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**PROPAGATION OF A-WAVE IN A PLANE PLATE**  
**EXPERIMENTAL STUDY**

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**ABSTRACT**

The propagation of the A-wave is investigated theoretically on a plane brass plate completely immersed in water or in contact with water on one side and air on the other side. The main characteristics of this wave are calculated: group and phase velocities as a function of frequency and energy distribution in a cross section of the plate.

An experimental study is then exhibited for 200 mm long plane brass plates of various thicknesses (0.2, 0.1 and 0.05 mm) immersed or semi-immersed in water. Using a time frequency representation, the experimental group and phase velocities are measured versus the frequency thickness product (F.H). The experimental dispersion curves are very close to the theoretical ones.

## Introduction.

Acoustical scattering by canonical shells have known a wide development over these ten last years. These studies show that an incident plane wave propagating towards a cylindrical shell, perpendicular to its axis, can generate several kinds of waves like Rayleigh waves or Whispering gallery waves. These waves appear by resonances. More recently in resonance scattering, for low frequencies, an other kind of wave have been observed on thin cylindrical shells filled with air [1-4]. This new kind of wave must be compared to the A-wave found in plates by Osborne and Hart [5] because they have similar characteristics of dispersion. From this fact, this wave is called A-wave. Because the energy of this wave at high frequency is essentially located in the surrounding liquid, this wave is also called Scholte-Stoneley wave. However, the resonances of the A-wave in cylindrical shells have been observed in a limited frequency range. This frequency window is all the more shorter than the ratio  $b/a$  of the shell is smaller ( $a$  and  $b$  are external and internal radii of the shell). Outside this frequency range, several alternatives can be devised: we can think that the A wave is not generated or is too much attenuated (in this last case, the wave disappears before the detection), or turn around the shell without attenuation (the A-wave is not detected). In this paper, we propose a systematic study of the A wave propagating on an immersed or semi-immersed plane plate. We show theoretically the main properties of this wave and in particular the different structures of the A-wave versus the frequency thickness product. The experimental study shows that the A wave is easily generated on plane plates and propagates without attenuation with the calculated group celerity.

## Theoretical calculus.

The notion of evanescent waves [6] is used to describe the modes of the immersed plane plates. Results concerning the Lamb waves have already been presented [7]. The same calculus can give the characteristics of the A and S waves of Osborne and Hart. The plate is considered (Fig. 1) as an homogeneous elastic solid having a thickness  $H$  and immersed in a fluid. Materials are characterised by the density  $\rho_S$  and  $\rho_F$  (solid and fluid) and by celerities  $c_L$  for the longitudinal wave,  $c_T$  for shear waves in the solid and  $c_F$  for the longitudinal wave in the fluid. The wave propagates in the  $Ox$  direction. In each medium, we assume a permanent sinusoidal excitation

(frequency  $F$ ) and we note as  $\vec{u}$  the complex displacement vector of each elementary wave such as  $\vec{u} = \vec{U}_0 \exp(\vec{K} \cdot \vec{r} - \omega t)$ . In each medium, a wave has a complex wave vector  $\vec{K}$  noted  $\vec{K} = \vec{K}' + j\vec{K}''$ . There are one wave in each fluid and four waves in the solid. At the two interfaces, we express the usual conditions (continuity of the stress and of the normal component of the displacement) and we constitute an homogeneous system where the unknowns are the components of displacements. If we develop the determinant of this system we obtain the expression given by N. Veksler [8]. This determinant vanishes for correct value of the complex component  $K_x$  common to wave vectors of the three media. Its value only depends on the product  $F.H$  (frequency thickness) and on the constants of the materials.

The phase velocity of the wave is given by the following expression:  $v_\phi = \frac{\omega}{K'_x}$ , where  $K'_x$  is the real part of  $K_x$ .

For a given product  $F.H$ , we can obtain several solutions to the problem: generalized Lamb wave [7] and Osborne and Hart waves. Only these last solutions (A and S waves) are characterized by  $K''_x = 0$  and  $K'_z = 0$  which is the main property of the Scholte-Stoneley wave propagating at the liquid/solid interface). These waves have no attenuation during their propagation along  $O\vec{x}$ . The A-wave has a large dispersion; its energy is concentrated in the plate and its proximity. The amplitude of the A-wave decreases exponentially from the interfaces.

When the fluid is removed for  $z < -\frac{H}{2}$ , the problem is similar to the previous one. The wave in vacuum vanishes and the linear system which proceeds is of the order five. For a given value  $F.H$  a wave is obtained, similar to those obtained by Osborne and Hart, and first calculated by Grabowska [9]. This wave has not a true antisymmetrical character, but is still named A-wave.

## Numerical results

The calculus has been effected with several materials. We present results obtained with brass, material which exists in very thin sheet (down to 0.05 mm of thickness) and is not submitted to strong corrosion in water. We use the following characteristics for the calculus:

$$\rho_S = 8600 \text{ kg.m}^{-3}$$

$$c_L = 4700 \text{ m.s}^{-1}$$

$$c_T = 2110 \text{ m.s}^{-1}$$

$$\rho_F = 998.2 \text{ kg.m}^{-3}$$

$$c_F = 1485 \text{ m.s}^{-1}$$

On Fig. 2.a, we plot the phase and group velocity of the A-wave versus the product F.H in an immersed and semi-immersed plate. The group velocity is defined by  $v_G = \frac{d\omega}{dK'_x}$ . We note that the phase velocity is always inferior to the velocity  $c_F$ . An accurate calculus shows that the limit reached by  $v_\phi$  and  $v_G$ , when the product F.H become infinite, is the Scholte Stoneley wave velocity  $c_S$ , at the interface brass/water ( $c_S = 1482.13 \text{ ms}^{-1}$ ). In both cases (Water/brass/water and water/brass/vacuum), the group velocity curve reaches a maximum for a F.H product close to 0.4 MHz.mm. These results are also obtained with other usual solids such as the stainless steel and the duraluminum. The maximum of the group velocity is always superior to  $c_F$ .

It is also possible to deduce the flux (the time averaged flux) of the acoustic Poynting vector carried out by the A-wave in the different mediums. We verify that the energy flux along the axis  $O\vec{z}$  is equal to zero, showing that the wave reemits no energy. On Fig. 2b, we represent the ratio of the flux along  $O\vec{x}$  axis and located in the plate to the flux along  $O\vec{x}$  axis located in the fluid. We note the two behaviours of the A-wave. When the product F.H is very high, the limit is those of the Scholte Stoneley wave (1.06%). For values of the product F.H greater than 0.8 MHz.mm, the energy of the wave is located, for the most part, in the liquid: the wave is essentially outside the plate and the characteristics of the A-wave depends on temperature like  $c_F$ . For values of the product F.H lower than 0.4 MHz.mm, the wave is essentially in the plate and the characteristics of the A-wave do not depends on the neighbouring liquid (and its temperature).

### Experimental set-up.

The study of A-wave propagation is carried out with three 200mm long and 0.2, 0.1 and 0.05 mm thick brass plates. The plate is immersed in distilled water which is more favourable to the propagation of the interfaces waves. The A-wave is produced at the edge of the plate by the conversion of an incident pulse

generated by 5MHz central frequency transducer [10]. At the end of the plate, the A-wave becomes a bulk wave which diffracts in all directions and is received by a second 5MHz transducer. The experimental principle is given on Fig. 3.a. The optimal signal is obtained for an angle  $\alpha = 0^\circ$  if the thickness of the plate is equal to 0.1 or 0.2 mm. For a lower thickness,  $\alpha$  must be close to  $20^\circ$ . In this case, an additional difficulty occurs: the conversion has a low efficiency. In order to improve this, the plate must be bent at its extremity and realizes a dihedral, the edge of which constitutes a better zone of conversion. The signals are amplified and digitized by a digital oscilloscope.

For the study of the A-wave propagation on a semi-immersed plate, we have made three plane boxes with the previous materials. The boxes are filled with air and the experimental setup is kept (Fig. 3.b). The same difficulties were encountered in order to generate A-wave at low frequencies.

### **Signal processing.**

The A-wave is very dispersive and, produces a long time signal. On Figs. 4a, 5a and 6a , we give the response at an impulse excitation duration inferior to  $1 \mu\text{s}$  for immersed plates. The thicknesses were respectively equal to 0.2, 0.1 and 0.05 mm and the propagation length was 200mm. These responses are very different . The analysis of Fig. 4a is easy: the spectral components of the signal have a product F.H superior to  $0.4 \text{ MHz}\cdot\text{mm}$  . The components of low frequencies are the fastest and arrive before the high frequencies components. With these impulse response, we can obtain the dispersion curve of the A wave in using a time-frequency treatment. A straight forward method, called sliding windows FFT, allows the treatment of the received signal. On a 5000 points long signal (corresponding to  $50 \mu\text{s}$ ), a 512 points Blackman window ( $5.12 \mu\text{s}$ ) is translated every 20 points ( $0.2 \mu\text{s}$ ). Successive Fourier Transforms are then performed with 4096 points, corresponding to 512 effective points completed with zeros: the frequency step is 24.2 kHz for the used frequency range. A sorting out of the maxima of the final time-frequency image will give the corresponding group delays. When the parameters of the method are correctly set, the relative error on group velocity is about 0.5 percent. It is then reduced to the sum of relative error made on the plate dimension measurements. This method gives results comparable to those obtained by the Wigner-Ville transformation without ghost

interference. This analysis can display small signals that are mixed with the A wave. As an example, we give the time frequency-representation obtained in the case of a 0.1mm thick brass plate (Fig. 7), we note three successive echos:

- a single travel of the A-wave on the plate
- a grazing bulk wave which travels in water near the plate
- a back and forth travel on the first side plus a single travel of the A-wave on the main surface.

### Results.

The A-wave propagation is first investigated in the three plane plates immersed in water. The results obtained by the method of the sliding F.F.T. are presented on Figs. 4b, 5b and 6b for plates of different thicknesses . On each figure, we have reproduced curves of the group celerity calculated for 16 and 20°C in the aim to show the influence of the temperature when the product F.H is high. The comparison with theoretical values is excellent: the experimental values are always enclosed by the two theoretical dispersion curves. The total round of error on experimental measurements is less than 0.5 percent on group velocity. For low frequencies, the A-wave group velocity is a function of H, L,  $\rho_s$ ,  $c_L$  and  $c_T$ . So if only the thickness is unknown it is possible to rapidly converge to an accurate value of it, simply by fitting experimental data into theoretical values.

When only A-wave is present in the time signal, the derivative of the spectrum phase may be used in order to calculate the phase and group dispersion curves. We calculate the F.F.T. of the signal and we extract the phase as a function of frequency. The exact phase of the A-wave can be deduced from the F.F.T. phase (Fig. 8). When the frequency increases, the phase leads to a straight line joining the origin (zero phase at nul frequency). The A-wave phase velocity is deduced from the phase  $\theta$  by  $V_\phi = -L \frac{2\pi f}{\theta}$  and the group velocity by

$$V_g = -L \frac{2\pi df}{d\theta} .$$

Using the phase of each spectrum, it was possible to obtain phase velocity for each plate, with a very good agreement with theoretical values (Fig. 9).

The results obtained with a semi-immersed plate are similar. On Fig. 10, experimental group dispersion curves are compared to theoretical ones. For low F.H, it is quite more difficult to generate A-wave, and phase velocity was obtained only for 0.2 and 0.1 mm thicknesses (Fig. 11).

## Conclusion

We have experimented the A-wave propagation on an immersed or semi-immersed plate in a simple way. Brass had been chosen for this study because sheets of various thicknesses exist (in particular very thin) with long lengths and a low cost. Various materials can be used such as duraluminum, inox steel or glass and they give similar results. The various existing brass thicknesses has provided the observation of the A-wave in a large F.H domain (0.05 up to 1MHz.mm). This study has pointed out some interesting properties of the A-wave:

- for any F.H value, the A-wave propagates without attenuation
- for low F.H values, the A-wave is located in the plate and is insensitive to the variation of the external medium characteristics: it is overall very dependent on the plate thickness or length, and to a lesser degree on  $c_L$  or  $c_T$ .
- for high F.H values, the A-wave is located in the fluid and is sensitive to the fluid parameters such as its temperature. It tends to become the Scholte wave at the liquid/solid plane interface.

Measurements of the A-wave also allow the testing of signal processing by sliding F.F.T. This method is reliable chiefly if several waves are mixed in a signal. If the signal belongs to a single wave, the phase spectrum gives the value of phase and group velocities.

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Figure captions:

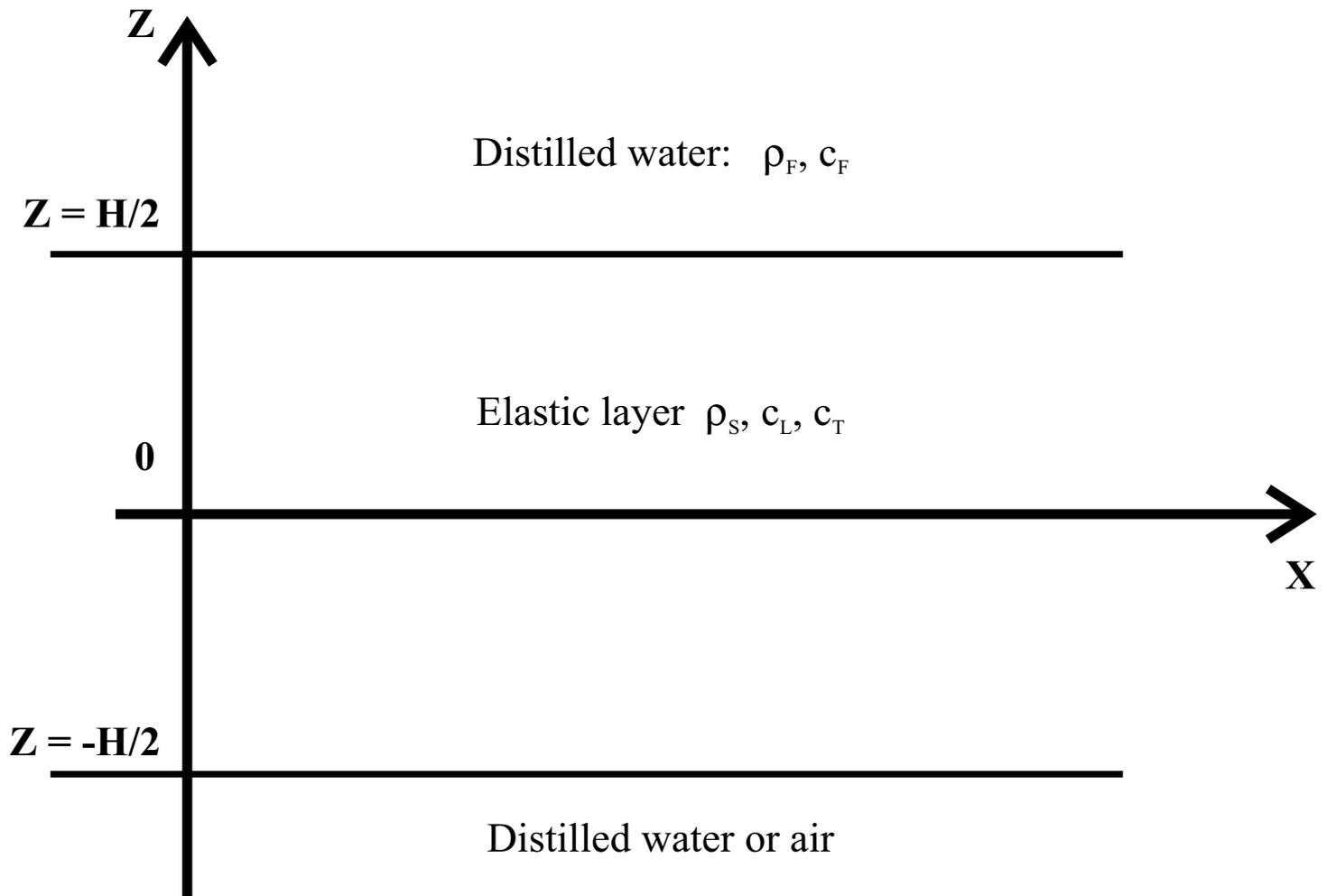
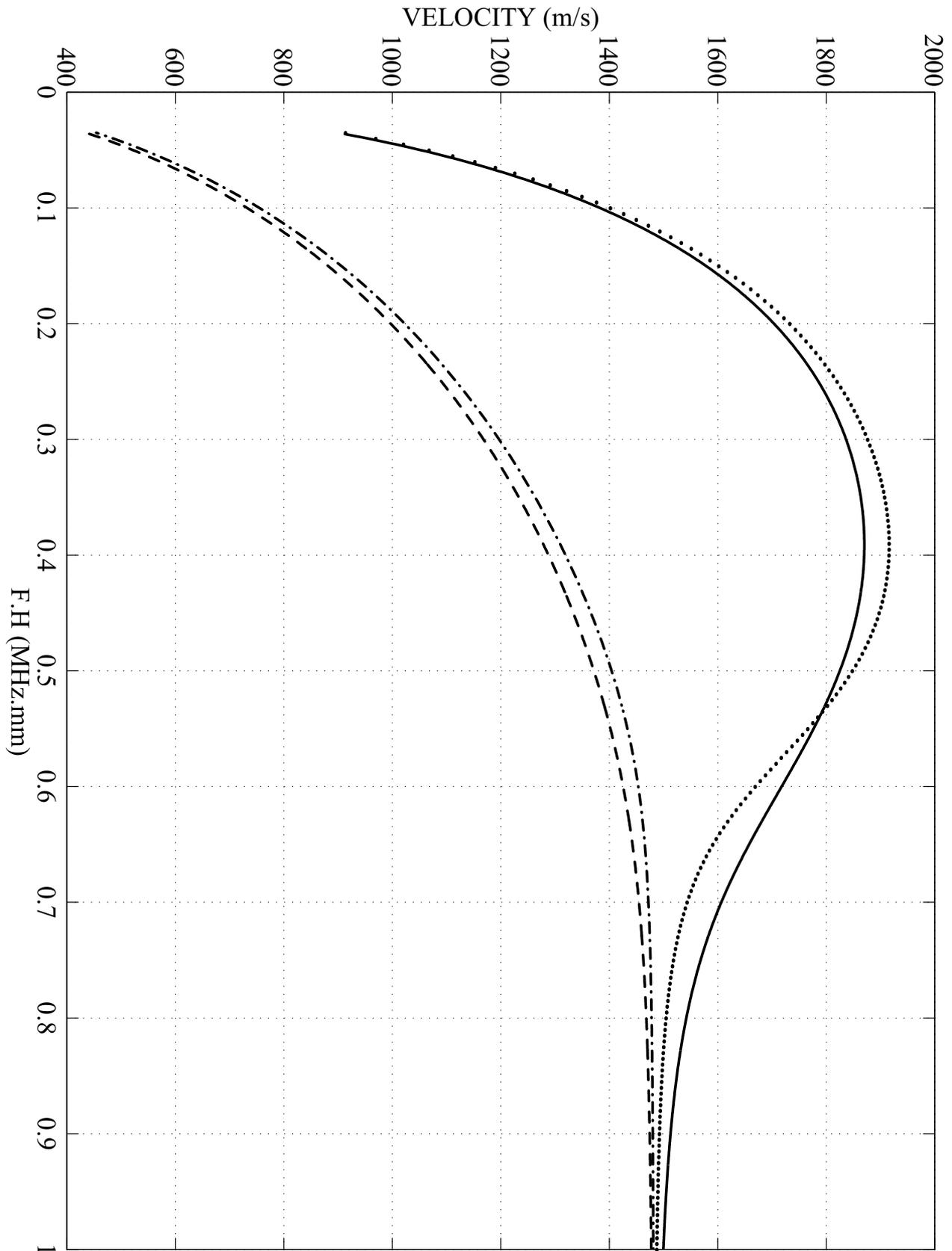


Figure 1. Geometry of the problem



**Figure 2.a.** Theoretical dispersion curves: A-wave in a plane immersed or semi immersed plate, respectively (—) and (---) group and phase velocities for the immersed plate, and respectively (···) and (-·-) group and phase velocities for the semi-immersed plate.

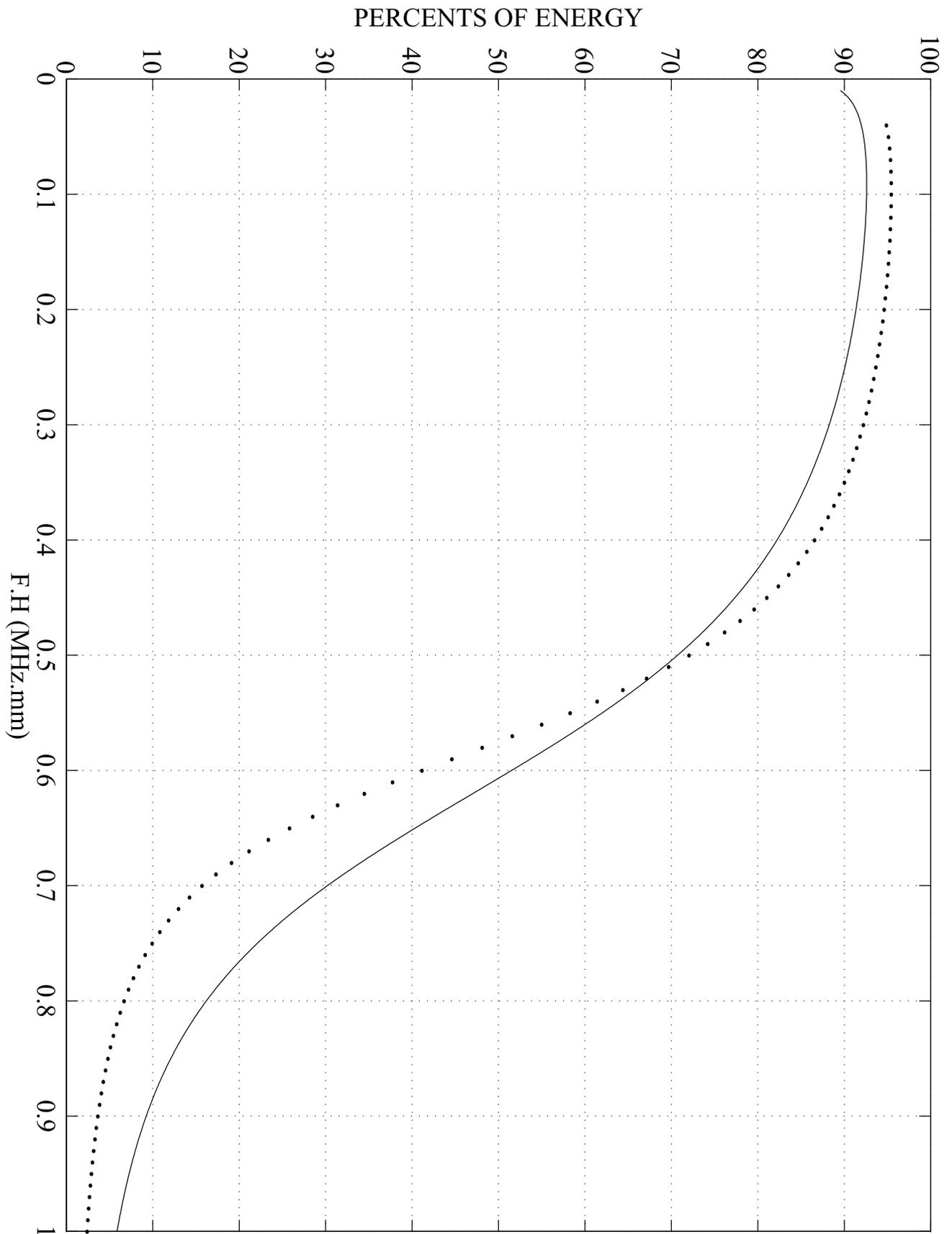
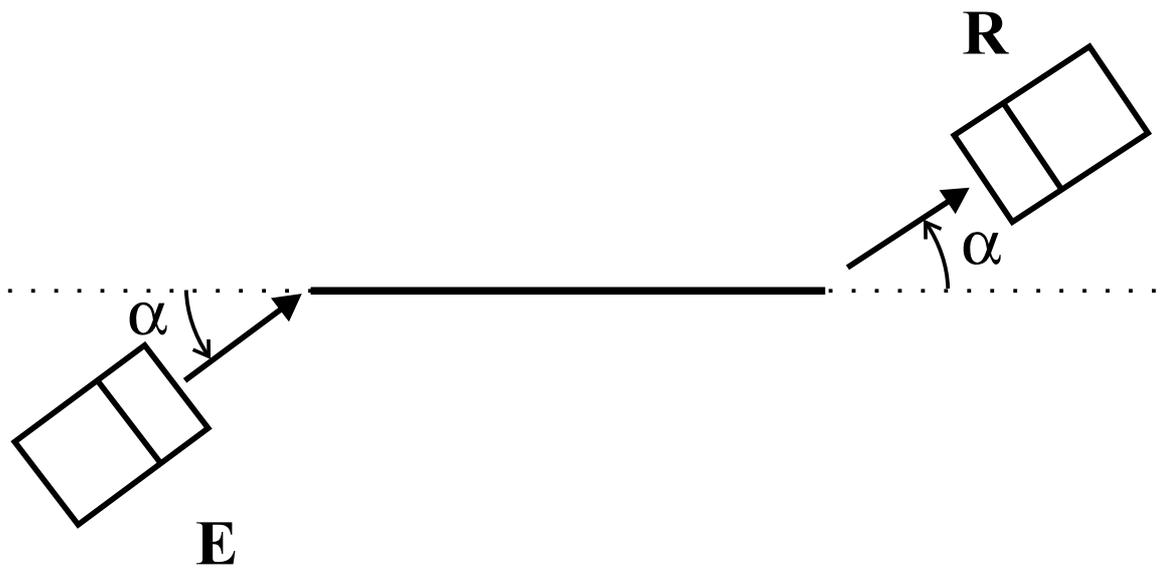
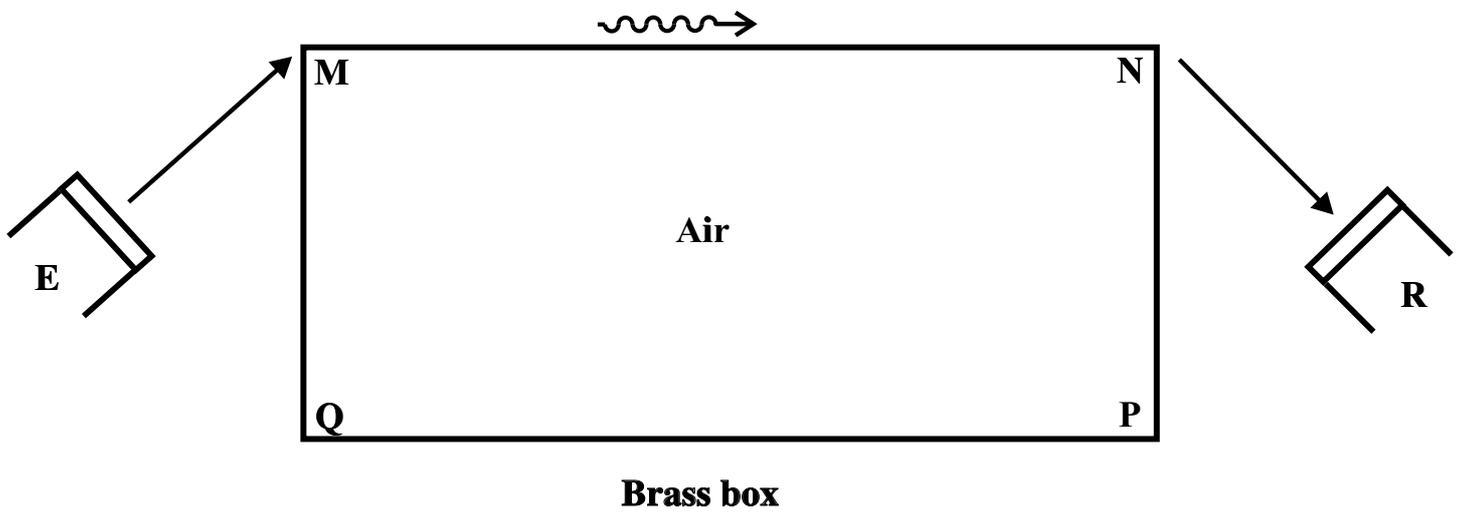


Figure 2.b. A-wave percentage of energy in the plate: (—) immersed plate, (· · ·) semi-immersed plate.



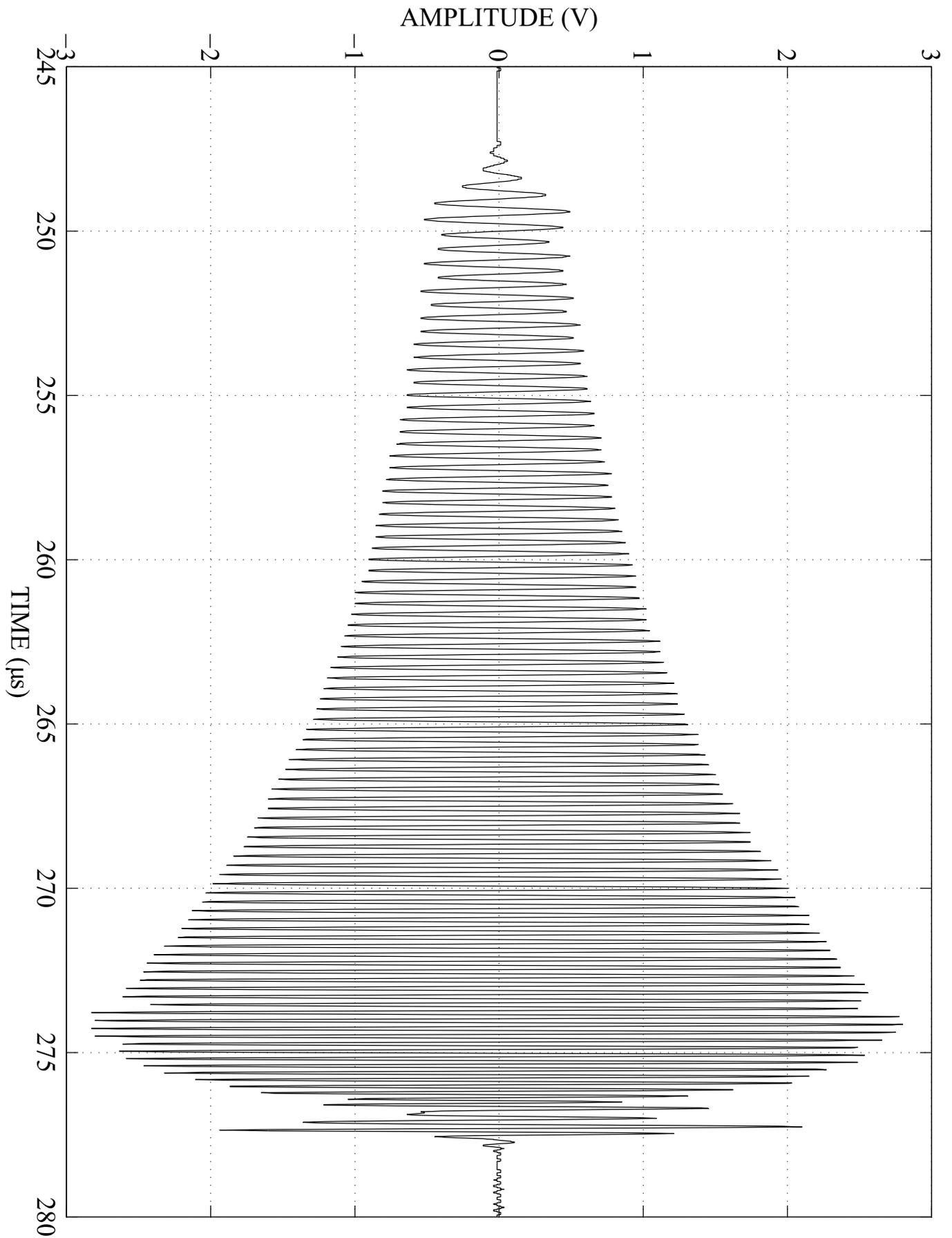
**Figure 3a.** Experimental setup for a plane immersed plate in distilled water.

**Distilled water**

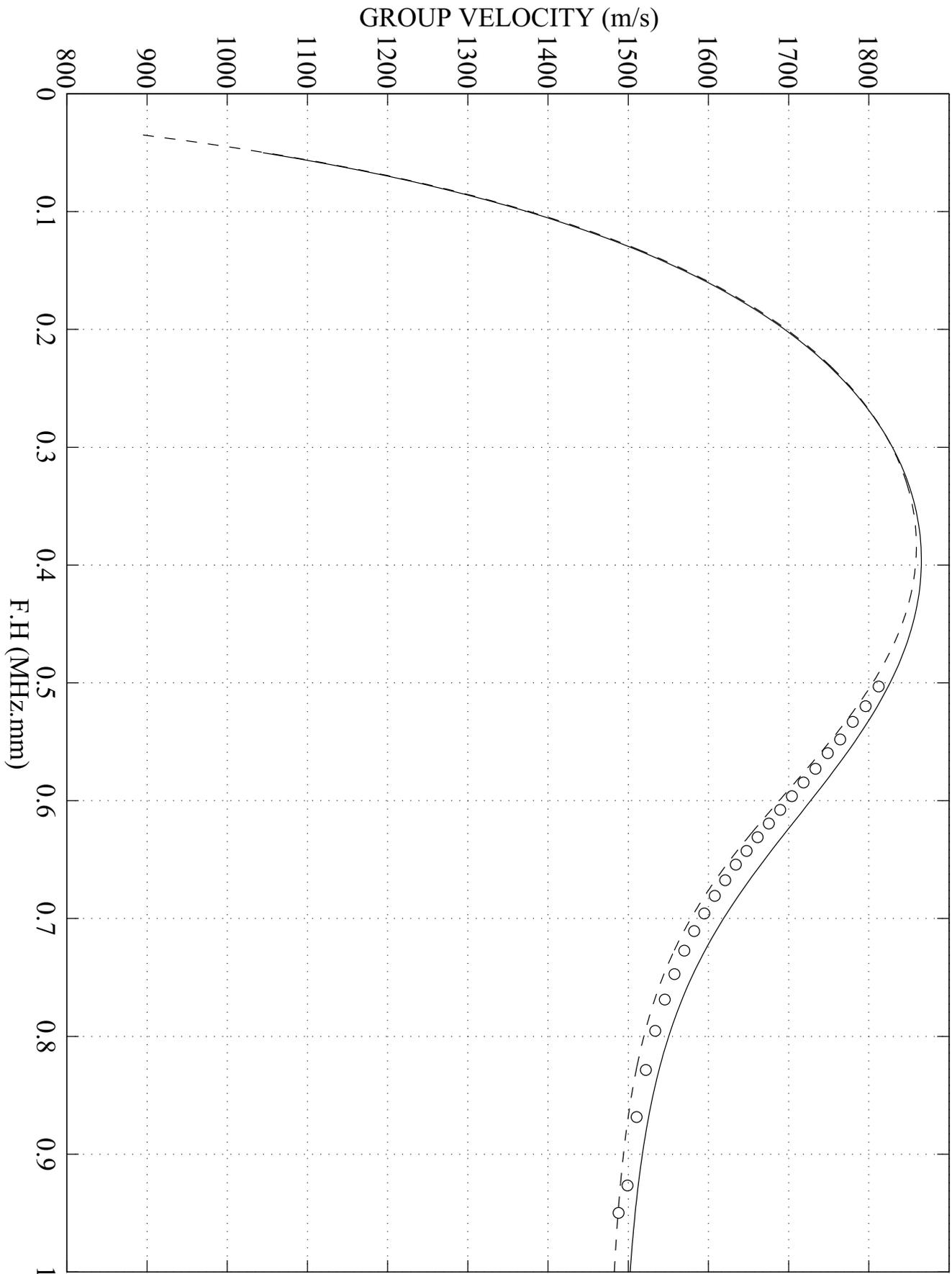


**Brass box**

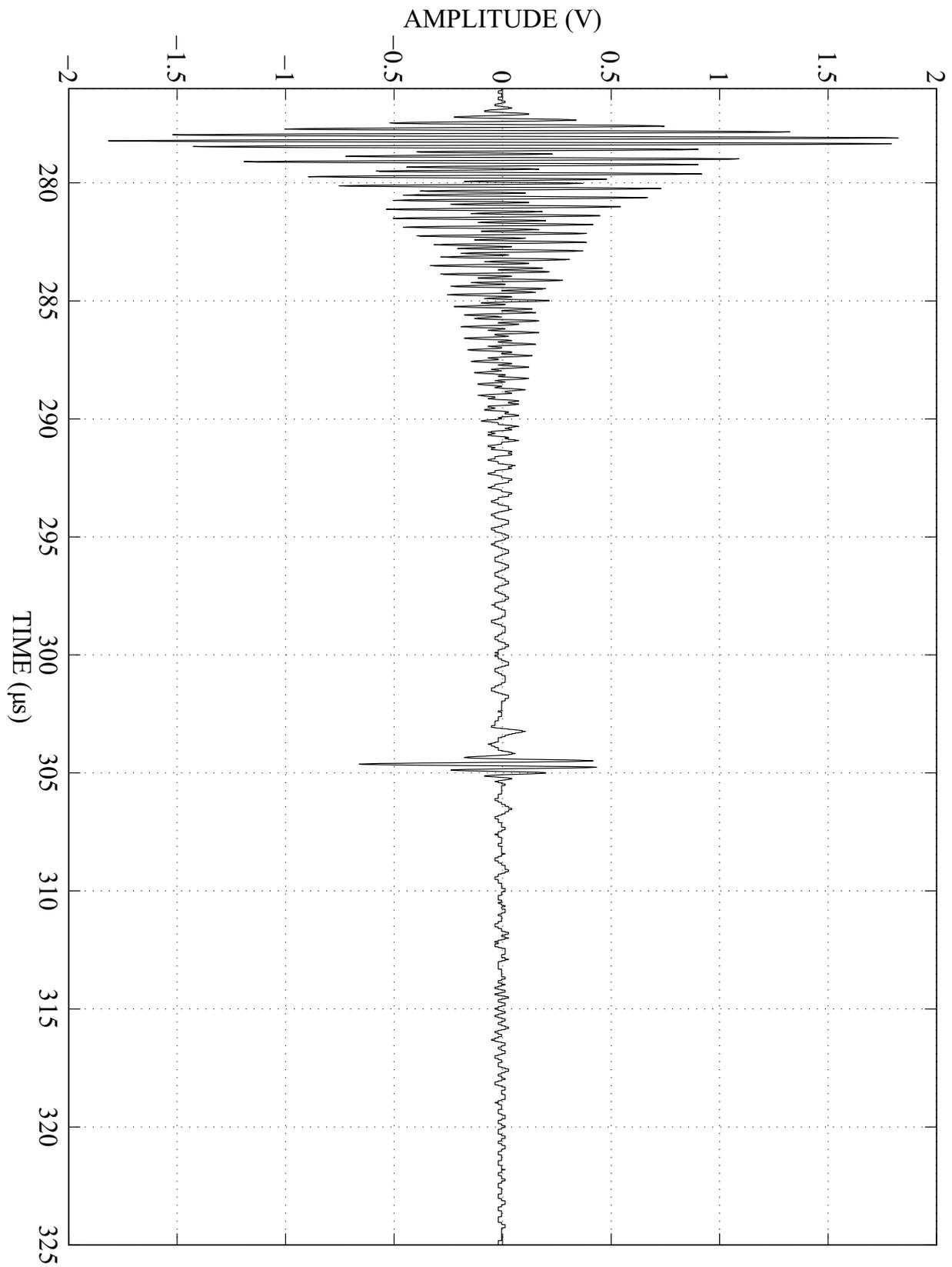
**Figure 3b.** Experimental setup for a plane semi-immersed plate in distilled water.



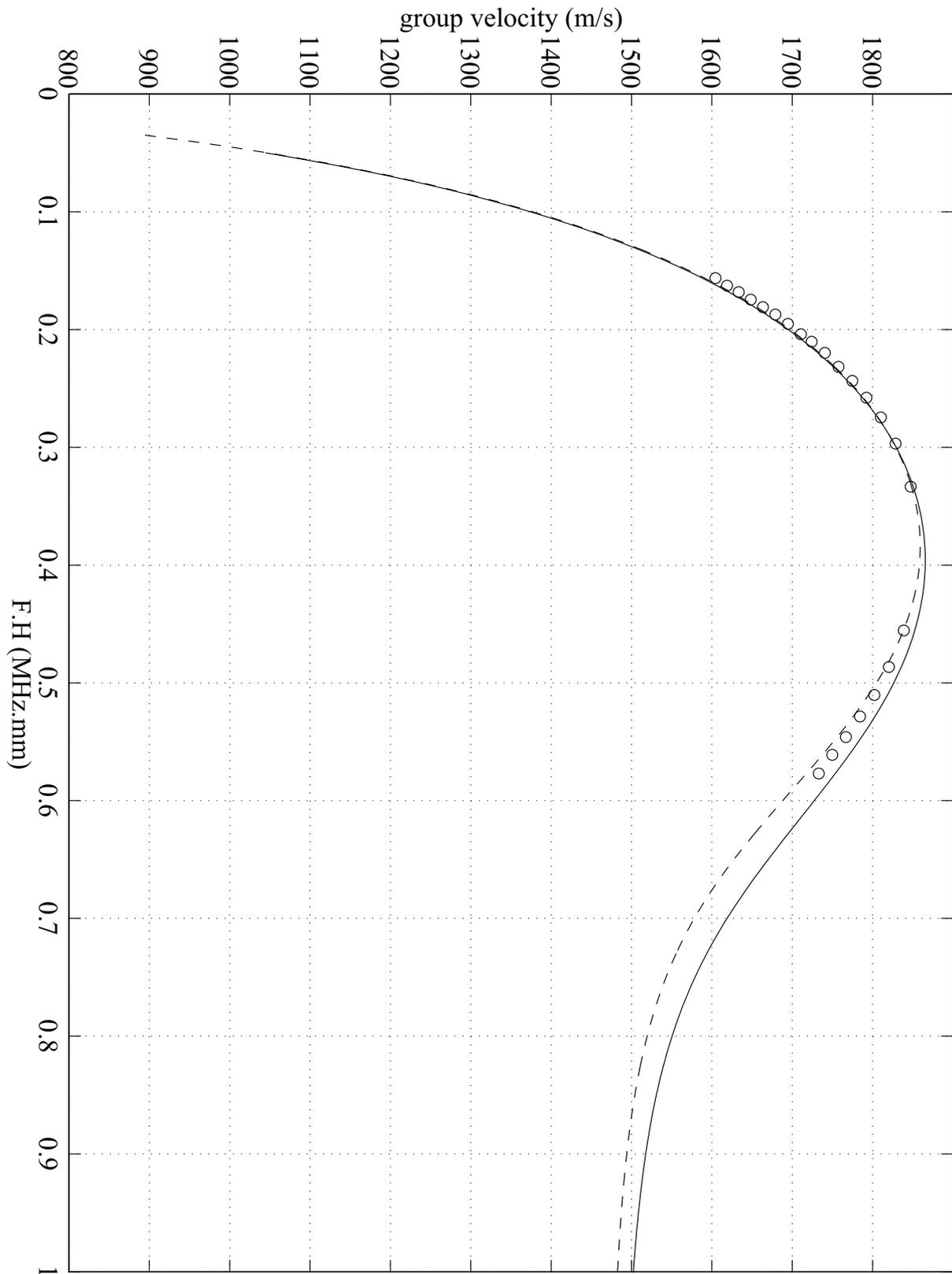
**Figure 4.** A-wave in an immersed plane brass plate  $H=0.2\text{mm}$   $L=200\text{mm}$ : (a) time signal.



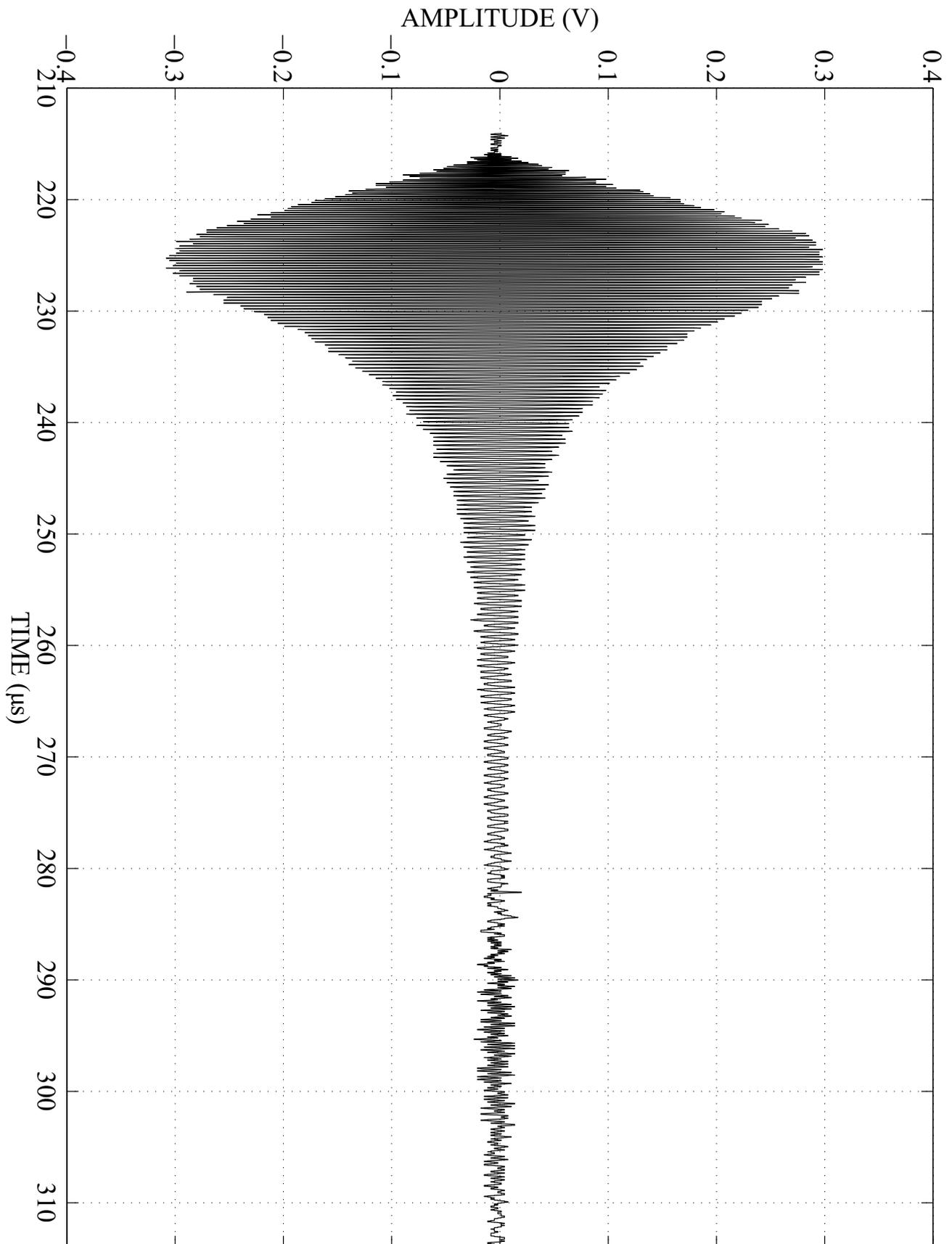
**Figure 4.** A-wave in an immersed plane brass plate  $H=0.2\text{mm}$   $L=200\text{mm}$ : (b) Corresponding group dispersion curves, (—) theoretical curve at  $T=20^\circ\text{C}$ , (---) theoretical curve at  $T=16^\circ\text{C}$ , (o o) experimental curve at  $T=18^\circ\text{C}$ .



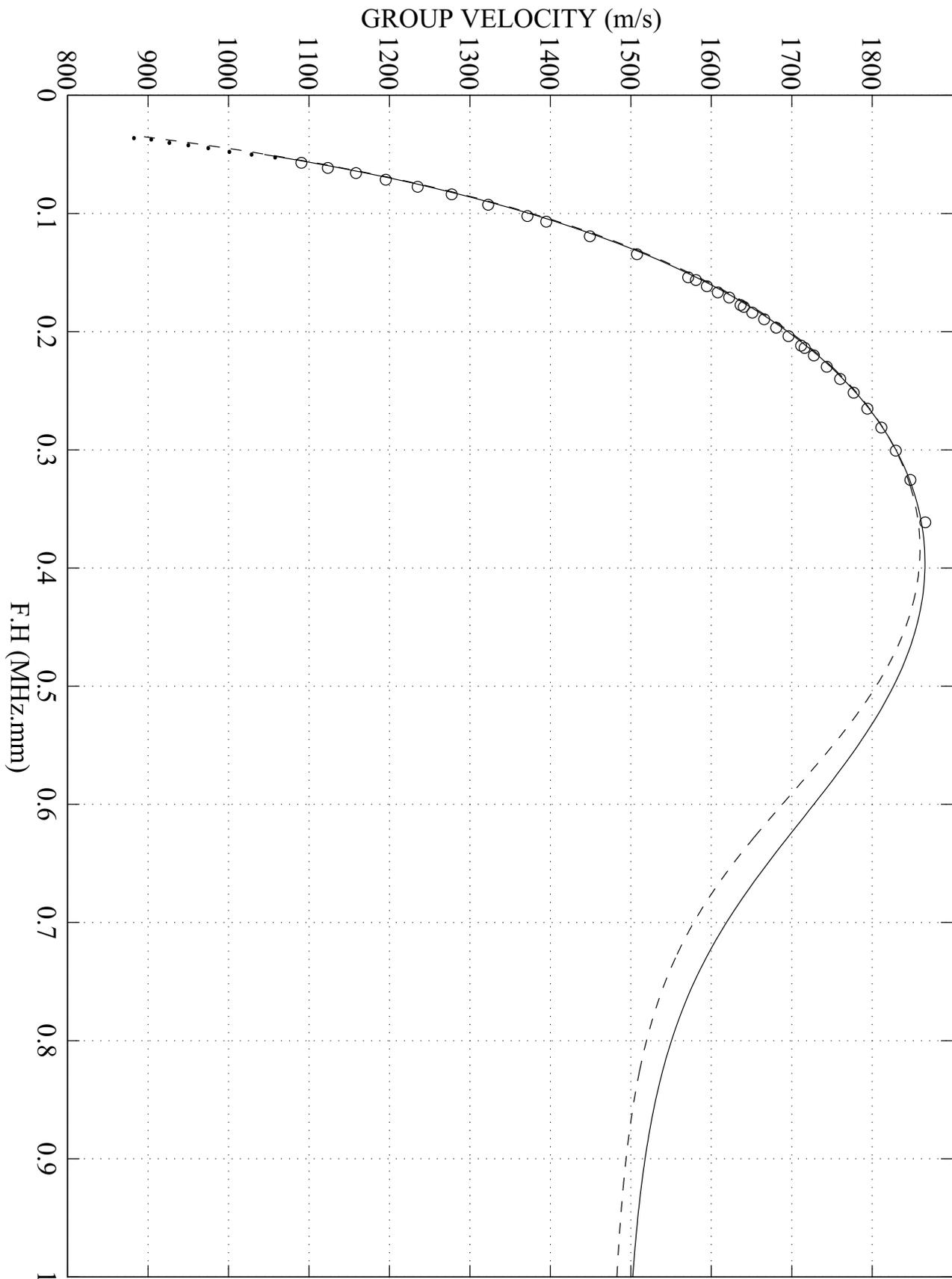
**Figure 5.** A-wave in an immersed plane brass plate  $H=0.1\text{mm}$   $L=200\text{mm}$ : (a) time signal.



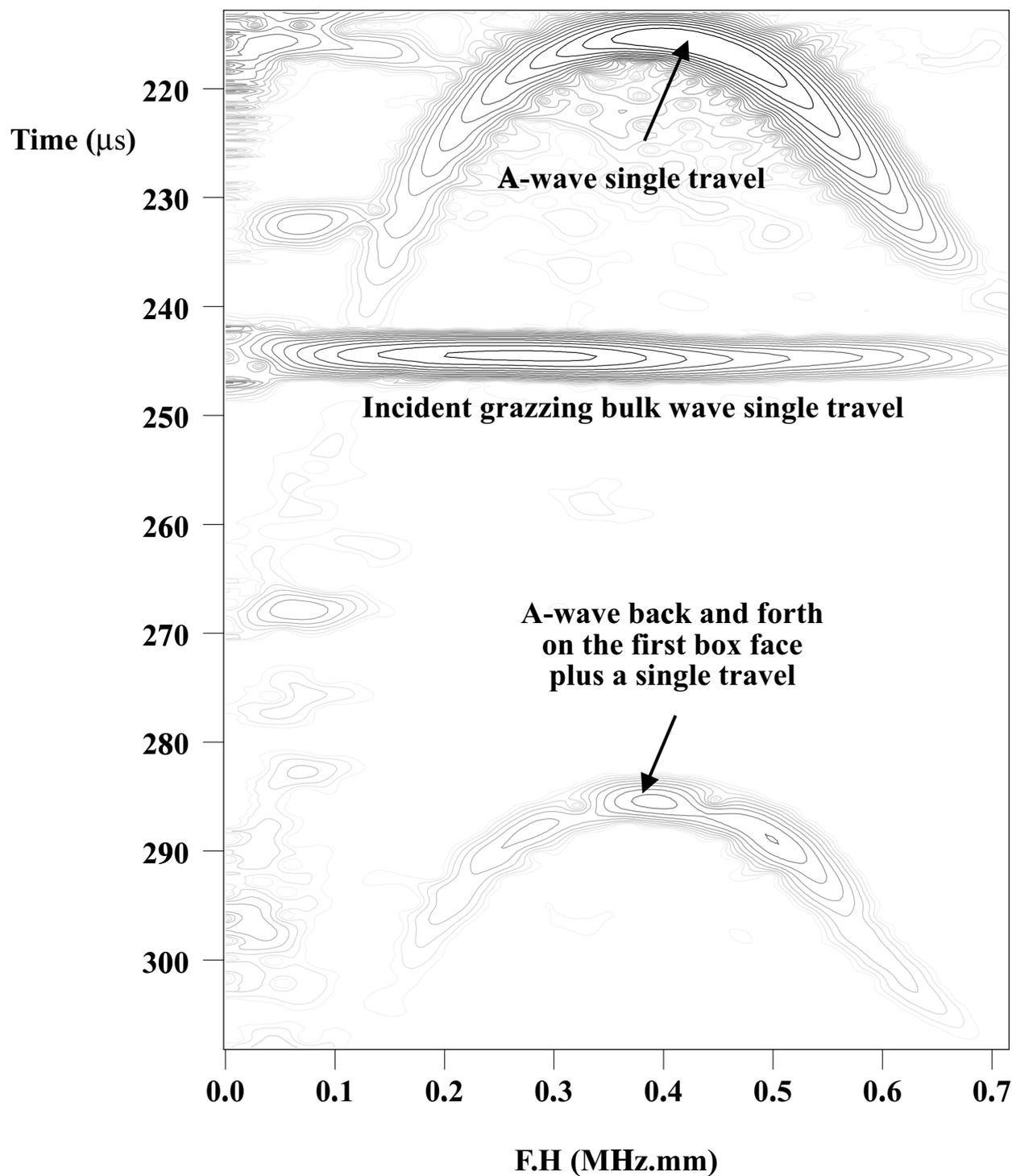
**Figure 5.** A-wave in an immersed plane brass plate  $H=0.1\text{mm}$   $L=200\text{mm}$ : (b) Corresponding group dispersion curves, (—) theoretical curve at  $T=20^\circ\text{C}$ , (---) theoretical curve at  $T=16^\circ\text{C}$ , (o o) experimental curve at  $T=18^\circ\text{C}$ .



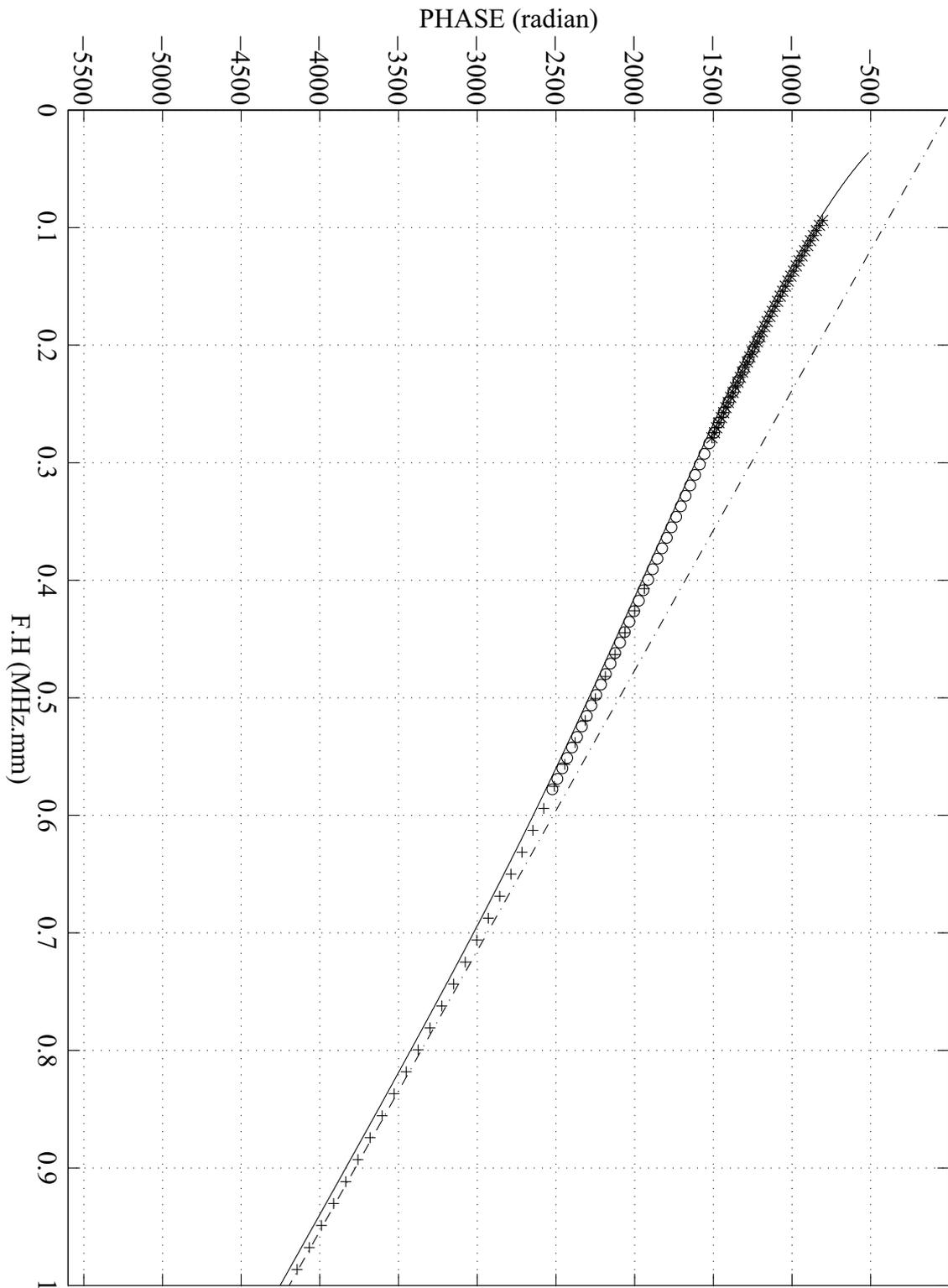
**Figure 6.** A-wave in an immersed plane brass plate  $d=0.05\text{mm}$   $L=200\text{mm}$ : (a) time signal.



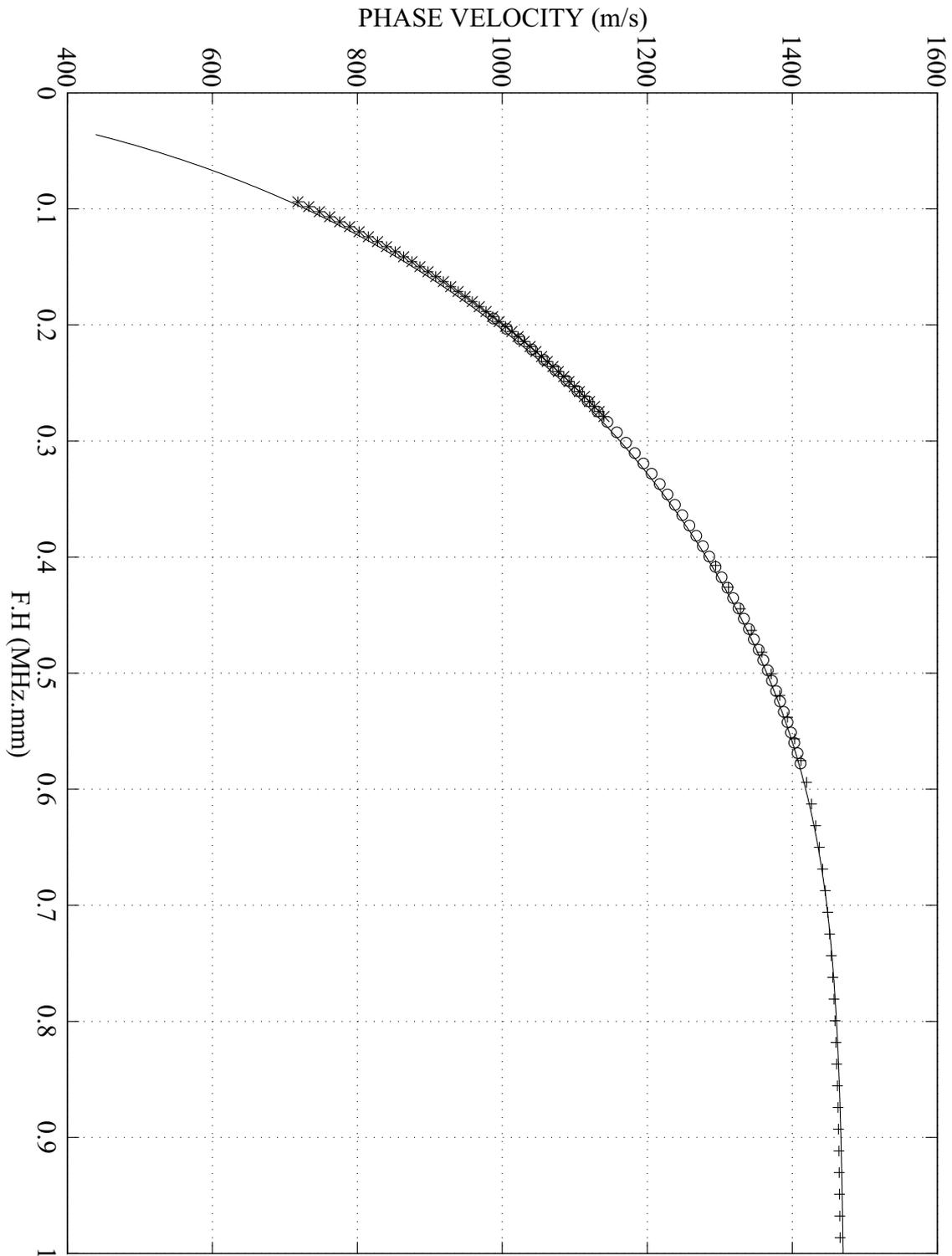
**Figure 6.** A-wave in an immersed plane brass plate  $d=0.05\text{mm}$   $L=200\text{mm}$ : (b) Corresponding group dispersion curves, (—) theoretical curve at  $T=20^{\circ}\text{C}$ , (---) theoretical curve at  $T=16^{\circ}\text{C}$ , (o o) experimental curve at  $T=18^{\circ}\text{C}$ .

**A-wave - water/plane brass plate/air (H=0.1mm)**

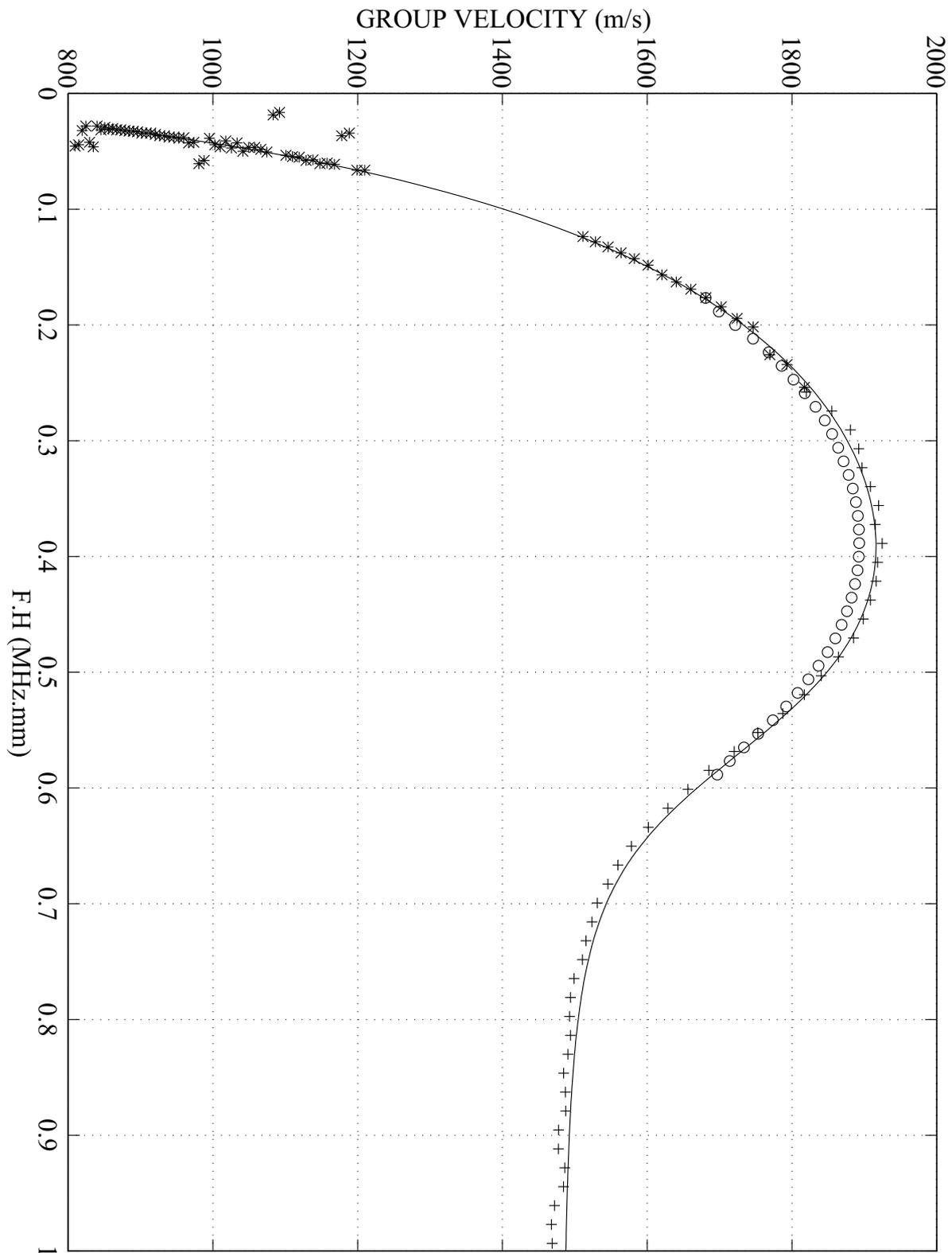
**Figure 7.** Time-frequency representation of A-wave in a semi-immersed plane brass plate with  $H=0.1\text{mm}$ .



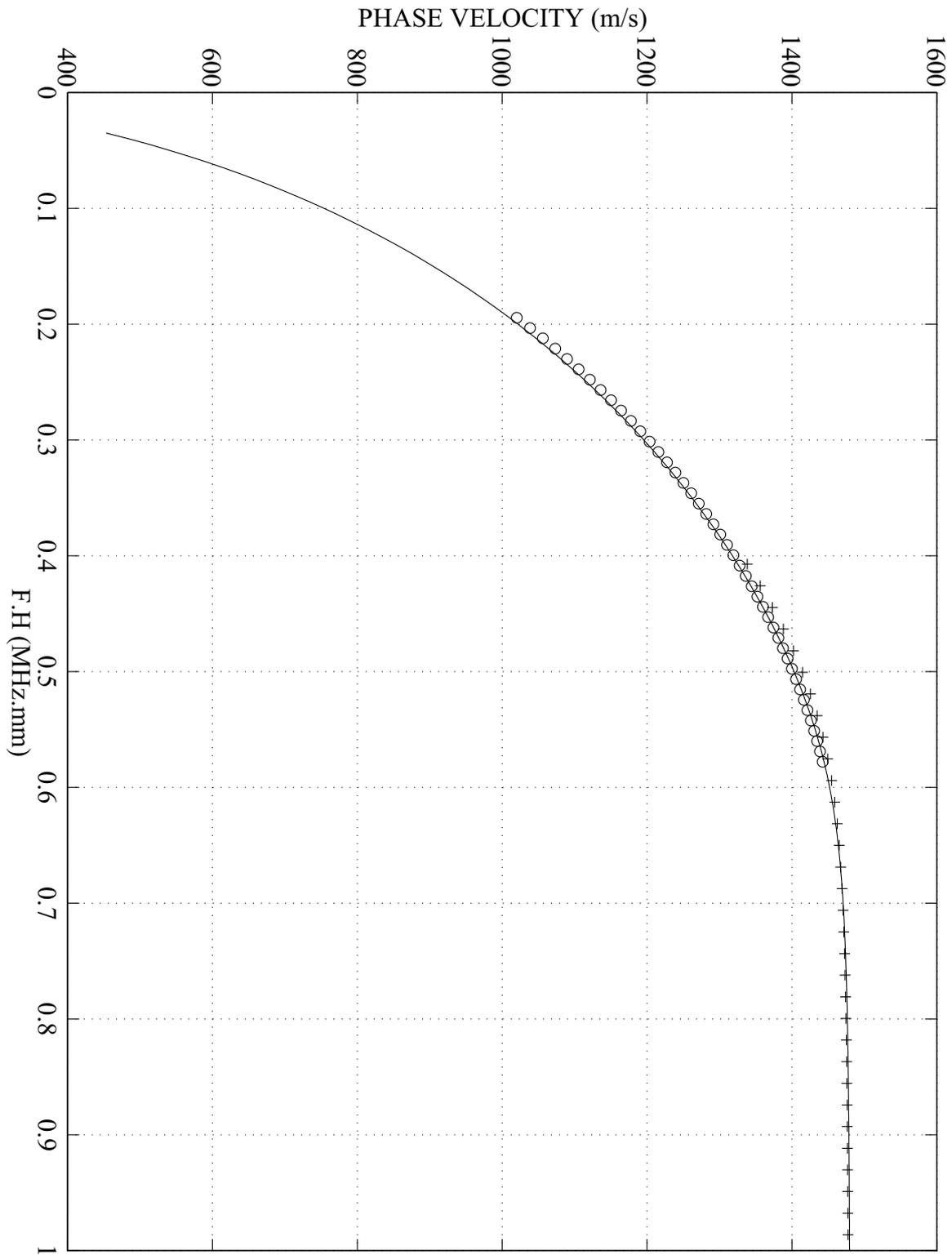
**Figure 8.** Reconstructed experimental phase for the A-wave on an immersed plane brass plate, (+ + +)  $H=0.2\text{mm}$ , (o o o)  $H=0.1\text{mm}$ , (\* \* \*)  $H=0.05\text{mm}$ ; (—) theoretical curve, (-.-) linear asymptote at high F.H passing at the origin.



**Figure 9.** Experimental phase velocity of A-wave in an immersed-plate for  $T=18^{\circ}\text{C}$ : (+ + +)  $H=0.2\text{mm}$ , (o o o)  $H=0.1\text{mm}$ , (\* \* \*)  $H=0.05\text{mm}$ , compared with theoretical phase velocity for  $T=18^{\circ}\text{C}$ .



**Figure 10.** Experimental group velocity of A-wave in a semi-immersed plate for  $T=18^{\circ}\text{C}$ : (+ + +)  $H=0.2\text{mm}$ , (o o)  $H=0.1\text{mm}$ , (\* \* \*)  $H=0.05\text{mm}$ , compared with theoretical group velocity for  $T=18^{\circ}\text{C}$ .



**Figure 11.** Experimental phase velocity of A-wave in a semi-immersed plate for  $T=18^{\circ}\text{C}$ : (+ + +)  $H=0.2\text{mm}$ , (o o)  $H=0.1\text{mm}$ , compared with theoretical phase velocity for  $T=18^{\circ}\text{C}$ .