

**Optical Characterisation of Surface and Interface Waves in Liquid Metal-Water Layers
Using PIV and Laser Vibrometer Techniques**

by

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ABSTRACT

Particle Image Velocimetry (PIV) and Laser Vibrometer techniques have been used to investigate interface waves in a fluid system under the influence of gravity waves. In a cylindrical or rectangular glass test cell are two layers of fluids: water and a liquid metal at room temperature (Ga-In-Sn alloy). The PIV method is used to determine the flow field within the transparent fluid and the deformation of the boundary layer between the two fluids. The interface waves in the fluid system has been stimulated by a shaker in a frequency range of 3-30 Hz . The resonant frequencies of the interfacial oscillations are measured with a single point laser vibrometer for different cell geometry and different heights of the water layer. The velocity vector plots in the water layer show different modes and orientations of the interfacial waves. From this vector plots horizontal and vertical velocity profiles are calculated to indicate instabilities and to compare the experimental results with numerical simulations. The measurement of the resonant frequencies shows an influence of the height of the water layer in the case of the cylindrical cell: the frequency of the basic modes increases with increasing water layer depth. In the rectangular cell a more complicated mode structure were observed. The optical characterisation of the interface layer and the flow field in the transparent fluid are this first steps in order to get a physical model of the nature of gravity waves in technical systems like the aluminium reduction cell. The efficient non-invasive methods PIV and Laser Vibrometer are applied in a new field of measurement techniques: the detection of interfaces waves in liquids.



Fig. 1. Unstable non-linear interface deformation in the system water-air

1. INTRODUCTION

The objective of this work is a model experiment of an aluminium reduction cell. Almost all the aluminium manufactured in the world is produced in a Hall-Heroult cell in which aluminium oxide, dissolved in a molten cryolite electrolyte, is electrolytically reduced to metal. A typical cell would have a current of 200 kA flowing in a predominantly downward direction from anode to cathode. This current, and currents flowing in adjacent cell components, generate strong magnetic fields (about 10 mT) acting in horizontal direction. The interaction of these currents and magnetic fields causes electromagnetic forces which are the origin of magnetohydrodynamic (MHD) phenomena. These phenomena are the deformation of the metal-electrolyte interface away from its otherwise flat horizontal shape and the electromagnetically driven flow of both electrolyte and aluminium. In effect, there are long wave-length, interfacial gravity waves, modified by the intense magnetic and electric fields in the cell (Fig.2). Under certain conditions these disturbances are observed to grow, disrupting operation of the cell (Davidson 1999).

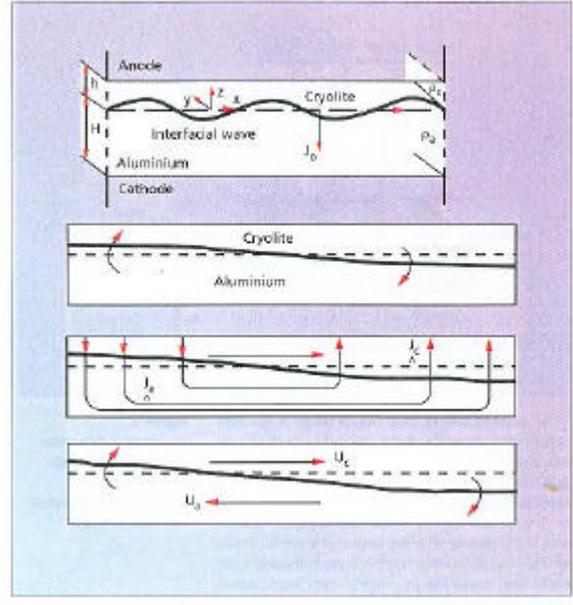
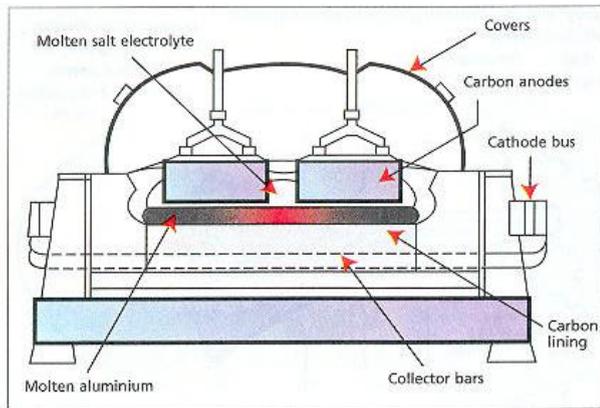


Fig. 2. Aluminium reduction cell (Davidson and Lindsay, 1998)
 a) Schematic drawing of Hall-Heroult cell
 b) Mechanism of interfacial waves

These instabilities have been the subject of much research over the last ten years. Numerous mathematical models for Hall cells have been described in the literature (Sneyd and Wang, 1994) (Davidson and Lindsay, 1998). But there are not many experimental investigations to measure these instabilities under laboratory conditions. In this paper a simplified model of the Hall-Heroult cell is described to investigate the movement inside the fluids and the interfacial waves depending on the applied electrical current and magnetic field using Particle Image Velocimetry (PIV) and Laser vibrometer (LV) (Fig. 3).

2. EXPERIMENTAL METHODS AND PROCEDURES

Figure 3. shows the block diagram of the model aluminium reduction cell. In a glass test cell are two layers of fluids: water and a liquid metal at room temperature (Ga-In-Sn alloy). The PIV (ILA) system is used to determine the motion of the particles within the transparent fluid and also the deformation of the boundary layer between the two fluids. The pulsed light sheet was generated by a gas laser with a opto-acoustic switch. An image processing system allows the calculation of velocity vector plots and the display topology of the interface in the light sheet (Fig.1).

The test cell has two electrodes on the bottom and the top to apply an electrolytic current. The magnetic field around the cell interacts with the electrolytic current and induces the gravity waves inside the fluid layers.

The first measurements due to investigate the behaviour of fluid systems without the influence of current and magnetic field when subjected to mechanical vibrations generated via a shaker (Fig.4). The apparatus was mounted on a electromagnetic shaker and was driven by a sine wave generator and AF amplifier. In the fluid systems water-air and liquid metal-water different vibration frequencies were used to coincide with the different resonant frequencies of the system (3 to 30 Hz).

The main interest of the measurement of the gravity waves in the test cell was the question: under which boundary conditions (aspect ratio and layer thickness) these waves becomes unstable and is it possible to generate to same waveform like the magnetohydrodynamic case. The excitation of internal gravity waves in single fluid has been studied in many theoretical and experimental works (e.g. Miles and Henderson, 1990), (Benielli and Sommeria, 1998). The main interest of this investigations was focused on parametric instabilities of natural frequencies of the fluid surface. In

this paper the authors only want to excite natural frequencies in order to stimulate gravity waves in the interface layer. Kageyama and Evans (1999) measured the eigenfrequencies of a mercury pool with a laser vibrometer. In the present case a Polytec Laser vibrometer with fiber probes was used to detect the oscillations at any point of the interface. This device measure the Doppler shift of a laser beam reflected from the interface. The system worked in the focused beam mode to minimise sensitivity to interface orientation and influence of the water surface. The vibrometer delivers an analog velocity signal and integrates it to obtain a displacement information. Time series of the vibrometer signals on two surface positions were stored in the computer subjected to Fourier analysis (FFT). During the vibrometer measurement a acceleration sensor detected the vibration of the shaker which was driven by a sine sweep from 3 to 30 MHz. From both signals the transfer function were calculated. Each measurement was carried out ten times and the eigenfrequencies were determined subjected to different aspect ratio and water layer height.

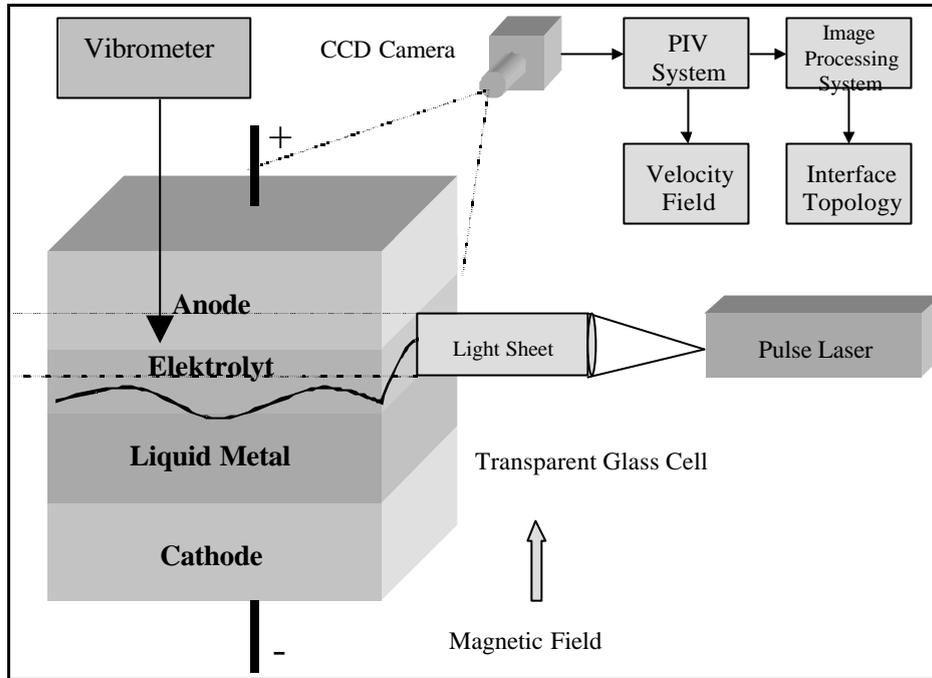


Fig. 3. Block diagram of the aluminium reduction test cell

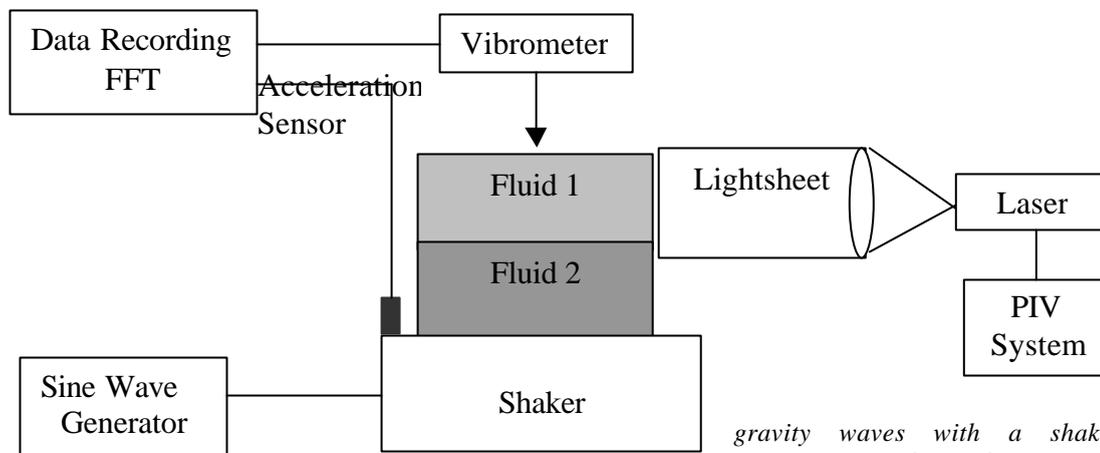


Fig. 4. Generation of gravity waves with a shaker and optical measurement of interface waves using PIV and laser vibrometer

3. RESULTS AND DISCUSSION

3.1 PIV measurements in the system water / air

In order to test the experimental apparatus the first PIV measurements were done in water with a free surface in a rectangular cell (48 mm x 24 mm x 35 mm). The water layer inside the cell was about 10 mm thick. A typical result of a stable gravity forced surface oscillation is shown in figure 5. The shaker frequency was 15 Hz, the magnitude 0.5 mm. The light sheet was located in the middle of the cell and shows a cut through the second harmonic waveform. With the fieldscan software from ILA velocity vector plots have been calculated at the surface and inside the water layer.

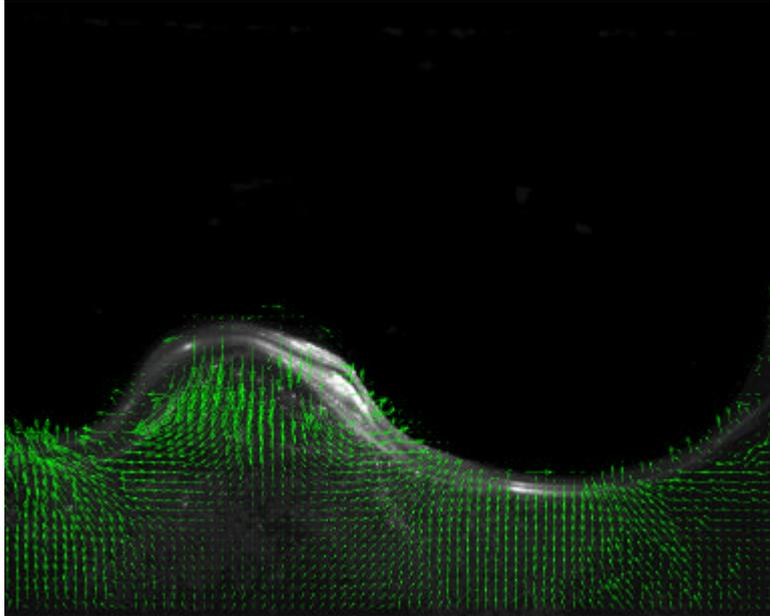


Fig. 5. Light sheet image and PIV velocity vector plot of a stable free surface oscillation of water at shaker frequency of 15 Hz and magnitude of 0.5 mm, second harmonic mode

If the shaker magnitude will be increased the surface oscillations become unstable. Figure 6 illustrates a typical example at a shaker magnitude of 1 mm for the same mode. A higher unstable mode at 20 MHz shows figure 1.

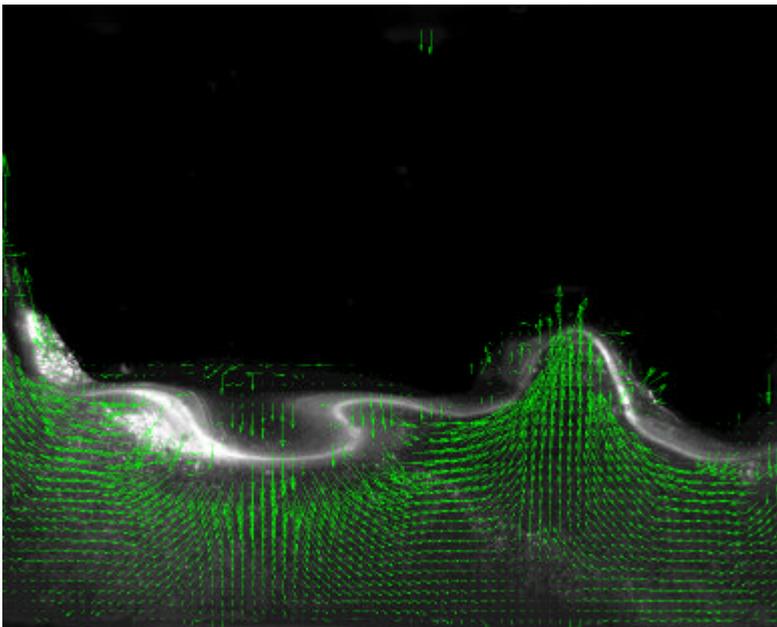
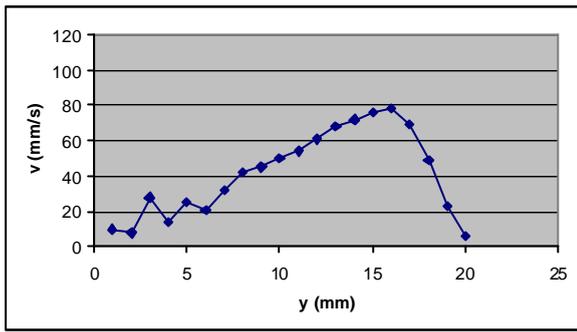
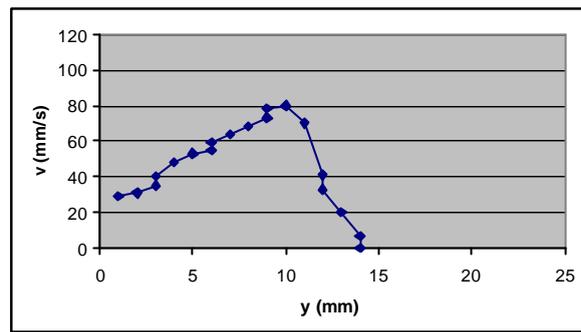


Fig. 6. Light sheet image and PIV velocity vector plot of a unstable free surface oscillation of water at shaker frequency of 15 Hz and magnitude of 1.0 mm

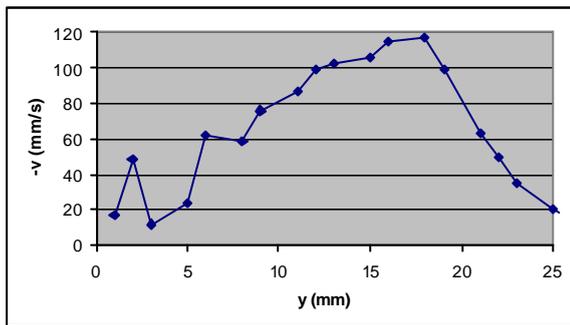
From the PIV vector plots horizontal and vertical velocity profiles are calculated to test the accuracy of the assumption that the system can be modelled by linear equation and to indicate instabilities. The profiles are located at the two peaks of the surface wave in figure 5.



a) *first peak upwards*



b) *second peak upwards*



c) *first peak downwards*

Fig. 7. Vertical profiles of the z -component at stable surface oscillations

In all three cases the profile is approximately linear and agrees apart from the surface induced mistakes at y values above 17 mm (10 mm at the second peak) with the theoretical prediction.

3.2 PIV measurements in the system In-Ga-Sn / water

The observation of the two fluid system Ga-In-Sn alloy and water with PIV yields only information about the water layer (Fig.8 and 9). To simulate the upper electrode the test cell was closed with a glass lid. Higher velocities and a 3d velocity field are characteristic for unstable non-linear interface oscillations at high magnitudes of the shaker. The plot of the absolute velocity value demonstrate the influence of the interface oscillation on the flow in the water layer up to the lid electrode.

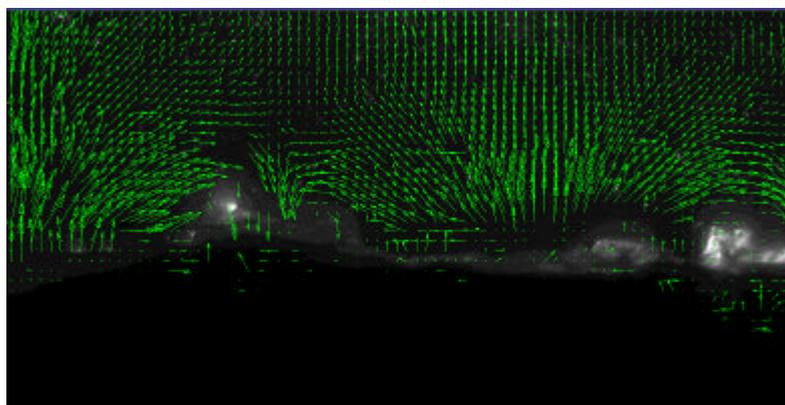


Fig. 8. Light sheet image and PIV velocity vector plot of a unstable interface oscillation In-Ga-Sn / water at shaker frequency of 10 Hz and magnitude of 1.0 mm

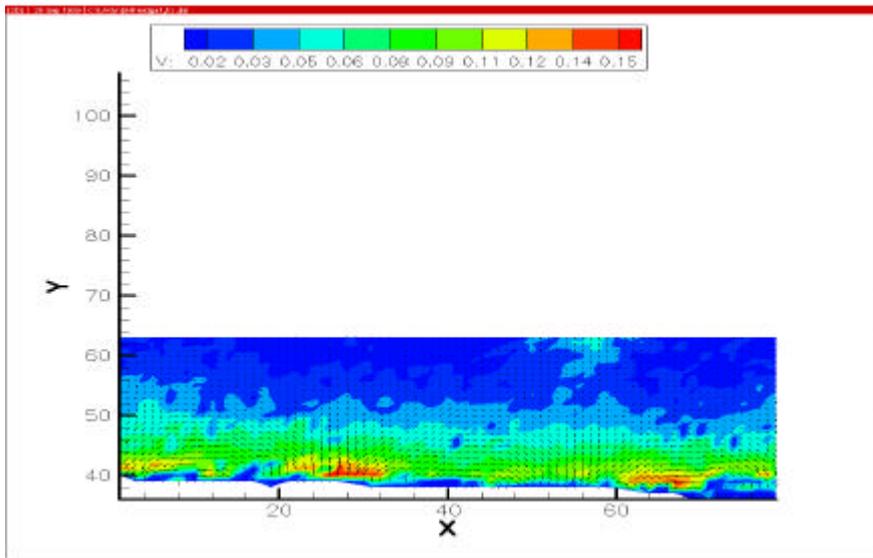


Fig. 9. Vector field and contour plot of velocity data in the water layer during stable interface oscillation of the system Ga-In-Sn alloy / water, $f= 13$ Hz, 0.5 mm magnitude

3.3 Vibrometer measurements

Figure 10 shows the transfer function (power spectrum) of the interface oscillations at the center of the pool in the range from 3 to 30 Hz stimulation frequency. The thickness of the water layer above the Ga-In Sn-alloy was 10 mm. First a cylindrical cell with 47 mm diameter was mounted on the shaker. The eigenfrequencies of the interface waves amount 8.8 Hz (first harmonic), 16.0 Hz (second harmonic) and 22.0 Hz (third harmonic).

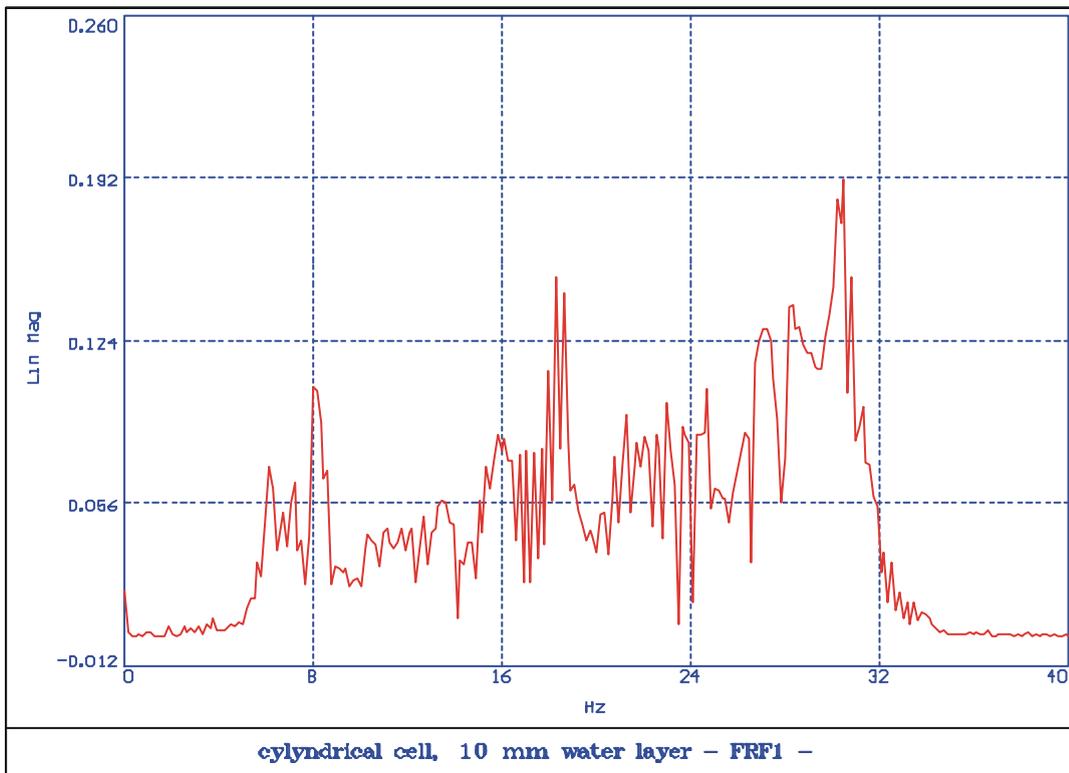
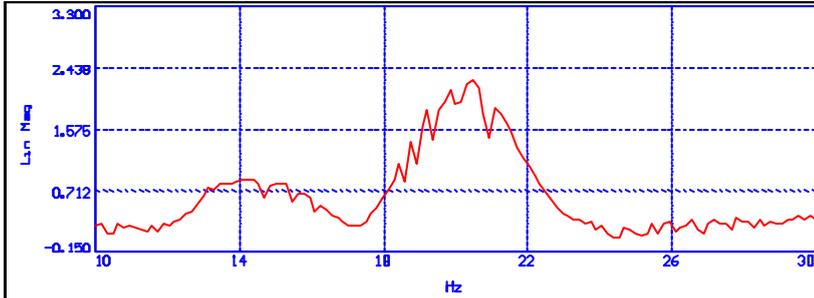


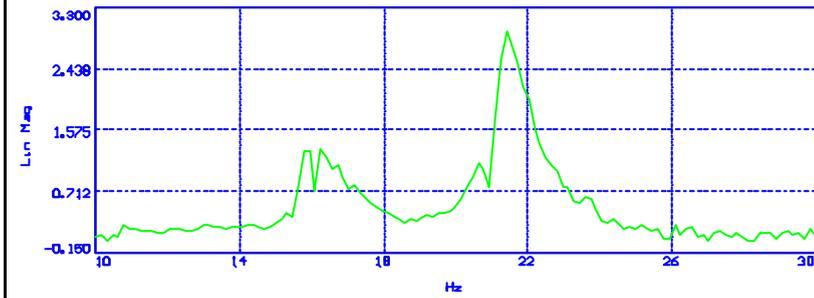
Fig. 10. Power spectrum of interface oscillation in a cylindrical pool with Ga-In-Sn alloy and 10 mm water layer

The peaks at 7.0 Hz and 18.8 Hz are due to sub-harmonic excitation, indicated by watching the phase signal. An increase of the thickness of the water layer at constant alloy mass (61 g) leads to a displacement of the eigenfrequencies in the direction of higher values and a change of the relative peak height.

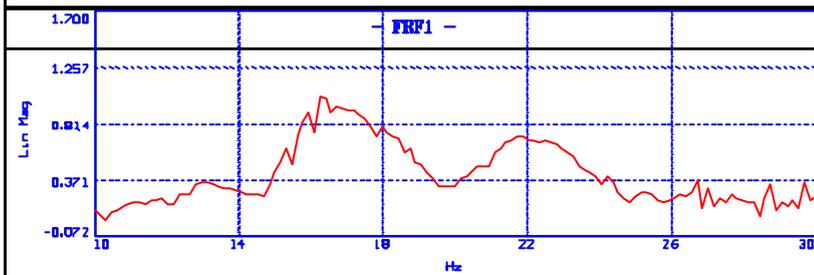
a) no water layer



b) 5 mm water layer



c) 10 mm water layer



d) 20 mm water layer

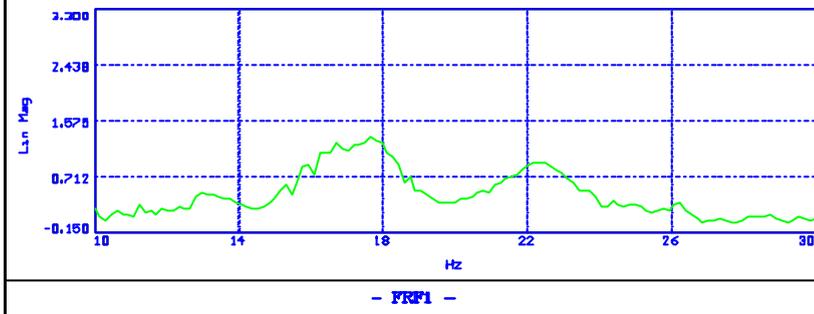


Fig. 11. Displacement of the eigenfrequencies as a function of the thickness of the water layer in the cylindrical test cell

4. SUMMARY

Optical measurement techniques like PIV and laser vibrometer are suitable to analyse interface oscillation of a two fluid system. Stable and unstable interface waves could be excited with an electromagnetic shaker in a frequency range between 3 and 30 Hz. The observed eigenfrequencies depend on the cell geometry and depth of the water layer above the liquid metal. In addition to harmonic interface waves some oscillations had sub-harmonic properties, called parametrically forced waves or Faraday instabilities. The optical investigation of the boundary layer and the flow field in the transparent part of the fluids are first important steps in order to get a complete physical model of the nature of gravity waves in aluminium reduction cells and other MHD-configurations.

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