Effect of a free-surface fluid layer on vibroacoustic response of a plate

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ABSTRACT

This experimental study points out the modifications of the behavior of a coupled system due to the introduction of a viscous fluid film between a gas volume and a vibrating plate. The tested configuration is composed by a cylindrical volume of gas with rigid walls excepted for one of the circular extremity witch is a thin aluminium plate. A rather low frequency domain is explored (30Hz-200Hz). The aim of this study is to reach to an optimization of this viscous fluid film in order to control the vibroacoustic behavior of the wall-film system and to dissipate maximum energy at chosen frequencies. For example, if water is used for the fluid film, surface waves appear at the fluid-gas interface if the vibrations are enough important. We observe a decrease of the natural frequencies mainly due to an added mass effect and also a decrease of the amplitude of the frequency response of the system compared to the response of a pure mass system. If a more viscous fluid is used for the film, for the same added mass, the decrease of the frequencies are equivalent to those observed with water, but less damping are observed : for the same vibration level of the plate, the surface-waves system do not appears and the fluid viscosity do not contribute to the system behavior. A simple model of the system will be also presented during the talk.

INTRODUCTION

In order to reduce the noise in a exhaust, treated walls are generally used. An other way is to inject heavier fluid in drops form (water for example) to consume the momentum energy, and if necessary to decrease the temperature. In this last configuration, the mass effect of the heavy fluid is used, but inside the drop all the points have the same velocity. If the viscosity of the chosen fluid is not zero, this type of kinematic do not permit to dissipate energy by this way.

In the same idea, precedent works (Bruneau 1984) evaluate the acoustic behavior of a free falling liquid wall. But the free boundary conditions on the two faces of the surface limiting gas and fluid, allow fluid velocity fields with small velocity gradient which do not used the viscosity of the fluid.

Other boundary conditions (adhesion to a wall) should induce greater velocity gradient, allowing an useful dissipation to take place.

Some experiments or models were published on a vibrating plate which interact with sloshing fluid in a container for partially filled container with flexible walls (Genevaux 1998) or a bottom plate (Amabili 1998) (Cheung 2002). In all these studies, the waves lengthes are greater than $0.01m$, so the behavior law of the free surface depends more on the gravity than on the superficial tension : sloshing frequencies are coupled with a flexible structure. For exemple, in (Cheung 2002), the aspect ratio between the fluid depth and the radius of a circular plate stay greater than 0.1. The authors do not simulate results for smaller fluid depth to avoid for long wave length the

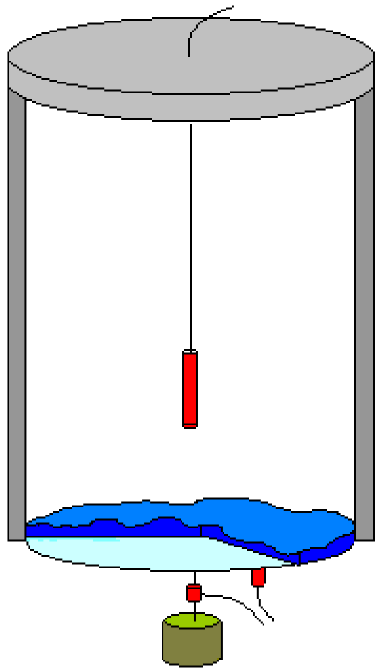

Figure 1: *The experimental configuration : a cavity, a plate and a heavy fluid film.*

non validity of their hypothesis of fluid without viscosity. The same limitation are present in the study of a vertical plate partially immersed in the fluid, in which an analytical solution is compared to experimental results (Genevaux 1998), as in (Amabili 1998) where an interaction of sloshing waves with a bottom plate is presented.

For thin films, several studies presents the evolutions of a falling film along a structure ((Ambrosini 2002) for example), but the vibrations of the structure are not considered. In theses cases, the waves at the free surface are due to the instability of the fluid flow under gravity.

In order to work in the domain of acoustic frequencies, we will consider higher frequencies. The length of the free surface waves are shorter than in the preceding studies, and superficial tension must be considered. Moreover, in order to use strong velocity gradient to dissipate energy, the aspect ratio between fluid depth and dimensions of the plate are very lesser than 1. To test this behavior, a configuration with a gas cavity, which interacts with a heavy fluid film, layered on a moving structure is designed. This study presents the first experimental results.

EXPERIMENTAL CONFIGURATION

The geometrical configuration is presented figure 1. A cylindrical tube with an inner diameter of $d = .290\,m$ and a length of $l = 0.803m$ was build in a polymeric transparent material. The thickness of the tube $e_t = 0.005\,m$ and the mechanical characteristics of the material reject the resonances frequencies of this tube far higher than the frequency range which will be explored.

The upper extremity of the tube is closed by a rigid plate in the same polymeric material in which several holes are made to guide the microphone. The choice of the hole, the orientation of the upper lid and the length of the microphone support introduced in the cavity, define the microphone position using the gravity.

The bottom extremity is closed by a circular aluminum plate whose diameter is $d_p = 0.320\,m$ and its thickness $e_p = 0.001\,m$. Its surfacic mass is then $\rho_p = 2.7\,kgm^{-2}$. This plate is considered clamped on a circular line corresponding to the tube diameter d.

An electro dynamic vibration generator (LDS V201) is connected to the center of the plate. The level of excitation is measured by a force transducer (Endevco 2311-500), and controled by Siglab software on a personal computer. The acceleration of the plate is also measured by an accelerometer (Endevco 256HX-100) whose small mass is $m_a = 0.0042\,kg$ and can be placed near ce plate center. We currently test the possibility to measure the free surface movement with a laser technic.

Between each test using different fluids, the container is washed, rinsed with water several times in order to limit the presence of surfactant liquid, and dried. The rod used to transmit the excitation is glued to the plate and is not moved between the described experiments. The frequency responses function of the accelerometer versus force and the pressure detected by the microphone versus force always presents maximums at the same frequencies. The presented curves are obtained by a step by step increase of frequency. Thus the excitation is purely harmonic.

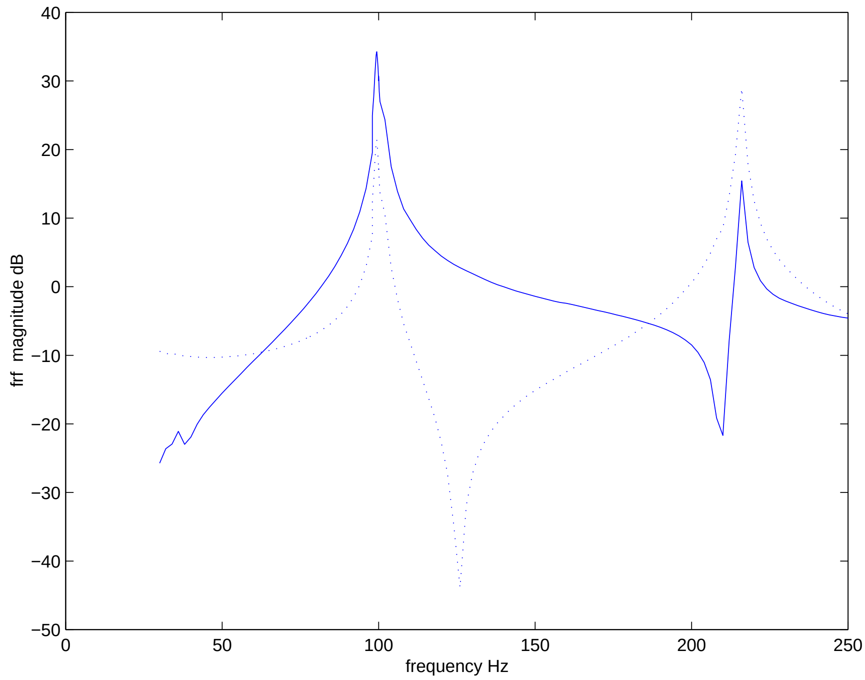

Figure 2: *Magnitudes of the frequencies response functions for the dry plate: continuous line, accelerometer/force; doted line, microphone/force.*

RESULTS AND INTERPRETATIONS

AN ADDED MASS EFFECT

A reference experiment without heavy fluid is first performed. The frequencies response for a large frequency band (20 Hz to 250 Hz) is presented figure 2. Pure harmonic excitation is always used, and frequencies are step by step explored. We can notice :

- The resonances for the frequency response of the microphone and the accelerometer coincide.
- A first resonance is located near 100 Hz. The plate is moving on the first mode shape of a clamped circular frequency : the mode shape is axisymetric and the amplitude is maximum at the center of the plate and there is no circular nodal line.
- The second resonance is near the first acoustic longitudinal mode of the cavity. Indeed, its theoretical frequency is given by,

$$f_{acoustic} = \frac{c}{2l} = \frac{340}{2\,0.803} = 211\,Hz, \tag{1}$$

  with c the celerity of sound.

Water is first used to test the influence of the water level on the frequency responses function. The heights of the water level stay less than $0.016\,m$ for all the presented experiments. We can define the ratio of added surfacic mass by,

$$\tilde{\rho} = \frac{\rho_f h}{\rho_p}, \tag{2}$$

with ρ_f the volumic mass of the fluid, h the thickness of the fluid film. With the increase of the water level, we can notice figure 3 :

- the resonance frequencies decrease.
- an other resonance appear (near $140Hz$ for a water level of $8mm$, with correspond to the first mode with a nodal diametral line.

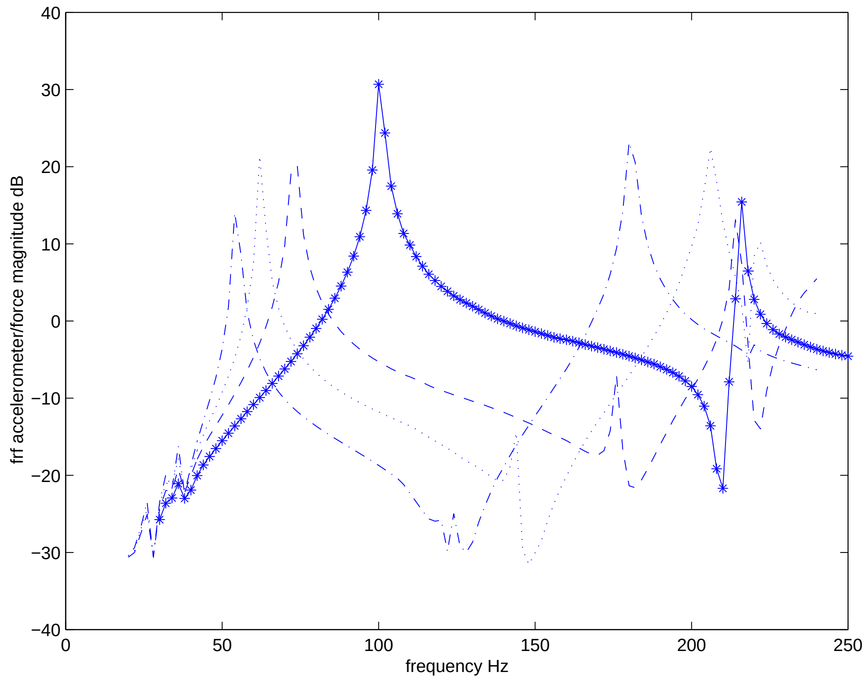

Figure 3: *Influence of the water level on the magnitude of the frequency response functions (accelerometer/force) :* $*$*, dry plate ;* $--$ $\tilde{\rho} = 1.71$ *film thickness* $4.6\,mm$ *;* $:$ $\tilde{\rho} = 2.97$ *film thickness* $8.0\,mm$*;* $-.-$ $\tilde{\rho} = 4.92$ *film thickness* $13.3\,mm$

- the amplitude (in dB) of the maximum of the response decrease, while for a simple system (spring-mass-dashpot) an increase of the mass with other parameters kept constant induces an increase of the amplitude. Nevertheless, their evolution versus the water level is nonmonotonic.
- for the first resonance frequencies, stationary waves can be observed on the free surface between the fluid and the gas. Their wave length (near $0.005\,m$) increase when the frequency decrease. This length is coherent with capillarity waves on the surface. Their amplitude is more important at the center of the plate, where the maximum of the mode shape of the plate is present.

At this step, it is not possible to detect if the damping is greater than for a pure higher mass system. Non linear behavior is maybe the source of the nonmonotonic evolution of the maximum levels. We will show in paragraph that the viscosity of water contributes to theses curves, and not only an added mass effect.

AN EFFECT OF THE AMPLITUDE OF THE EXCITATION

We need to test the dependance of the frequency response functions to the amplitude of the excitation. We performed this experiment for water levels corresponding from 0 to $0.0133m$. Non linear effects are observed figure 4:

- a small increase of the frequency resonance with the amplitude of excitation ,
- a decrease of the amplitude of the maximum,
- it exists a minimum level of excitation that must be reached in order for the waves to take place. In the figure 4, this level is between 6 and $13\,ms^{-2}$. It is corresponding to a jump of the damping which is measured by half-power method (see figure 5). This jump is not observed for the system without fluid (stars). We will call it *critical level of excitation*. Is this a parametric instability ?

If this non-linear effects appears in the fluid, they can be due to the important oscillation of the fluid domain for which the amplitude of the waves are of the same order than the water level. This is coherent with the decrease of the damping when the water level is increased. Unfortunately, we are not able for the moment, to measure the amplitudes of the waves.

This paragraph shows that it is absolutely necessary to control the amplitude of the excitation. For all the following experiments, the amplitude of the acceleration measured at the center of the plate will be constant.

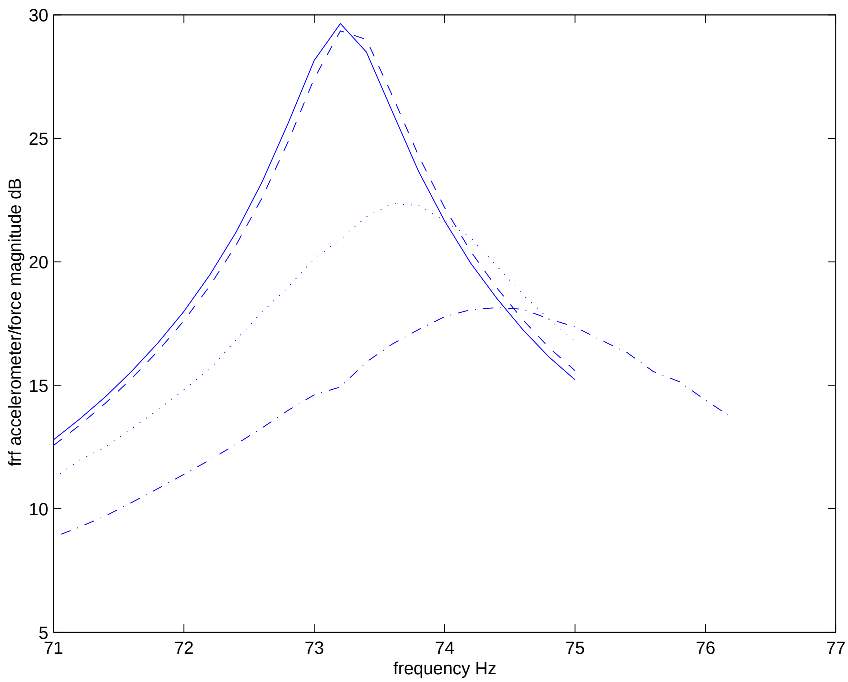

Figure 4: *Influence of the amplitude of the excitation (measured at the center of the plate) on the frequency response function (accelerometer/force) of water added mass for a water level of* $0.0046m$ $\tilde{\rho} = 1.70$ *:* $-$ $3.16\,ms^{-2}$ *;* $--$ $3.33\,ms^{-2}$ *;* $-.-$ $12.7\,ms^{-2}$ *; :* $25.3\,ms^{-2}$.

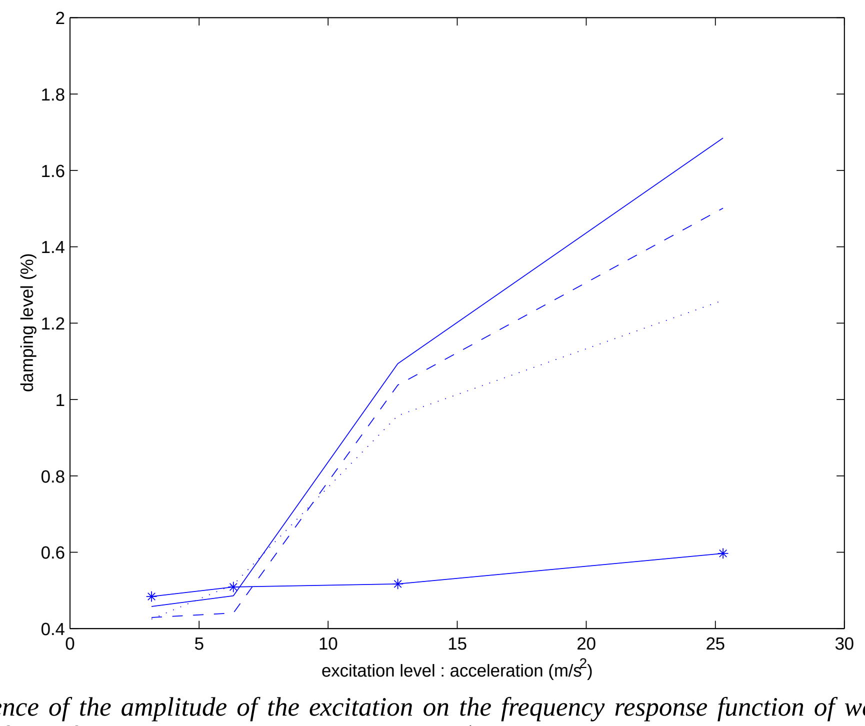

Figure 5: *Influence of the amplitude of the excitation on the frequency response function of water added mass (accelerometer/force) for several water levels :* $*$ $0.0\,m$ *;* $-$ $4.6\,mm$ *;* $--$ $8.0\,mm$ *; :* $13.3\,mm$*. When the surface waves appear (between the excitation levels* 6 *and* $13ms^{-2}$*), the damping jumps to greater values.*

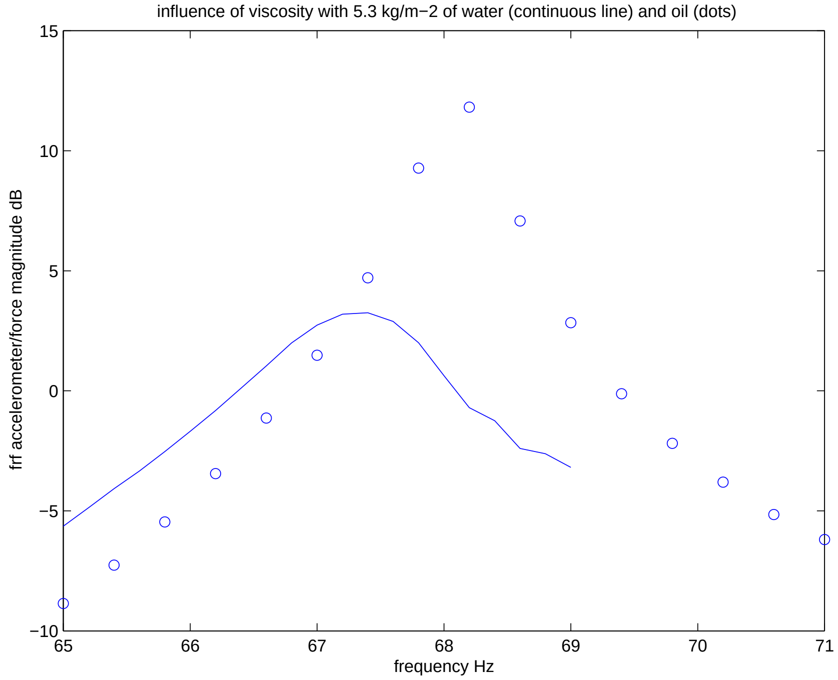

Figure 6: *Influence of the viscosity on the frequency response function (accelerometer/force) for an added mass of* $\tilde{\rho} = 1.96$ *: - water (film thickness* $5.3mm$*) ; o oil (film thickness* $7.2mm$*). At first sight, a surprising result*

A VISCOSITY EFFECT

To point out the influence of the viscosity, the water is then replaced by oil. We use a basic lubrication oil for cars (Esso 15W40) with a very higher viscosity than water. The figure 6 shows that the amplitude of the maximum of the frequency response is $10\,dB$ higher than the amplitude with water. We notice also that no stationary waves appear at the free surface between oil and gas, although the amplitudes of the accelerations at the center of the plate are identical. The critical excitation level (see preceding paragraph) for oil is higher than for water.

On the face of it, this result is surprising. In fact, the viscosity is so strong that the oil-film is moved like the plate : no local relative fluid velocity appears between the oil and the plate. The non existence of speed gradient in the fluid, induced that its viscosity gives any contribution to the frequency response of the system. It means that we observe with this oil, only the added mass effect. The preceding curves (figure 3) contain the contribution of the viscosity and the added mass. This is confirmed by the measure of the damping near the first frequency response maximum ($-3\,dB$ technique). For dry plate and for an oil film, the measured dampings are rather equal to 0.25%, and with water to 0.6%.

A SURFACE TENSION EFFECT

The existence or not of stationary waves at the free surface plays an important role. When they exist, the surface tension affects the relation between the frequency and the wave length. For water, we modify this characteristics by introducing drop by drop a surfactant product. The figure 7 shows that the resonance frequency is a little bit increased from the first drop, and after does not move with the increase of the quantity of surfactant.

These behavior is coherent with the increase of the rigidity of the free surface due to the presence of the surfactant.

CONCLUSION AND SEVERAL IDEAS FOR THE MODELLING

This experimental study shows that the presence of a heavy fluid film on the surface of a vibrating structure which is coupled to a cavity, permits to dissipate energy at the resonance frequency. This behavior is conditioned by :

- the added mass effect,
- the existence or not of stationary waves on the free gas-fluid surface,
- the viscosity which dissipates energy, but can also vanishes the stationary waves,
- the surface tension of this free surface,

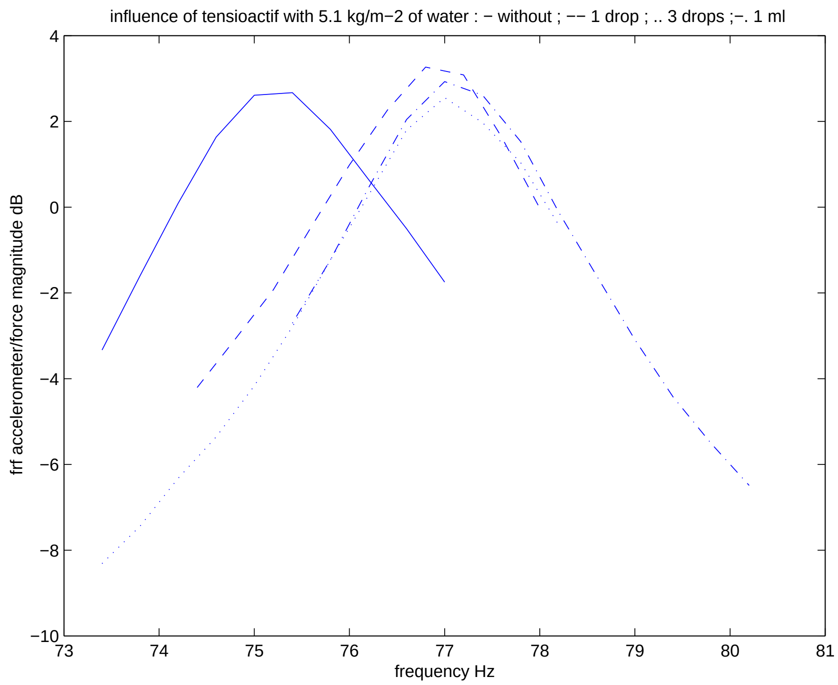

Figure 7: *Influence of the presence of surfactant product on the frequency response function (accelerometer/force) added mass of* $\tilde{\rho} = 1.89$ *(film thickness* $5.1mm$*): the frequency resonance is increased from the first drop. - water without surfactant ; - - 1 drop of surfactant ; -.- 2 drops ; : 1* ml

- the amplitude of the movement, and their associated non linear mechanisms.

An optimization of the characteristics of the fluid film must be achieved in order to control the added dissipation due to its presence. The modelling of this coupled problem may use this set of equations :

- the hypothesis of periodic motion of the structure and of the fluid particles.
- a classical behavior law for the structure using plate kinematics.
- for this plate, boundary conditions on the clamped circular.
- in the fluid domain we should use a linearized Navier-Stockes equation for viscous fluid term (Lamb 1993).
- the boundary conditions on the circular tube of diameter d must not be used : the wave length on the free surface are very lesser than d. Therefore, this boundary condition do not influence the free surface shape. The pattern are not axisymetric. A 2D periodic pattern is the only hypothesis which must be made.
- the surface tension, and in a first step, a linear model for the free surface will give us the relation between the observed frequency and the wave length. The non linear model for finite waves can also be used (Lamb 1993).

A Rayleigh-Ritz technique can be used (Géraldin 1996) : choice of a modal shape of the plate, choice of an modal velocity shape for the fluid which respects the kinematic conditions at the fluid-structure interface. Minimization of the Rayleigh coefficient according to the parameter ξ (equal to the ratio between the wave amplitude and the maximum plate amplitude). The added dissipation is then evaluated in a second step by considering the obtained fluid velocity field. The comparison between the model and the experiments will be presented during the talk.

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