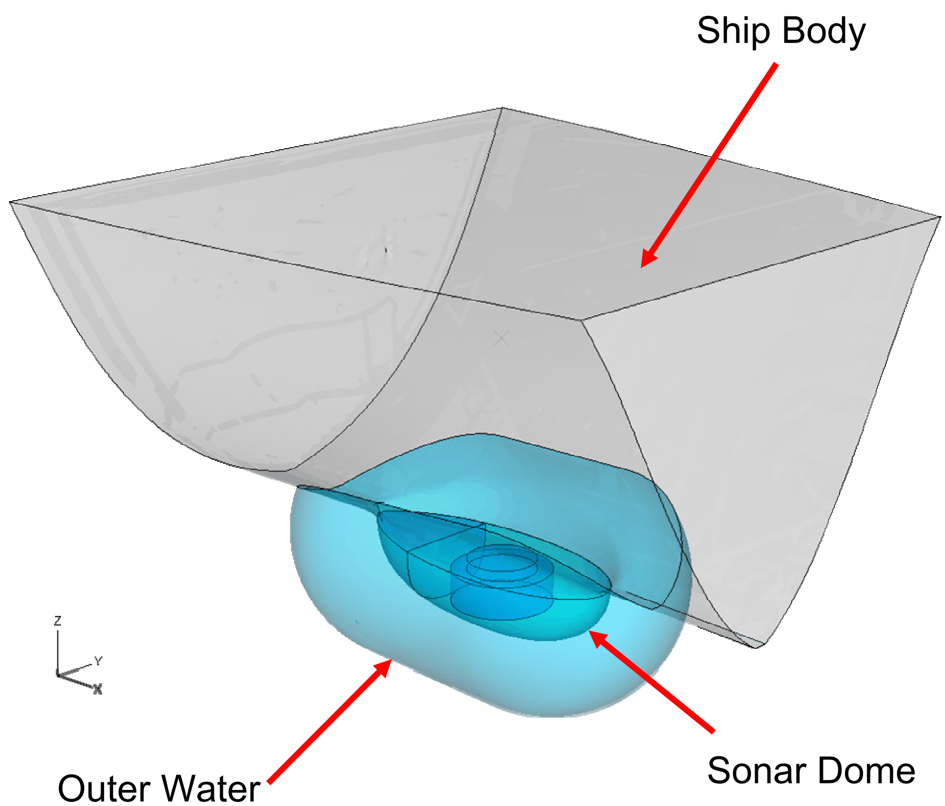

Figure 4. Sonar dome model (including ship hull) used for shock analysis

2.4 Acoustic propagation

In this case, we analyze two complementary scenarios. In the first one, we examine the outward propagation of acoustic waves generated at the sonar sensor location. These waves pass through the inner fluid and the baffle, excite the sonar dome, and the acoustic waves set up by the dome vibration then pass into the external water. In the second scenario, we examine the opposite – the propagation of acoustic waves, initially planar, as they interact with the sonar dome. These analyses are performed in the time domain in ABAQUS/Explicit. As the frequency range of interest is between 4 and 12 kHz, we require only a small fluid island around the dome. The top edges of the dome are completely constrained, as in the previous cases.

In the outward propagation study, sinusoidal acoustic pressures are prescribed at the sonar sensor and emanate radially. We are interested in the acoustic pressure at various points in the external fluid close to the sonar dome. Figure 5 shows a contour plot of the steady-state acoustic pressures in the external fluid caused by sonar-generated sound at a specific exciting frequency.

In the inward propagation study, we examine the structural response as a plane sound wave passes over the structure from the front to the back. In this analysis, we use the scattered wave formulation. In this formulation, we load the structural and the fluid interface surfaces with a planar incident wave. The pressure degrees of freedom at the nodes in the fluid represent the scattered pressure component. Figure 6 shows the steady-state acoustic pressure field in the external fluid set up by such an excitation at one specific frequency.

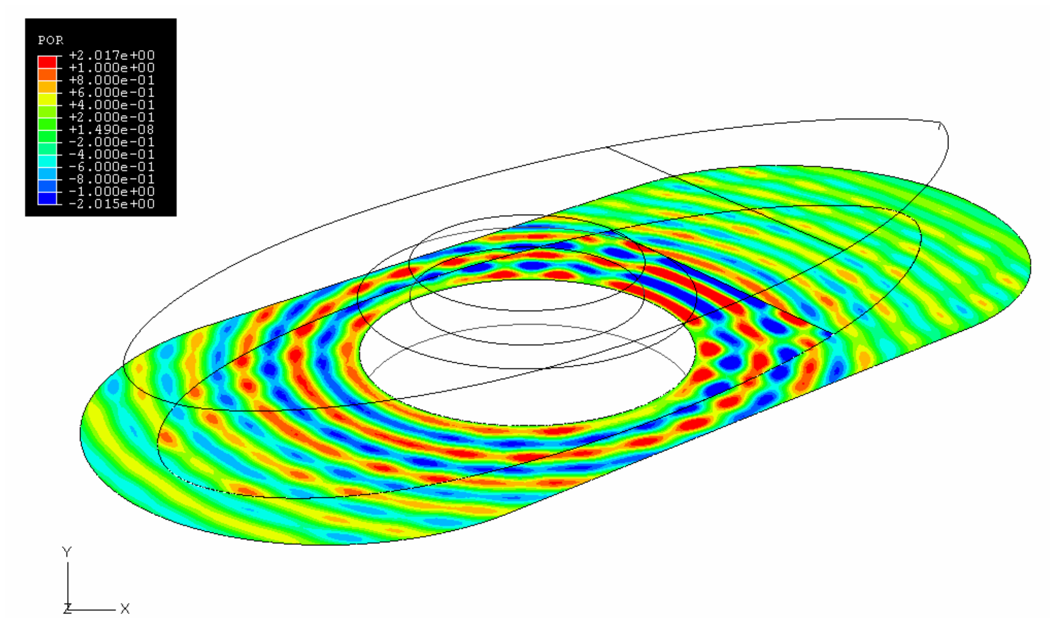

Figure 5. Acoustic pressure contours in the external fluid due to sonar-generated sound

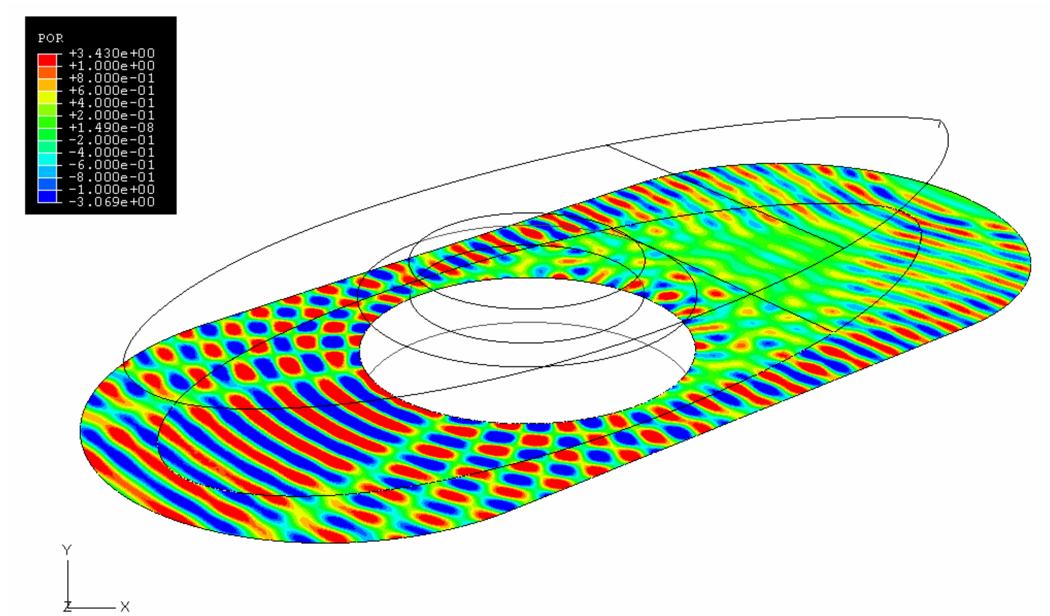

Figure 6. Scattered acoustic pressure contours in the external fluid due a planar incident wave passing over the sonar dome from front to back

3. Summary

This paper reviewed several different analyses. Each analyis was designed to examine a different aspect of the structural-acoustic behavior of a sonar dome with inner water located in an infinite fluid medium. It may be concluded that ABAQUS provides an attractive set of features that enable such analyses to be performed successfully and efficiently.