On the use of bounded beam effects to characterize fluids in containers

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Abstract

Recently, several papers have appeared on the characterization of fluids by means of laser excitation if the fluid is fully accessible \cite{1} or by means of pulse echo techniques if a fluid is contained in a small container \cite{2}. However, in many practical applications fluids are contained in large containers whereas through transmission or pulse echo is not evident and often impossible for example due to damping effects or inaccessibility. The current paper introduces a technique which is based on bounded beam effects. If a container is radiated with ultrasound at a Lamb wave angle, then the reflected bounded beam is deformed considerably. The characteristics of this reflected beam are influenced by the properties of the fluid and can be used as a way to characterize fluids without having to rely on accessibility on both sides of the container or on pulse echo techniques.

1. Introduction

This paper is a response to the many requests and suggestions of several sources in the beverage industry and also in the dock industry over the last couple of years for studying the possibility of fluid characterization in closed containers in a non-destructive way. In the existing literature one method is based on time of flight measurements and can be found in Abrehouch et al. \cite{1}. The method requires access to both sides of a container and at least requires containers that are thin enough so that damping does not prevent sound from traveling from one side of the container to the other. Hence application to large containers is not realistic. The method studied here is based on beam deformations in reflection on the skin of a closed container, which only requires access from one side and is therefore an inviting technique for relatively large containers. It is known that bounded beams show non specular reflection phenomena at the Rayleigh angle for liquid-solid structures \cite{3-7} or at a Lamb angle on a liquid-solid-liquid structure \cite{8-10}. However as far as we know, all papers dealing with the latter case study the situation where a plate separates two identical liquids. In this paper, we consider an isotropic plate in between two different liquids. The upper liquid is always water, while the lower liquid can be any kind of liquid. First we show that critical angles corresponding to the generation of leaky Lamb waves of order higher than zero are practically not influenced by the nature of the lower liquid. This leads to the conclusion that for a considered plate, a fixed critical angle can be chosen. What will change however are the properties of effects that are connected to that critical angle. In particular, if a bounded beam is incident from the upper liquid on a plate in between that upper liquid and a lower liquid, the generation of leaky Lamb waves will induce deformation of the reflected beam. Consequently a sensitivity study is done on the influence of density and wave velocity of the lower liquid on the characteristics of the deformed reflected beam. Finally it is shown that measuring the characteristics of the reflected deformed beam enables us to distinguish between oil and water for the lower liquid. The latter is done by means of numerical simulations and by means of experiments using a Schlieren experimental setup.

2. Numerical simulations

Numerical simulations occur by using a Fourier transform of the incident beam and then letting each plane wave interact with the container skin. This individual interaction is simulated by writing transmitted and reflected fields as a superposition of all possible propagation bulk modes and then requiring continuity of normal stress and normal displacement on each interface. The incident profile is given by a Gauss function

\begin{equation}
 f(x) = \exp\left(-x^2/W^2\right)
\end{equation}

Numerous simulations have convinced us that the dispersion curves are not significantly altered if the lower liquid changes. This means (at least for Lamb modes of order higher than zero) that the Lamb angles are invariant. Hence the strategy to perform liquid characterization will consist of fixing the angle of incidence at a certain critical angle corresponding to the generation of Lamb waves of order higher than zero and study the influence of the liquid underneath the plate on the beam deformation phenomena that occur at that

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critical angle. In other words we will study differences in the Schoch effect features by changing the lower liquid.

3. Sensitivity Analysis

In this section we consider as an example a stainless steel plate of 4mm thickness in between water and a virtual liquid. The virtual liquid is characterized by the same wave velocity as water, but has a varying density. We consider an incidence angle of $15^\circ$ which corresponds to a critical sound velocity of 5720m/s and coincides with the generation of first order symmetrical Lamb waves. Several calculations have shown us that there is never an invertible function that relates the reflected beam characteristics with the physical parameters of the lower liquid. Below, we show just a few cases of our sensitivity analysis.

3.1. Sensitivity of reflected beam profile on density of lower liquid

In Fig. 1 the reflected beam profile is plotted as a function of the density of the lower liquid for a sound wave velocity equal to the one in water. The Schoch effect is clearly visible.

3.2. Sensitivity of reflected beam profile on wave velocity in lower liquid

In this section we consider the same situation as in the previous one except for the fact that we maintain a constant density of 1000kg/m$^3$ and vary the wave velocity for the lower liquid. The results are shown in Fig. 2. It is seen that the height of the dip as well as its position are influenced by the wave velocity in the lower liquid.

4. Example: Oil and Water

As in the sensitivity analysis again we consider an angle of incidence of $15^\circ$. In this section we study the ability of the proposed method to distinguish between liquids in the same container. First in Fig. 3 the numerical example is shown for a 4mm thick stainless steel plate separating water and consequently three different liquids.

It is seen that the profile looks different for water, sunflower oil and brine. This motivated us to perform experiments on such liquids. For practical reasons the experiments were performed on a relatively thin pyrex...
glass container (a petri dish) as depicted in Fig. 4 and at a frequency of 3MHz.

This is the principle of a Schlieren setup. For practicality we have inverted the obtained pictures so dark regions correspond to the presence of sound while light areas corresponds to spots with no sound. Simulations have been performed for a pyrex glass plate in between water and the liquids.

**Figure 4**: Schematic of the pyrex glass container used in our experiments. The sponge serves as a simulator for thick containers. Sound impinges from above.

The skin thickness was 1.8mm. The physical beam width was 1cm. The sponge (see Fig. 4) was used to prevent secondary reflections inside the container and therefore enabled us to experimentally simulate the situation for much larger containers. The liquids we have used are sunflower oil and water. From dispersion curves for pyrex glass it can be found through Snell’s law that for 3MHz and a thickness of 1.8mm the critical angle corresponding to the $S_1$ mode is $15.8^\circ$. We have applied this angle in the subsequent experiments. A Schlieren setup was used in order to visualize the incident and reflected beam. Schlieren pictures are obtained by penetrating the region of interest with a coherent wide parallel laser beam. This light is then focussed on a black spot whence no light can reach a projection screen behind the black spot. In the event of deflections or diffraction in the region of interest, a part of the laser light will miss the black spot and will illuminate the screen.

**Figure 5**: Numerical simulations of the reflected beam profiles (in amplitude) for oil and water as the liquid inside the pyrex glass container of Fig. 4.

This corresponds physically with the experimental situation because the absorbing sponge simulates the effect of a half infinite space. In Fig. 5 the numerical simulations are shown for the water case and also for the sunflower oil case. The main difference that should

**Figure 6**: Schlieren picture of the incident and reflected sound beam on the container as depicted in Fig. 4. The added solid arrow starts at $X'=0$ and has a physical length of 1cm.

**Figure 7**: Same as Fig. 6 except that this is the case for sunflower oil instead of water. It is noticed that the second lobe is wider, which is in agreement with the numerical simulation of Fig. 5.
be noticed on Schlieren pictures is the difference in width of the nonspecular lobe, which is much wider for sunflower oil than for water. Indeed if we compare this to the obtained Schlieren pictures (see Figs 6-7), we find agreement. Schlieren pictures cannot be used for exact amplitude determination, whence only qualitative comparison is possible.

5. Concluding Remarks

It is shown that bounded beam effects in reflection on closed containers are susceptible to the kind of contained liquid. The possibility is studied to perform inversion of the parameters of the reflected beam pattern in order to obtain the characteristics of the contained liquid, but it is shown that such an inversion is not realistic because there is not an invertible function that links the reflected beam pattern to the liquid characteristics. Nevertheless it is shown that the technique is certainly possible to distinguish between different liquids by means of a ‘true or false’ test method.

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7. References