Asymmetrical Propagation of Powerful Sound in Double-Layer Liquid

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Abstract

The asymmetry sound propagation has been observed experimentally in coupling double-layer of liquids with different cavitation thresholds. When the sound wave propagates from the high threshold liquid to the low one, it is possible that both two liquids can avoid the cavitation under suitable driving pressure. However, the driving pressure will cavitate the low-threshold liquid though the high-threshold liquid keeps uncavitated when the sound propagates oppositely. The additional attenuation due to cavitation makes the distribution of the sound field different between two opposite propagations, leading to the asymmetrical sound propagation. The observations can be reproduced by the numerical simulation in framework of the modified two-phase fluid theory.

Keywords: asymmetric transmission, frequency spectrum broadening, sound pressure

Introduction

The electron diode, invented by Fleming more than one hundred years ago, is widely applied in modern circuit to revolutionize our life dramatically. Besides, it is the first component of realizing one-direction propagation of energy. It has encouraged people to investigate the asymmetric transmission of other kinds of energy. Recently, with the development of numerical calculation, people return to the research of asymmetric transmission of energy, and have made significant progress. Li *et al.* numerically simulated the coupled Frenkel-Kontorova lattice model and find the microphenomenon of it deviates from the Fourier thermal conductivity law.[1] The asymmetric energy transmission phenomenon which is named as heat rectification was reported. After that, investigation on heat rectification by equivalent LC transmission circuit also supports the phenomenon of heat rectification.[2] The asymmetric transmission of acoustic energy, namely the acoustic-diode, is also proposed and verified by experiment during the same period.[3] The asymmetry transmission systems mentioned above are usually carefully designed. During our research on the propagation of sound wave in cavitating liquid, we find the asymmetric transmission also exists in a simple double-layer liquid system when powerful ultrasound transmits through it. Further more, the direction of sound energy rectification can be reversed under different driving sound pressure.

Model and mechanism

We consider a simple harmonic sound wave propagating from one end with driving pressure amplitude P_{dr} to the other end with output pressure amplitude p_{out} in a 1-dimensional two layers of liquids coupled by a sound passing membrane. Both thicknesses of the left and right liquids are a. For the transmission from the left liquid to the right one (L-R transmission), $P_{dr}=P_L$, and $p_{out}=p_R$ (Fig. 1). Otherwise $P_{dr}=P_R$, and $p_{out}=p_L$ for the R-L transmission. Let Q_L and Q_R to be the cavitation threshold pressures of the left and the right liquids, and $Q_L<Q_R$ without loss of generality. The asymmetry can exist between the L-R and R-L transmissions. If $Q_L>P_{dr}\geq Q_R$, it is possible that there is no cavitation in both left and right liquids for the L-R transmission. At first there should be no cavitation in the left liquid due to $P_{dr}<Q_L$. The sound pressure amplitude at the interface between two liquids, $p(0)$, has been decayed by the left liquid, so that $p(0)<P_{dr}$. If $p(0)$ is further lower than the threshold pressure of the right liquid Q_R, then the right liquid can not be cavitated too. Therefore, there is no any cavitation to be taken place for the L-R transmission. On the contrary, for the R-L transmission the right liquid will be cavitated because of $P_{dr}\geq Q_R$. As is well known, the cavitation will yield an additional attenuation called cavitation screening,[5] leading to that the R-L transmission is more difficult than the L-R transmission. In other words, the sound wave is rectified in this system.

Asymmetrical sound transmission system

For verifying the mechanism of asymmetrical transmission, we design the experimental system as shown in Fig. 2. The cross section of the rectangle glass container is $0.09\times0.09\text{m}^2$ and each layer length of the host liquids a is 0.1 m. Both end faces of the container are stainless steel plates of 0.5 mm in thickness, and two ultrasound transducers (40

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kHz) are bonded to the outer sides of two end faces. A waterproof sound passing membrane is positioned at the middle of container to separate the left- and right-liquids. In our experiment, the host liquids are 30 vol% alcohol solution (AS(30%)), AS(20%) and water, and their cavitation threshold pressures are 0.4 bar, 0.5 bar and 0.9 bar respectively. Acoustic absorbing material is attached to the internal lateral face of the container to eliminate the reflection of sound wave as much as possible. During the experiment the liquids are cycled continuously so that the properties of the host liquids keep unchanged. The temperature of host liquids is maintained at 20±2ºC.

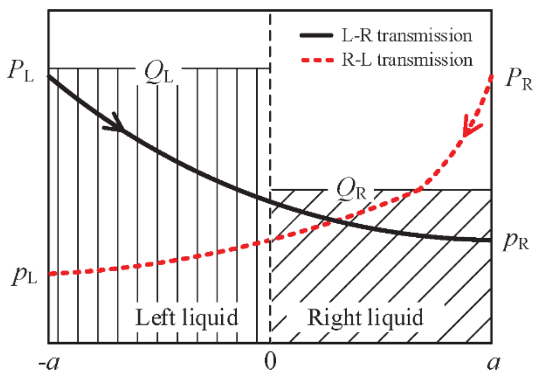

FIG. 1: Asymmetrical Propagation in double –layer cavitating liquids

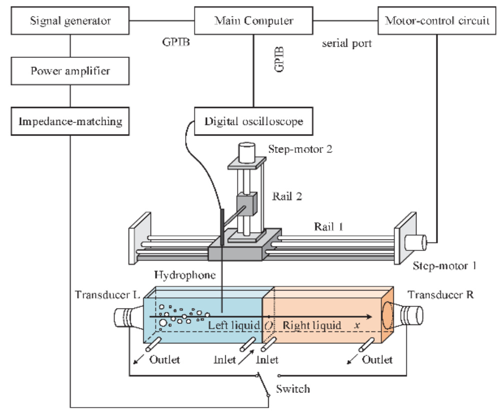

FIG. 2 Schematic diagram of the experimental system

A sinusoidal signal at about 40 kHz is output by a function generator (Agilent 28335A, US), then amplified by a power amplifier (B&K 2716, Denmark) to drive the transducer L or R after impedance matching. The L-R transmission with P_{dr}=P_L and p_{out}=p_R, or the R-L transmission with P_{dr}=P_R and p_{out}=p_L is chosen by a switch. A programmed scanning system has been constructed for quickly and precisely measuring the sound field in the container. There are two orthogonal guide rails parallel and perpendicular to the container in the system, respectively. Two slide blocks are rode on them respectively (Fig. 2). A needle hydrophone(RESON, TC4013, Denmark) is held at the vertical slide block to measure the sound pressure in the container. Both two blocks are driven by step-motors via the motor-control circuit at the spatial resolution 0.05 mm. The output of the hydrophone is fed to a digital oscilloscope (Agilent Infiniium 54810, US). The function generator, motor-control circuit, and oscilloscope are programmably controlled by a main computer through its GPIB and serial port. The amplitude of fundamental pressure is obtained by FFT calculation and calibration based on the time-domain data acquired by the oscilloscope. The measuring step of the horizontal block is 5 mm. Every amplitude data has been binned over itself and its left and right adjacent measurements to smooth the spatial jumping due to cavitation.

Experimental observations

In our experiment the right liquid has been set as AS(30%) whose threshold pressure is the lowest among the host liquids, that is, Q_R=0.4 bar, while the left liquid can be chosen one of other host liquids.

At the beginning, the water with the threshold pressure Q_L=0.9 bar is chosen as the left liquid, and P_{dr} is set to be 0.6 bar, so Q_L>P_{dr}>Q_R, the same case mentioned in section II. Figure 3(a) shows the distribution of sound pressure amplitude $p(x)$ in this system, which consists with our prediction in Section II (see Fig.1). Indeed, hardly any cavitation bubbles have been observed in both two liquids in the L-R transmission. Nevertheless, in the R-L transmission some bubbles are clearly visible in the right liquid. As a result, the sound propagation is asymmetric between the L-R and R-L transmissions, that is, p_R>p_L.

Then, we set P_{dr}=1.8 bar, so P_{dr}>Q_L>Q_R. The distribution of $p(x)$ is plotted in Fig. 3(b) where the asymmetry between the L-R and R-L transmissions is still observed. $p(x)$ almost maintains higher than Q_L and Q_R in the L-R transmission, whereas only keeps higher than Q_R in the right liquid in the R-L transmission. Furthermore, p_R<p_L. It is a new

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mechanism of the asymmetric transmission and differs from that described above or in Section II. We believe larger scope of cavitation leads to greater attenuation, leading to $p_R<p_L$. These experiments show the direction of the rectification is dependent on P_{dr} with respect to the cavitation threshold pressures.

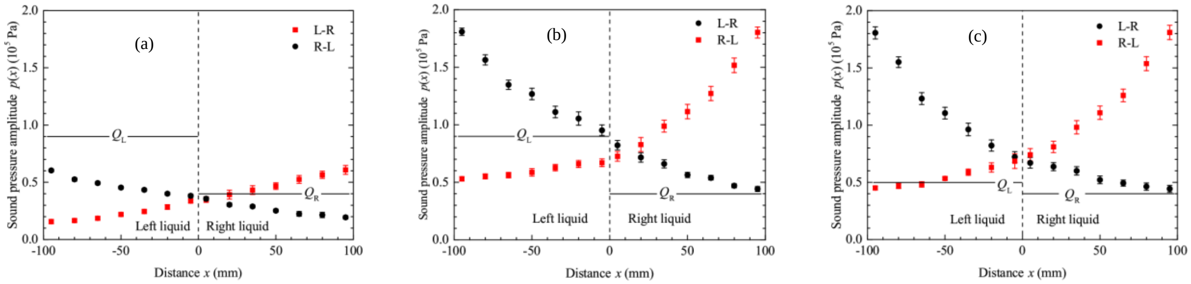

FIG. 3 Distributions of sound pressure amplitude in (a) water-AS(30%) driven by P_{dr}=0.6 bar, (b) water-AS(30%) driven by P_{dr}=1.8 bar, and (c) AS(20%)-AS(30%) driven by P_{dr}=1.8 bar, respectively.

Finally, we note that the system will loss the asymmetry if the gap between Q_L and Q_R vanishes. To verify it, we set the left liquid as AS(20%) whose cavitation threshold is 0.5 bar, near to that of the right liquid, and P_{dr}=1.8 bar. The observation of $p(x)$ in the L-R and R-L transmissions shows that output sound pressures p_R and p_L are approximately identical (see Fig. 3(c)). We can conclude that a large threshold gap is necessary for realizing the remarkable asymmetry in sound propagation.

Theory and simulation

The sound wave propagating in cavitating liquid can be described by the Helmholtz equation[6]

$$\nabla^2 p + k_m^2 p = 0, \tag{1}$$

where p is the sound pressure amplitude and k_m is the complex wave number expressed as:

$$k_m = \frac{\omega}{c_m} - \mathrm{i}\alpha_\eta, \tag{2}$$

with c_m and α_η being the acoustic velocity and attenuation coefficient in bubbly liquid respectively. Both c_m and α_η are tedious functions of the volume fraction of the two-phase liquid $\beta(x)$.[6] For our experimental condition, we assume the volume fraction $\beta(x)$ is proportional to the local sound pressure $p(x)$ exceeding the cavitation threshold $Q(x)$, that is,

$$\beta(x) = \begin{cases} 0 & p(x) < Q(x) \\ B[p(x) - Q(x)] & p(x) \geq Q(x) \end{cases}, \tag{3}$$

where B is a model parameter.

In the theoretical model of Ref. [6], the authors only take account of the attenuation caused by cavitation bubbles. In our situation the bulk attenuation of the host liquids is not ignorable, so that an additional attenuation coefficient α_0 has been inserted into α_η [7], that is, $\alpha_0 + \alpha_\eta \rightarrow \alpha_\eta$.

By solving Eq.(1) the sound pressure distribution can be acquired. For our double-layer liquid, water-AS(30%), the cavitation threshold function $Q(x)$ can be expressed as

$$Q(x) = \begin{cases} Q_L & -a \leq x \leq 0 \\ Q_R & 0 < x \leq a \end{cases}, \tag{4}$$

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where a=0.1 m, Q_L=0.9 bar, and Q_R=0.4 bar, respectively. Parameters used in numerical simulation are the same as those in Ref. [6]. The bulk attenuation coefficient α_0 is set as 4.0 m^{-1} and $B=2.0\times10^{-8}$ Pa^{-1}.

Figure 4 shows the calculated distributions of the sound pressure amplitude in the water-AS(30%) driven by 0.4 bar, 0.6 bar, 1.8 bar and 1.4 bar, respectively. It is obvious that there is no any asymmetric transmission to be appeared in the double-layer liquid if the driving sound pressure amplitude is lower than both Blake threshold pressures Q_L and Q_R (see Fig. 4(a)). When P_{dr} rises, P_{dr}=0.6 bar for example, the distribution of the sound pressure (Fig. 4(b)) shows that the system undergoes the asymmetric transmission as Fig. 3(a). If P_{dr}=1.8 bar, the distribution (Fig. 4(c)) reproduces the experimental asymmetric transmission of Fig. 3(b).

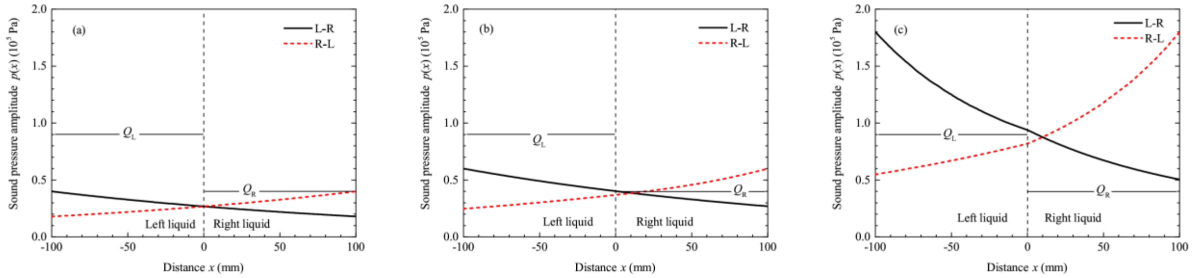

FIG. 4 Calculated distributions of the sound pressure amplitude in water-AS(30%) driven by (a) P_{dr}=0.4 bar, (b) P_{dr}=0.6 bar, and (c) P_{dr}=1.8 bar, respectively.

Conclusion and discussion

We propose a model which is composed of two liquids with different cavitation thresholds to realize the asymmetric transmission of sound wave. Experimental results show there exists two kinds of rectifying mechanism of sound wave, and the direction and efficiency of rectification is related to the driving sound pressure and the cavitation threshold pressures of the two liquids. The dependency of the rectification effect on these factors is analyzed in more details according to numerical simulation. In the future, we will explore the method to improve the asymmetry and perfect the theory.

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