AIP Applied Physics Letters

Influence of gases on Lamb waves propagations in resonator

Lianqun Zhou, Jean-François Manceau, and François Bastien

Citation: Appl. Phys. Lett. **95**, 223505 (2009); doi: 10.1063/1.3268785
View online: http://dx.doi.org/10.1063/1.3268785
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v95/i22
Published by the American Institute of Physics.

Influence of gases on Lamb waves propagations in resonator

Lianqun Zhou,[1] Jean-François Manceau,[2,a)] and François Bastien[2]
[1]*Changchun Institute of Optics, Fine Mechanics, and Physics, Chinese Academy of Sciences, Changchun 130033, People's Republic of China; Graduate School of Chinese Academy of Sciences, Beijing 100039, People's Republic of China; and Department of MN2S, FEMTO-ST Institute, CNRS, Université de Franche-Comté, 25044 Besançon, France*
[2]*Department of MN2S FEMTO-ST Institute, CNRS, Université de Franche-Comté, ENSMM, UTBM, 32 avenue de l'Observatoire, 25044 Besançon, France*

(Received 10 September 2009; accepted 5 November 2009; published online 3 December 2009)

We investigate gases effects on the Lamb wave resonant modes. Various frequency ranges are studied for the antisymmetric mode considering wave velocities either higher or lower than the gas sound velocity. We observe that the relative frequency shifts in the low frequency range of the antisymmetric mode is rather important; in the high frequency range of this mode, the quality factor decreases quickly when the Lamb wave phase velocity approaches the gas sound velocity. We find a good agreement between calculations and experiments in air and helium. The results suggest the possibility to get aerodynamics parameters of gas flow. © *2009 American Institute of Physics*. [doi:10.1063/1.3268785]

Aerodynamics is a branch of fluid mechanics, mainly dealing with the boundary layer,[1,2] that has a long history, especially in gases vibration relaxation, wind tunnel, and chemical reaction.[2–4] As Lamb waves have large sensitivity and low attenuation,[5] they have the potential to be used in these fields, but there are so far few results reported in the literature. As the gases are very light, people usually check the dispersion curves by comparing the measurements in air with calculated results in vacuum.[6–8]

When Lamb waves propagate in a solid membrane with a wavelength much greater than the thickness of the membrane (d), we have two modes, namely, the antisymmetric mode A_0 and the symmetric mode S_0. The result is based on the assumption that the membrane is infinite; whereas in reality, especially in micro sensor fields, the membrane is a few millimeters wide.[9,10] With a width-limited membrane, the boundary conditions at the lateral extremities give rise to resonant modes. These resonant modes are originating from Lamb wave modes A_0 or S_0. These modes are called here MA_0 and MS_0 and can be characterized by their Q factor. In this letter, we will study theoretically and experimentally the MA_0 modes. We will show the possibility to use these resonant modes to study the influence of gases which is different from state of the art methods.[6,11,12]

When fluids are present on surfaces of the membrane and taken into account for the propagation of the waves, the MA_0 modes are disturbed by the fluid. But the MS_0 are practically not disturbed, because the particle displacement in MS_0 is mainly parallel to the surface and the volume of fluid affected is very small compared to the case of mode MA_0. Accordingly, we only discuss the MA_0 modes in this letter. In a first approximation we can distinguish between the following two cases:

(1) The case where the resonant mode MA_0 is considered with $V_L < V_f$, that is to say when the phase Lamb wave velocity (V_L) is smaller than the phase velocity of sound in the fluid (V_f). This case will be noted MALF with LF for low frequency.

(2) The case where MA_0 is considered with $V_L > V_f$, that is to say when phase Lamb wave velocity is greater than the phase velocity of sound in the fluid. This case will be noted MAHF with HF for high frequency. If the fluid is a liquid, this case is difficult to use because of the very high attenuation,[13] but it is different in gases as we will show later.

When Lamb waves propagate in infinite solid membrane with fluid on both sides, we can consider that Lamb wave is the combination of two waves in the membrane and one wave in the fluid.[14] This physical problem has been analyzed theoretically by potential function method and partial wave theory.[14] The equation system accepts nonattenuated Lamb wave solutions if we consider the wave number k as real. In air this solution corresponds to $V_L < V_f$ (case MALF). We can obtain the dispersion curves for the vacuum and the air cases and the difference between these two conditions are clearly shown in Fig. 1. This means that the air boundary conditions can affect the Lamb wave propagation and the dispersion curve. And in that case, there also exist evanescent waves (EW) in the gas which should be sensitive to the gas characteristics. If we accept a complex solution for the wave number k, we will get a wave in the fluid propagating with an oblique direction out of the solid-fluid plane. Therefore, the Lamb wave can be considered as a leaky Lamb wave and the energy of this "Lamb wave" decreases due to

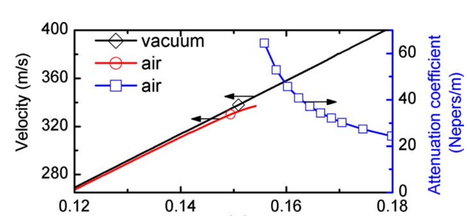

FIG. 1. (Color online) Calculated dispersion curves and attenuation curves: *V-kd* dispersion curves for MALF case and α-*kd* curves for MAHF case.

[a)]Electronic mail: jfmanceau@femto-st.fr.

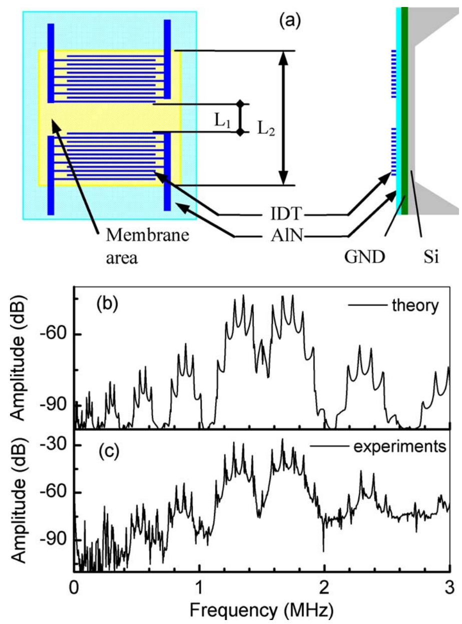

FIG. 2. (Color online) Calculated and experimental responses of the A_0 Lamb wave resonance modes (MA_0 case) are as follows: (a) Experimental device, length ($L1=2.94$ mm and $L2=7.84$ mm), thickness (IDT: 0.2 μm, AlN: 1.8 μm, GND: 0.2 μm, and Membrane: 12 ± 3 μm) and IDT period: 400 μm; (b) Calculated response of the A_0 Lamb wave resonance modes; and (c) Experimental response of the A_0 Lamb wave resonance modes in the helium.

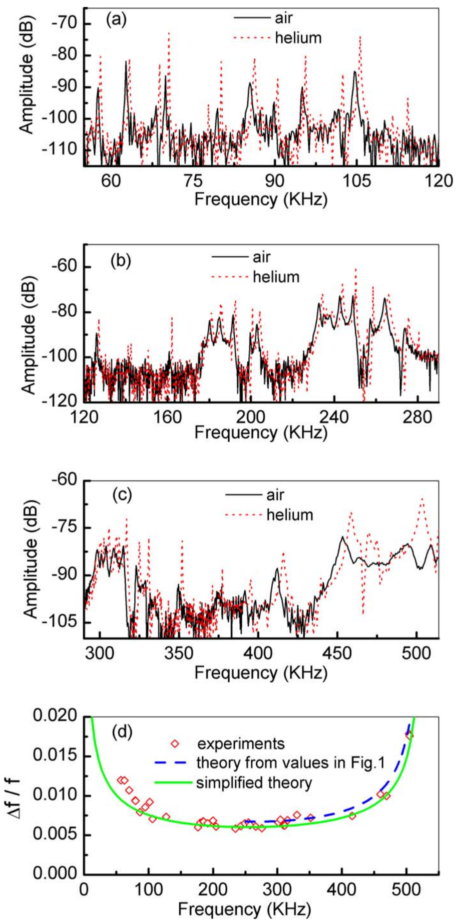

FIG. 3. (Color online) Experimental and analytical low frequency responses of A_0 mode (MALF case): [(a)–(c)] Measurements of MALF case by sweeping the frequency response; (d) Comparison between the experiments and theory of the frequency shifts in MALF case.

losses. In liquid, the wave amplitude decreases too fast along the solid, a few wavelengths and is difficult to detect with the opposite interdigital transducer (IDT). In air, this leaky mode corresponds to the case MAHF and calculated attenuation coefficient (α) is moderate, as shown as Fig. 1. This wave can be detected directly by using the response of our device.

Another calculation has been performed for the distribution of resonant modes associated with Lamb wave A_0 and the structure of the device used here is sketched in Fig. 2(a). These calculations take into account the interferences of wave emitted by IDT and the reflections at both ends of the membrane, the results are given in Fig. 2(b). We note that the electromagnetic interaction between the input and the output IDT are not taken into account in the model.

In order to verify these calculations and check the influences of the gas layer on the Lamb wave propagations, we do experiments using air and helium. Both experiments are performed at room temperature and at atmospheric pressure. When we sweep the helium response from 0 Hz to 3 MHz, we obtain the curve shown in Fig. 2(c), which is globally very similar to the calculated response shown in Fig. 2(b). This proves that our Lamb wave resonant modes calculations are appropriate. The following experiments are performed to verify the gas influences by using these Lamb wave resonant modes. The first experiment is done for the low frequency range resonant A_0 mode and the result is shown in Figs. 3(a)–3(c), which shows clearly the frequency shifts corresponding to the MALF case. We make a simplified theory to check the relative frequency shifts ($\Delta f/f$) as $(\rho_{air}\delta_{air}-\rho_{helium}\delta_{helium})/M$, in which ρ is density of the gas, δ is the EW penetration depths, and M is the mass per area of the membrane. The comparison between the calculations and experiments for the frequency shifts, shown in Fig. 3(d), agrees quite well. The shape of the curve looks like a letter 'U', which means that there are two ranges of frequency suitable for sensing. The reasons for this shape are that the evanescent penetration depths depend both on the magnitude of the wavelength which is large at low frequency and the velocity of the Lamb wave as it approaches the velocity of sound. This indicates a good potential in application for sensing fields, especially gas biochemical reaction.

The experiments for high frequency of resonant A_0 mode, demonstrated in Fig. 4(a), show mainly attenuation.

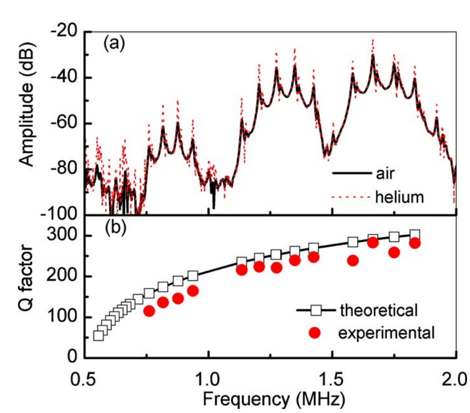

FIG. 4. (Color online) Experimental and analytical high frequency responses of A_0 mode (MAHF case): (a) Measurements of MAHF case by sweeping the frequency response; and (b) Comparison between the experiments and theory of Q factor for MAHF in air.

Here, we have the possibility to evaluate the losses in air quantitatively due to the leaky wave. The corresponding resonance factor will be noted Q_L. Experiments give the Q factor in helium Q_{He} and in air Q_{Air}. The attenuation in helium is mainly due to losses when the wave is reflected on the extremity (border) of the membrane. These losses will be considered the same with air, as the viscosity of the helium and air are small enough, and is not taken into account here. But, in air we have also to consider losses due to the leaky wave. Then in first approximation we put the deduced value of Q_L from Fig. 1 to $1/Q_L+1/Q_{He}=1/Q_{Air}$. The comparison between experiment and theory is rather good [see Fig. 4(b)]. The discrepancy is due to the fact that physical losses in the volume are not taken into account but it only amounts to a small factor. When the V_L approaches V_f in the MAHF case, the Q factor will decrease quickly and nonlinearly. There exists a critical point around V_f, where the Q factor becomes theoretically almost zero. This decrease mainly depends on the sound velocity and density of the medium. As the density influences of the gas can be retrieved by the MALF case, the MAHF case can easily give the influence of the sound velocity.

In conclusion, we demonstrate the effects of gases layers on the Lamb waves propagations and responses by theoretical and experimental analysis. The good agreements between theory and experiment demonstrate the following result: the presence of gases in the low frequency resonant modes of A_0 mainly affect the frequency shifts and the relative frequency shifts are different depending on the frequency of the resonant modes; the high frequency resonant modes of A_0 are mainly attenuated by the presence of gases, and these influences could be detected and analyzed by checking the Q factor. These different effects can be used at the same time based on only one device by sweeping the Lamb wave resonant modes. Therefore, it is possible with these three different behaviors (MALF, MAHF, and MS_0) to get three different parameters simultaneously, for example two gases parameters (density and velocity) and the temperature. It is also possible to get the aerodynamics parameters in a gas flow, and further investigations on this direction are in progress.

The authors gratefully acknowledge technical support from Engineer J. Y. Rauch and P. Blind. The authors also wish to thank the French Embassy PhD Program.

[1]M. Eckert, Centaurus **50**, 233 (2008).
[2]I. Tani, Annu. Rev. Fluid Mech. **9**, 87 (1977).
[3]J. F. Clarke, Rep. Prog. Phys. **41**, 807 (1978).
[4]C. G. Elles and F. F. Crim, Annu. Rev. Phys. Chem. **57**, 273 (2006).
[5]T. Laurent, F. Bastien, J. Pommier, A. Cachard, D. Remiens, and E. Cattan, Sens. Actuators, A **87**, 26 (2000).
[6]S. D. Holland and D. E. Chimenti, Appl. Phys. Lett. **83**, 2704 (2003).
[7]C. Prada, O. Balogun, and T. W. Murray, Appl. Phys. Lett. **87**, 194109 (2005).
[8]A. A. Maznev and A. G. Every, Appl. Phys. Lett. **95**, 011903 (2009).
[9]N. T. Nguyen and R. M. White, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **47**, 1463 (2000).
[10]S. W. Wenzel and R. M. White, Sens. Actuators, A **22**, 700 (1989).
[11]M. X. Deng and J. F. Pei, Appl. Phys. Lett. **90**, 121902 (2007).
[12]F. Lefevre, F. Jenot, M. Ouaftouh, M. Duquennoy, P. Poussot, and M. Ourak, Rev. Sci. Instrum. **80**, 014901 (2009).
[13]Y. C. Lee and Sh. H. Kuo, Appl. Phys. Lett. **89**, 031920 (2006).
[14]I. A. Viktorov, *Rayleigh and Lamb waves* (Plenum, New York, 1967).