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Experimental study of energy pumping in acoustics

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Abstract

This paper presents an experimental vibro-acoustic set-up that aims to reproduce the energy pumping phenomenon between an acoustic medium and an essentially nonlinear oscillator. It shows a one-way irreversible transfer of energy between the first acoustic mode in a tube and a thin visco-elastic membrane. Various observed aspects of energy pumping are presented : behaviors under sinusoidal forcing, pumping threshold, resonance capture and transient response.

1 Introduction

This paper deals with the energy pumping phenomenon for acoustic applications. The concept of energy pumping has been introduced by Vakakis and Gendelman [1,2,3] in 2001 : the idea is to passively reduce the vibrations in a linear system (discrete or continuous) by attaching to it an essentially non linear damped oscillator. Under suitable conditions, a one-way irreversible transfer of energy can occur from the linear system to the nonlinear one, leading to an efficient cancellation of the oscillations in the linear system.

Many recent papers have been published around this interesting new concept, and to its application to various fields. For instance, the idea of using several nonlinear oscillators to improve the pumping has been investigated in [4], and a first experimental validation of pumping has been demonstrated in [5] on a two degrees of freedom mechanical system.

In this paper we succinctly describe a simple two degrees of freedom model of which the main goal is to design an experimental set-up that permits to observe the energy pumping between an acoustic medium and a thin visco-elastic membrane. Then we present our experimental results. The first is the observation of different regimes under harmonic forced excitation between which a pumping threshold appears, corresponding to a non linear modes bifurcation. The resonance capture phenomenon [2] is also highlighted. The other results are the noise level reduction in permanent regime and the faster sound extinction in transient response resulting from energy pumping. This first verification of energy pumping in acoustics is a first step toward the design of new generation of passive acoustic absorbers that would be efficient at lower frequencies, where absorber materials are ineffective.

2 Models and design of the experimental set-up

The energy pumping phenomenon consists to damp a linear system by adding a non linear absorber and the simplest way to observe it is to consider a two degrees of freedom system (figure 1) consisting of two oscillators connected by mean of a small stiffness coupling spring. The first oscillator is a classical linear spring-mass system. The second one is composed of a mass, a nonlinear cubic spring (without linear stiffness), and a damper. Rescaling time with the natural period of the linear oscillator, the non dimensional

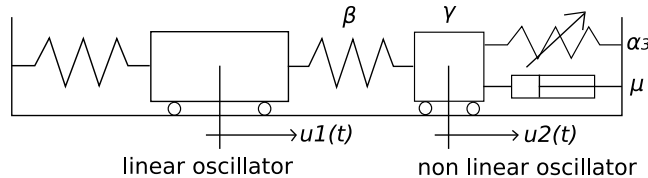


Figure 1: *Two degrees of freedom mechanical system.*

equations for the positions $u_1(t)$ and $u_2(t)$ of the masses are :

$$\begin{aligned} \ddot{u}_1 + u_1 + \beta(u_1 - u_2) &= 0 \\ \gamma\ddot{u}_2 + \alpha_3 u_2^3 + \mu\dot{u}_2 + \beta(u_2 - u_1) &= 0 \end{aligned} \quad (1)$$

with γ the mass ratio of the two masses, β the small coupling coefficient, μ the damping factor in the nonlinear oscillator and α_3 the cubic stiffness coefficient.

The free solutions of (1) have been already discussed in [6] to illustrate the energy pumping. The periodic solutions of the undamped system have also been analysed to show the connection between the pumping and the non linear modes of the system.

Our aim is to experimentally reproduce the pumping phenomenon in a system where the linear oscillator is an acoustic medium. So we replace the linear mechanical oscillator by the air vibrating on the first acoustic mode in a tube, the coupling stiffness by the air in a coupling box and the nonlinear oscillator by a thin visco-elastic membrane as presented on figure 2.

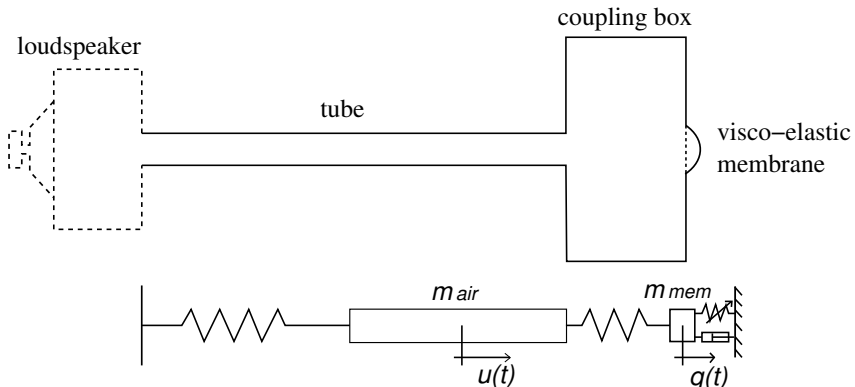


Figure 2: *Principle of the acoustic experimental set-up equivalent to the two d.o.f. mechanical system of figure 1.*

A continuous model associated to this principle can be obtained by taking Helmholtz equation for the air contained in the tube, and the nonlinear plate equation of the Von Karman type for the thin membrane. A Kelvin-Voigt model is adopted to account for the viscosity in the membrane : the Piola-Kirchhoff second stress tensor \mathbf{S} is related to the Green-Lagrange strain tensor \mathbf{E} and strain velocity tensor $\dot{\mathbf{E}}$ by $\mathbf{S} = \mathbf{D} : (\mathbf{E} + \eta\dot{\mathbf{E}})$, where \mathbf{D} is a classical fourth order Hooke elastic tensor and η is the damping factor. As a first approximation, the continuous model can be reduced to a two degrees of freedom system by taking $u(x, t) = u(t)\cos(\frac{\pi x}{L})$ for the air in the tube (first undamped mode), and $w(r, t) = q(t)(1 - (\frac{r}{R})^2)$ for the transversal displacement of the circular membrane (parabolic shape function). The two coordinates $u(t)$ and $q(t)$ correspond to the displacement at the end of the tube and at the center of the membrane. In the box, the acoustic velocity is supposed to be negligible and the pressure is thus considered as spatially uniform. It is related to the volume variation by $p = \rho c^2 \frac{\Delta V}{V}$ with $\Delta V = u(t)S_t - q(t)\frac{hS_m}{2}$.

Applying a classical Galerkin method, we get the following reduced system :

$$\begin{aligned} \ddot{u} + u + \beta(u - q) &= 0 \\ \gamma\ddot{q} + \alpha_3(2\eta\omega q^2\dot{q} + q^3) + \beta(q - u) &= 0 \end{aligned} \quad (2)$$

which is similar to (1) except for the dissipative term which is here nonlinear, because of the geometrical nonlinearity in the membrane. Since the membrane performs large amplitude oscillations, the linear stiffness of the membrane has been neglected in (2). This model reduction yields to explicit formulae for the coefficients β , γ and α_3 with respect to the physical characteristics of the set-up. The natural pulsation of the linear oscillator being $\omega = \frac{\pi c}{L}$, we have

$$\beta = \frac{2 S_t L}{\pi V} \quad \gamma = \frac{8 h S_t \rho_m}{3 L S_m \rho_{air}} \quad \alpha_3 = \frac{32}{3(1-\nu^2)\pi^2} \frac{E}{\rho_{air} c^2} \frac{h^3 L S_t}{R^4 S_m} \quad (3)$$

where h , R , S_m and ρ_m are the membrane thickness, radius, section and density, L and S_t are the tube length and section, V is the volume of the coupling box, E the Young modulus of the membrane, ρ_{air} the density of the air and c the sound speed.

This model allowed us to simulate the problem and determine which values of the different parameters led the energy pumping. Then the experimental set-up has been designed to get $\omega \approx 580 \text{rd/s}$ ($\approx 92 \text{Hz}$) $\beta \approx 0.1$, $\gamma \approx 1$, $\alpha_3 \approx 10^{-2}$. With these values, the energy pumping can be obtained under pressures and velocities compatible with the experimental conditions. The physical parameters are $L = 2 \text{ m}$, $R = 0.03$, $S_t = 0.0069 \text{ m}^2$, $h = 0.46 \text{ mm}$, $E = 1.3 \cdot 10^6 \text{ Pa}$, $\eta = 0.002$, $\rho_m = 1000 \text{ kg.m}^{-3}$, $\rho_{air} = 1.2 \text{ kg.m}^{-3}$, $c = 340 \text{ m.s}^{-1}$, $V = 0.028 \text{ m}^2$.

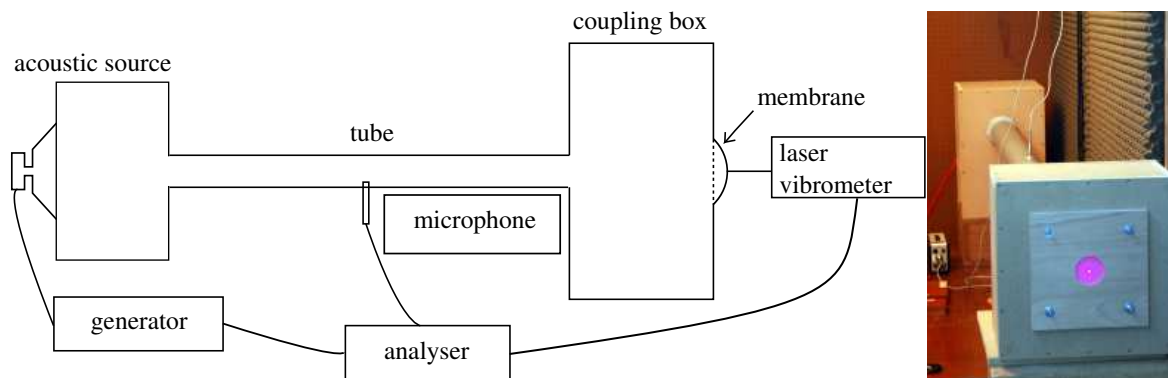


Figure 3: *The experimental set-up. A generator is used to control the loudspeaker. Two measurements are here possible : a microphone measures the pressure in the middle of the tube (easily related to the displacement u of the air at the end of the tube) and a laser vibrometer measures the velocity of the membrane center.*

3 Experimental results

3.1 Harmonic forced excitation

On figure 4 A, B et C, we can observe a threshold for the appearance of energy pumping. Two stable regimes exist, one without pumping (figure 4 A) when the level of the source is below the threshold, the other with pumping (figure 4 C) when the level is above the threshold. An unstable regime (figure 4 B) also exists around the threshold, the pumping is here intermittently activated. The regime without pumping corresponds to the second nonlinear vibration mode localized on the tube and the regime with pumping corresponds to the first nonlinear vibration mode localized on the membrane as explained in [6]. For the first mode to predominate, a minimum of energy to be brought to the system is required. This minimum corresponds to the energy pumping appearance threshold. This concepts of threshold and mode bifurcation are also well described in [2,7].

We can also observe the resonance capture phenomenon associated to the bifurcation on figure 5 which is simply a zoom of the figures 4 A(channels 2 and 3) and 4 C(channels 2 and 3). It is clearly visible that during the bifurcation from the mode without pumping to the mode with pumping, a phase shift takes place on the membrane vibrations and that a 1:1 resonance capture appears between the linear system and the nonlinear absorber. The change of localization is also visible : without pumping, vibrations are localized on the tube and with pumping, it is localized on the membrane, meaning that the membrane vibrates instead the air in the tube, a particularly interesting property.

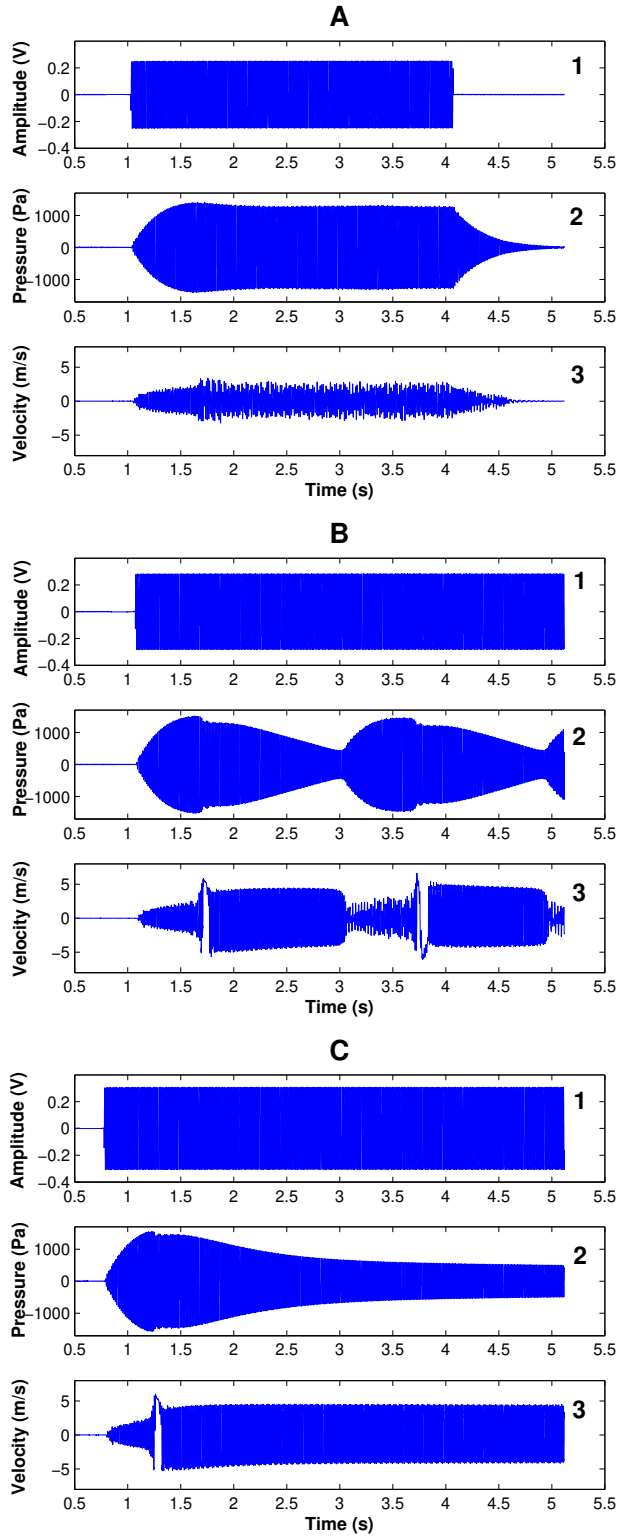


Figure 4: Three different experimental observations : a regime without pumping (A) for an excitation level below the threshold of pumping appearance, a regime with pumping (C) for an excitation level above the threshold and an unstable intermediate regime (B) where the pumping is intermittent for an excitation level around the threshold. The curves 1, 2 and 3 correspond respectively to the excitation signal, the pressure in the middle of the tube and the velocity of the membrane center.

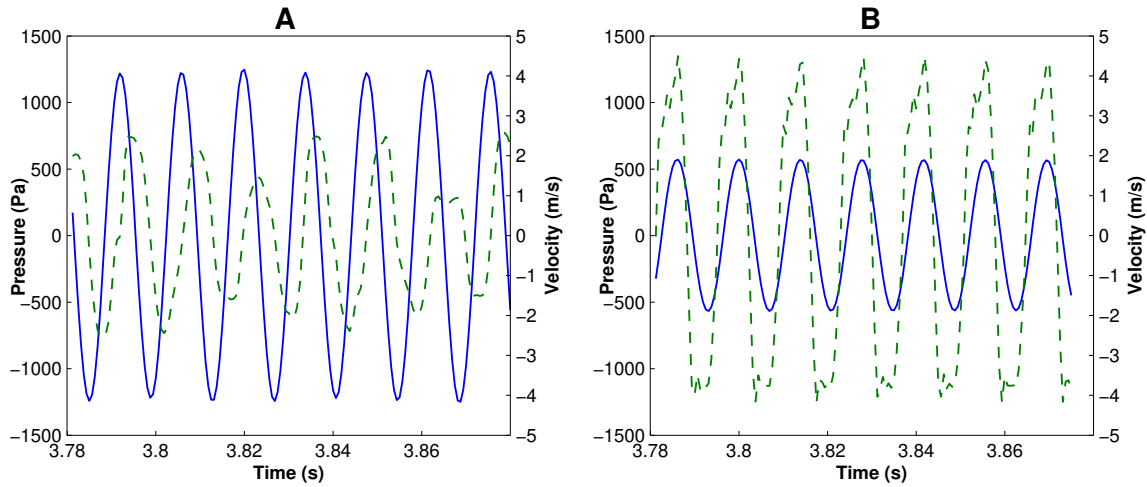


Figure 5: *Resonance capture : zoom of figure 4 to observe the phases of the signals without pumping (A) and with pumping (B). The continuous line shows the pressure in the middle of the tube and the dash line shows the velocity of the membrane center.*

3.2 Noise reduction by energy pumping

In order to clearly observe the reduction of the noise level obtained in the tube resulting from the energy pumping phenomenon, we recorded the signals in two configurations : the first one just before the pumping appearance and the second just after, so that in both cases the level of the source is almost the same. We observe on figure 6 a reduction by a factor of two of the sound amplitude associated to a significant increase of the vibrations of the membrane when pumping is active.

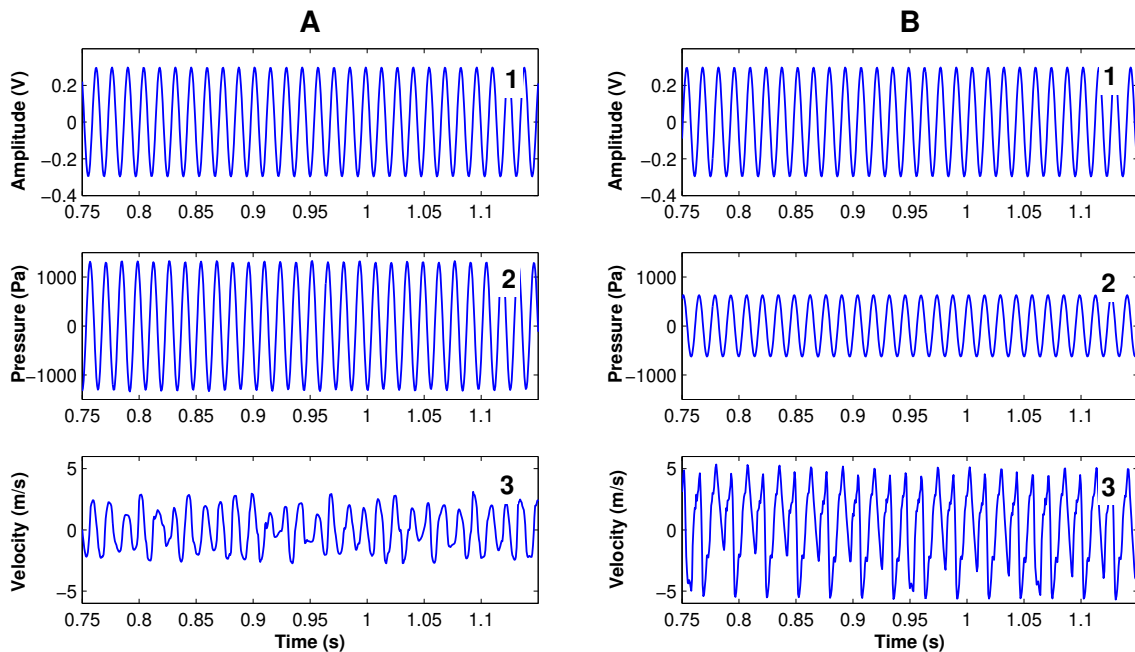


Figure 6: *Noise reduction in the tube by energy pumping. For the same excitation level, we have on A the mode without pumping and on B the mode with pumping. The curves 1, 2 and 3 still correspond respectively to the excitation signal, the pressure in the middle of the tube and the velocity of the membrane center.*

3.3 Free oscillations

The pumping phenomenon is also interesting to rapidly damp the free oscillations after an impulse excitation. Experimentally, we cannot use a single impulse to start the motion. Instead, we use a harmonic forced excitation at the natural frequency of the set-up. This signal is suddenly turned off, and we observe then the free oscillations of the system. In the case of the curve figure 7 A, we are below the energy threshold for the pumping, and we observe a classical exponential decrease of the pressure in the tube. For a higher value of the initial energy, we have activated the pumping phenomenon as it can be seen in figure 7 B. We can see a linear decrease of the pressure amplitude in the tube, whilst the velocity of the membrane remains important. The unusual fact is that a bigger impulse (above the threshold) is there more rapidly cancelled than a smaller one (below the threshold). It should be noticed that the pumping occurs until the almost complete cancellation of the oscillations in the tube. This observation is of prime interest : we can clearly see an irreversible transfer of energy between the acoustic medium and the membrane. These behaviors are similar to those obtained experimentally and numerically on the two d.o.f. mechanical system [4,5,7].

In the configuration of the figure 7, the pumping threshold is about 125 dB for the sound level in the tube and the level corresponding to the curve B2 is 137 dB. These values are indeed too important for the human hear yet. A part of our future work is then to design the system for lower threshold.

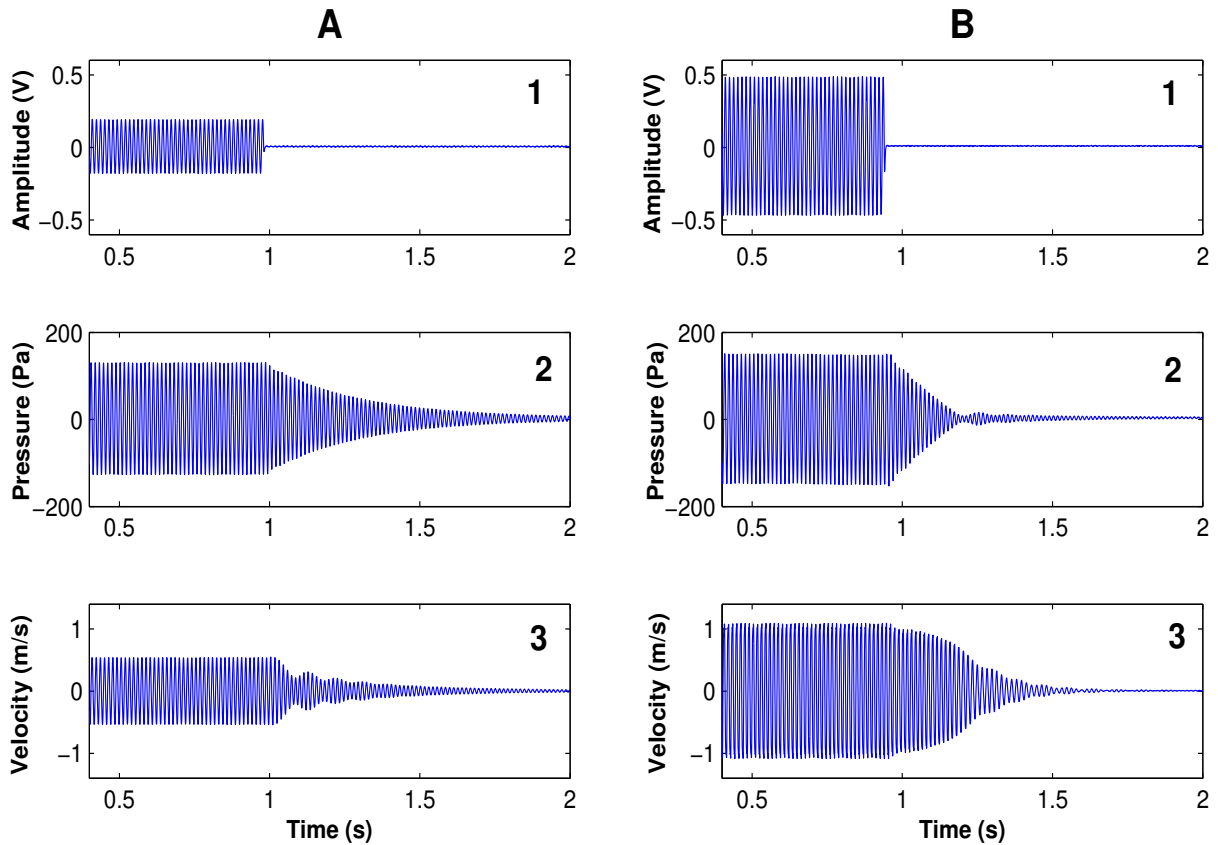


Figure 7: Observation of the free oscillations of the system after turning off the source. On A curves, the initial excitation level is below the pumping threshold. On B curves, the initial excitation level is above the threshold. The curves 1, 2 and 3 still correspond respectively to the excitation signal, the pressure in the middle of the tube and the velocity of the membrane center.

4 Conclusion

This experimental device permits to show an irreversible transfer from an acoustic medium to a visco-elastic membrane, acting as an energy sink. Many well known results about energy pumping phenomenon have been observed here on an acoustic medium. It is a first step toward a more complete understanding of low frequency noise reduction by using essentially nonlinear oscillators. Parametric optimisation is now scheduled, together with an insight of potential acoustic applications.

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