COMPLEX SHOCK LOADING ON SUBMARINE OIL PIPELINES

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1. INTRODUCTION

Underwater explosions are one of the most dangerous accidental loads that a submarine pipeline can experience. Not only can they completely destroy a structure, they can also cause a significant damage to the marine environment. Therefore, careful dynamic analysis of a pipeline when it is being subjected to a hydrodynamic shock wave is one of the primary goals when the safety of an offshore installation is a concern.

The paper concerns with a structural analysis of a fluid-filled submerged elastic circular cylindrical shell subjected to a shock wave. The interaction between a circular cylindrical shell and a hydrodynamic shock wave has been a subject of intensive investigation for the last few decades. In the vast majority of the published works, a step-exponential shock wave was considered, i.e. a shock wave with exponentially decaying pressure behind the front. Although this well-studied classical model allows a very accurate analysis in some cases, quite often more complex models are required. This occurs, for example, when reflections of a shock wave from rigid walls and/or the free surface are present. In this case, the pressure pattern behind the wave front can become quite complicated.

The situation when the free surface has an influence on the interaction process is of special practical interest. In this case, along with the first (primary) peak of pressure, a shock wave has a few secondary peaks [2]. The most noticeable of those is the second (negative) one. It is associated with the reflection of a shock wave from the free surface, and its magnitude can be of the same order as the magnitude of the primary one. Therefore, it is almost certain that the influence of a shock wave with such a complex pressure profile will differ quite significantly from the case when a step-exponential shock wave is analyzed. Thus, addressing shock loads with multiple pressure peaks appears to be worth pursuing.

There is another reason for the discussed study to receive some attention. As it has recently been found [3], the stress state of a submerged fluid-filled shell is determined by multiple wave effects in both interior fluid and a shell. This observation was made for a step-exponential shock wave. Since shock waves with multiple pressure peaks bring the next level of complexity into the wave patterns of the process, it is reasonable to expect that resonance-like phenomena are likely to happen in this case. Obviously, the study of these phenomena is of considerable practical interest. Therefore, there is a need to extend the previously accomplished research to the case of a shock wave with a more complex pressure profile.

2. MATHEMATICAL APPROACH

The equations of shell dynamics are derived using Hamilton's principle and Love's classical expression for strain-energy [4]. The fluids are assumed to be linearly compressible, and driven by the wave equation. Both fluids and a shell are coupled through the dynamic boundary condition on a shell surface. Therefore, we are dealing with two wave equations for fluid potentials, coupled with the system of equations for shell displacements, all of them being time-dependant.

As to the used methodology, the problem was solved in two steps. First, hydrodynamic pressure was obtained under the assumption that the normal displacements of a shell are known. At this stage, separation of variables was used to eliminate the space coordinates, and the Laplace transform was applied to the time one. As a result, a series representation for the total hydrodynamic pressure at the shell surface was obtained, containing, in integral form, the normal displacements (which were still unknown). Then, the derived analytical solution for the pressure was numerically coupled with the shell equations, and the spectral technique was used here. Finally, the developed hybrid analytical-numerical solution was used to simulate the interaction, and, in particular, the stress-strain state. More detailed discussion on the proposed solution scheme can be found in [3].

3. RESULTS AND CONCLUSIONS

A steel shell submerged into water and filled with oil was considered. The radius of a shell and the wall thickness were 0.50 m and 0.005 m respectively. A shock wave with one primary (positive) pressure peak and one secondary (negative) peak was considered to model a real underwater explosion similar to the one addressed in [2]. The magnitude of the secondary peak was chosen to be equal to a half of that of the primary peak. The influence of three different shock waves was analyzed. All of them had the primary peak at 0 ms (i.e. at the moment of the initial contact between a shock wave and a shell), and the secondary peaks at 0.42 ms (SW-A), 0.14 ms (SW-B), and 0.82 ms (SW-C). The magnitudes of the pressure peaks

(1250 kPa and –600 kPa) were adopted from the experimental data [2], and were the same for all the considered shock waves. The primary and secondary peaks were assumed to have the same rate of exponential decay [1]. The results were compared to a step-exponential shock wave with only one positive peak at 0 ms (SW-0).

Figure 1 shows the dynamics of the transverse stress for SW-A, SW-B, and SW-0 at the rear point of a shell. One can see that the maximum stress for SW-A is about 35% higher than that for SW-0, whereas the difference between the stresses caused by SW-B and SW-0 is insignificant (in terms of the maximum magnitude). Therefore, the resonance does take place, and it is not the magnitude of the secondary peak that determines the destructive effect that a shock wave has on a structure but the timing when the peak occurs. Namely, it has been observed that the resonance happens only if the secondary peak occurs at times close to 0.4 ms. For all other timings, the secondary peak does not cause any significant increase of stresses. Note that the maximum stresses for SW-A and SW-0 have different signs.

The observed timing of resonance has a clear physical interpretation. First, we recall that it takes $\pi r_0/c_1$ for an elastic wave originated at the front point of the shell to reach the rear point (here c_1 is the sound speed in the shell material, and r_0 is the radius of a shell), and $2r_0/c_2$ for a hydrodynamic wave in the interior fluid to come to the same point (c_2 is the sound speed in the interior fluid). Then, it becomes clear that the hydrodynamic wave in the interior fluid (caused by the primary peak of pressure) and the elastic waves in a shell (caused by the secondary peak) will arrive at the rear point at the same time, superposing and causing much higher stresses, only if the secondary peak occurs at about $t_s=r_0(2/c_2-\pi/c_1)$. For the considered system, this formula gives $t_s\sim0.48$ ms. The observed timing is slightly different because the elastic waves, as long as they have reached the rear point, need some time to actually superpose to cause a significant increase of stresses.

For the considered geometry, we define R_0 as the distance between the source of the shock wave and the free surface. Then, it is easy to show that the resonance only happens when

$$r_0=2R_0c_1c_2/(c_0(2c_1-\pi c_2)), \qquad (1)$$

where c_0 is the sound speed in the exterior fluid. In particular, for the considered system (water-steel-oil) we have $r_0\sim1.5R_0$. This formula allows one to determine the location of an explosive that is particularly dangerous for a specific pipeline, and also to predict the radius of a pipeline that will be most sensitive to an explosion with specific parameters. It should be especially noted that the distance between the source of a shock wave and a structure is not present in formula (1). Similar formulas can be derived for other geometries common in offshore engineering (rigid walls, sea bed etc.), allowing a preliminary analysis of maximum stresses without any complicated computations.

The conducted study results in the following conclusions. (1) A destructive influence that an explosion can have on an underwater pipeline significantly depends on the location of an explosive with respect to a structure and the free surface and/or walls and other obstacles. (2) When a submarine oil pipeline is being designed, a dynamic analysis of the whole system is important: it is necessary to make sure that, for the particular conditions of installation, all the resonance phenomena caused by the reflections of a potential shock wave are taken into consideration as a possible risk factor.

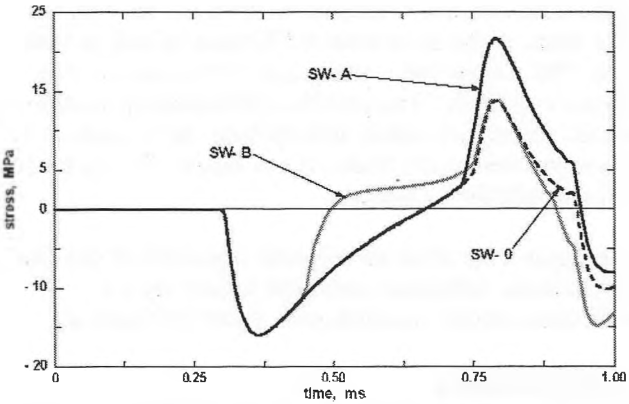

Figure 1. Transverse stresses in a submarine oil pipeline for three different shock waves.

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