SHOCK WAVE REFLECTION AND FOCUSING PHENOMENA IN FLUID-INTERACTING SHELL SYSTEMS

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1. INTRODUCTION

Submerged circular cylindrical shells containing fluids are common in ocean engineering and naval architecture applications (underwater oil pipelines for example), but compared to their evacuated counterpart, have received relatively little attention [1, 2, 3]. The present work concerns with the analysis of the hydrodynamic fields induced in such systems by an external shock loading. Particular attention is paid to the case of two different fluids inside and outside the shell as it is the most practically interesting scenario. The effect of the different phenomena observed in the fluid on the stress-strain state is of definite practical interest as well.

2. MATHEMATICAL APPROACH

The model of irrotational, inviscid, and linearly compressible fluid is used, and the shell is assumed to be thin enough for the linear theory of shells to apply; additionally, Love-Kirchhoff hypothesis is assumed to hold true as well [4]. The fluids and the shell are coupled through the dynamic boundary condition on the interface.

A semi-analytical solution has been developed, and the separation of variables was used in combination with the Laplace transform to obtain the hydrodynamic pressure in modal form. The finite difference technique was employed to obtain the harmonics of the shell displacements. The simulated images based on the solution developed were compared to the available experimental ones for some of the pressure components [5], and a very good agreement was observed.

3. RESULTS AND CONCLUSIONS

A steel shell was considered with the thickness and radius of 0.005 m and 0.5 m, respectively. The interaction with a cylindrical incident wave [5] with the rate of exponential decay of 0.0001314 s, and the pressure in the front of 10 kPa, was analyzed. Three scenarios of fluid contact were addressed: identical fluids (ς=1.00), the internal fluid with the acoustic speed lower than that in the external one (ς=0.50), and the other way around (ς=1.50), ς being the ratio of the internal and external acoustic speeds.

Fig. 1 shows the dynamics of the acoustic field when the fluids are identical. Of primary interest to us here are the reflection and focusing, thus we note the Mach stems clearly visible inside the shell at t=1.80 (also seen in the experiments [5] as well), reflected wave at t=2.10, and the focusing that occurs after the reflection takes place. This is the classical "reflection-focusing" pattern observed earlier for reflection in cylindrical cavities [5], but it is of interest to note how the phenomena in the internal fluid manifest themselves in the external fluid (the elastic interface makes such transition possible).

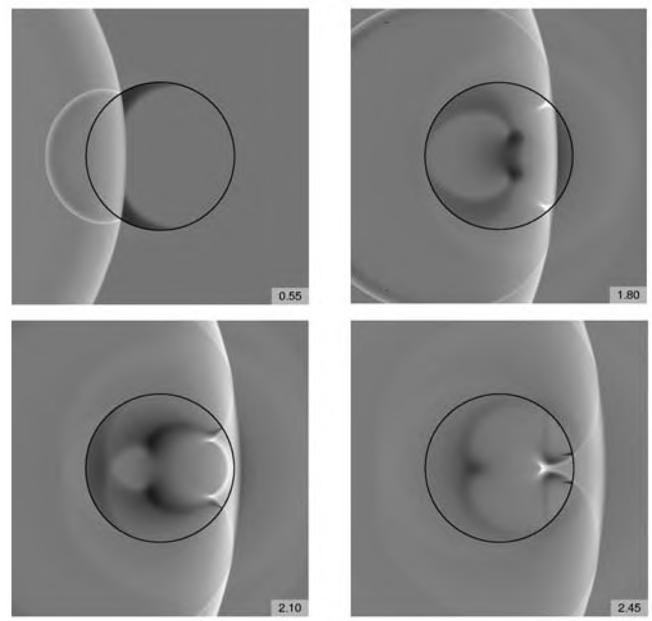

Figure 1. The dynamics of the acoustic field for the case of two identical fluids (ς=1.00).

Fig. 2 shows the dynamics of the acoustic field when the acoustic speed in the internal fluid is lower than that in the external one, ς=0.50. We observe that the hydrodynamic pattern in this case is dramatically different – not only the shape of the internal wave is no longer convex, there is no "reflection-focusing" sequence observed anymore. Instead, we observe the pre-reflection focusing at t=3.90 followed by the reflection shortly after, and then the secondary, post-reflection focusing. Thus, in the case of ς<1.00 a new, "focusing-reflection-focusing" sequence is possible which means that the case of two different fluids can be not only qualitatively, but also phenomenologically different. We note that the pre-reflection focusing occurs shortly before the internal wave falls on the back wall, and that could have important implications in terms of the stress-strain state. We also note that the internal shock wave is no longer a geometrical continuation of the external one.

Fig. 3 shows the dynamics of the acoustic field when the acoustic speed in the internal fluid is higher than that in the external one, ς=1.50. In this case, the internal shock wave is not a geometrical continuation of the external one either, but in a different way, i.e. it has an even higher curvature than the incident wave. The internal wave reaches the tail region ahead of the external one, and the Mach stems of the internal reflection are not only clearly visible inside the shell, but also manifest themselves in the external fluid. In terms of the sequence of the reflection and focusing phenomena, they are the same as in the case of two identical fluids, but are shifted in time and occur earlier than in that case. The appearance of the reflection and focusing patterns is very similar as well. This scenario where the internal acoustic speed is higher than the external is, therefore, less unique than its $\varsigma<1.00$ counterpart. We also note what could be referred to as the "leaking" of the internal shock wave into the external fluid, t=1.40.

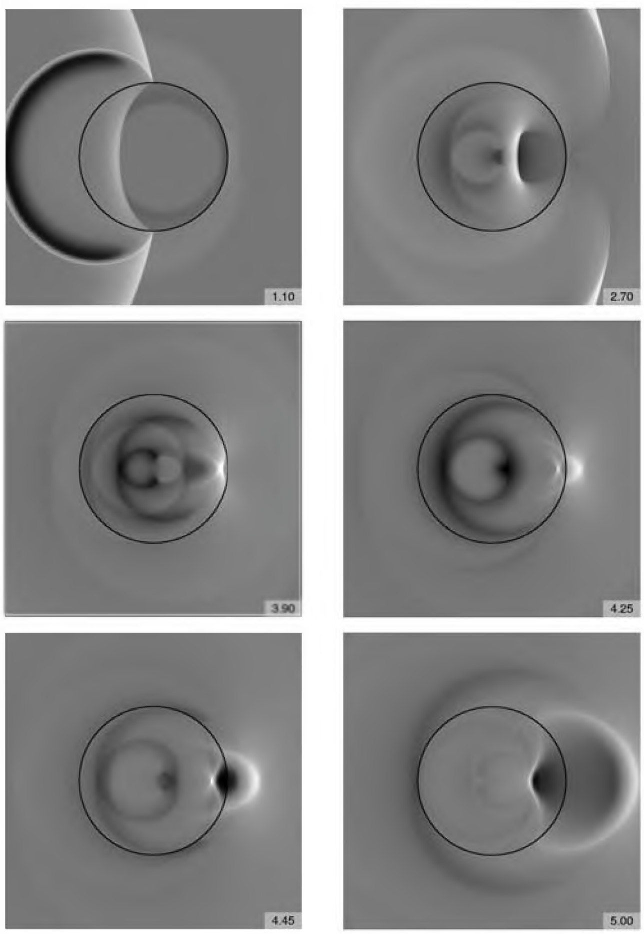

Figure 2. The dynamics of the acoustic field for the case of $\varsigma=0.50$.

We can therefore conclude that the classical "reflection-focusing" [5] pattern is not always present in the fluid-contacting shell systems, and other scenarios are possible, depending on the ratio of the internal and external acoustic speeds. In particular, a more complex and practically interesting "focusing-reflection-focusing" scenario could occur.

Another aspect we would like to comment on is the effect of the shock wave reflection and focusing effects on the stress-strain state of the shell. The case of two identical fluids was addressed in some detail in [6], but not that of the different fluids. When $\varsigma>1.00$, the effects observed in the $\varsigma=1.00$ case are simply shifted in time, as were the reflection and focusing themselves. When $\varsigma<1.00$, however, the pre-reflection focusing in some cases occurs very close to the shell surface thus causing a high tensile stress in the tail region very late in the interaction. For example, when $\varsigma=0.50$, this peak stress can be up to 60% of the highest compressive stress observed in the shell. This effect is of noticeable practical importance, and is being currently further investigated.

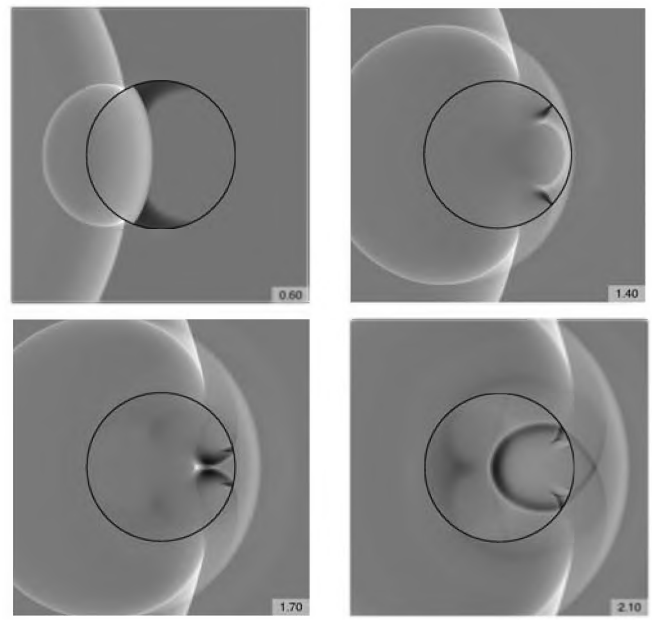

Figure 3. The dynamics of the acoustic field for the case of $\varsigma=1.50$.

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