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Ultra high quality factor resonators operated in fluids

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ABSTRACT

Maximal quality factors are often a synonym for high performances for resonator based sensing devices. When vibrating within a fluid, several damping mechanisms dramatically reduce their performances. We propose a new concept to drastically reduce acoustic radiation damping. A specifically designed cavity enclosing the resonator is presented, able to couple the radiated field back in the resonator. Experiments on a custom tuning fork have been carried out and a cavity design is presented. This enclosing cavity tenfold its quality factor to reach $Q = 75{,}000$ in air at atmospheric pressure, passing through the established physical limits and setting a new record. The presented concept can be extended to many areas of physics employing high quality factor resonators, allowing the exploration of completely new geometries.

1. Introduction

Flexural mechanical resonators have been extensively used in many areas of physics as sensing elements. They are most often sealed under vacuum, in order to minimize any coupling with the surroundings that could affect their excellent resonance characteristics. Many applications however require a complete immersion within a fluid medium. It is for example used for highly sensitive chemical sensing platforms [1], but also for in situ force measurements such as the photo acoustic detection [2], the resonant optothermoacoustic detection [3] or precise temperature measurements [4]. They have also been extensively studied at the nanometer scale, when fluid structure interaction cannot always be modeled according to macroscopic laws [5–7].

The surrounding fluid modifies the characteristics of the resonance, and the sensor performances can be strongly reduced compared to vacuum. The amount of damping experienced usually explains most of the performance losses, therefore its reduction is of significant interest.

It is now established that viscous and acoustic radiation damping are the two dominant damping sources for flexural mechanical resonators vibrating within a fluid [8–10]. Originating both from a fluid-structure interaction but relying on two different physical properties of the fluid that are viscosity and compressibility, these two effects behave differently with respect to the resonator geometry. In a previous study, we reported a shape optimization to maximize the quality factor of a resonator immersed within a fluid [11]. We obtained a record quality factor of $Q = 41{,}000$ in air at atmospheric pressure, and showed the existence of physical limit materializing the trade off between viscous and acoustic dampings.

In this paper, we show that this physical limit can be repelled by introducing an acoustic containment barrier around the resonator. Its function is to prevent acoustic energy to be radiated far from the resonator. The radiated acoustic energy is coupled with the mechanical resonator within the confinement barrier, hence transforming the system into a coupled acoustic resonant system. If the cavity is carefully designed, the effective resonant behavior turns out to be that of a flexural mechanical resonator only subject to viscous damping.

2. Principle of acoustic energy containment

Simplified models are particularly useful to better understand the evolution of the quality factor of flexural mechanical resonators [12,13]. In this work, we will use a simplified approach of the fluid structure interaction to focus on the new presented principle. The total quality factor of such structures is usually expressed as follows, considering all loss mechanisms as independent [11]. In particular, we suppose that compressibility and viscosity can be decoupled as independent loss mechanisms:

$$\frac{1}{Q} = \frac{1}{Q_s} + \frac{1}{Q_v} + \frac{1}{Q_a}, \qquad (1)$$

with Q_s expressing the anchor and thermoelasctic damping, Q_v the viscous damping and Q_a the acoustic damping. Quality factor Q_s mainly depends on the material used for the fabrication of the tun-

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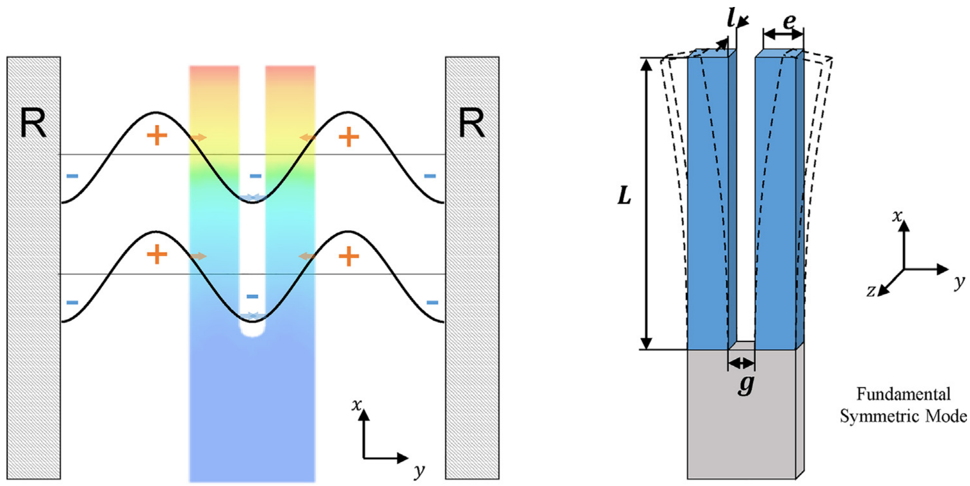

Fig. 1. (Left) Principle of the acoustic energy containment using acoustic reflectors (R) around the resonator. The acoustic eigenmode frequency formed within the cavity closed by the reflector must match the mechanical eigenmode frequency of the tuning fork. Color code on the left schematic indicates the amplitude of the displacement in the y direction, ranging from blue to red. (Right) Schematic of a tuning fork vibrating on its fundamental flexural mode of vibration. (For interpretation of the references to color in this legend, the reader is referred to the web version of the article.)

ing fork, the geometry, as well as the decoupling efforts brought to isolate the clamping areas of the resonator from its vibrating zones.

Viscous damping is an irreversible mechanism since dissipation occurs with friction within the fluid layers. A finite quality factor Q_v can be attributed to this loss mechanism. This fundamentally differs from the acoustic radiation emission, which consists in a mechanical energy transfer from the resonator vibration to an acoustic wave. Back conversion is hence possible in principle, and we propose to contain the radiated acoustic energy within a resonant acoustic cavity placed around the resonator. The new coupled system, composed of the mechanical resonator on one hand and the acoustic resonator on the other hand, forms a new resonator with drastically reduced acoustic radiation damping.

In general, the new resonant system displays new resonance characteristic with no obvious relation to the two original components. The coupled system study has hence to be considered. In the following, we will assume that the acoustic coupling is weak, which allows us to neglect the influence of the coupling on the resonance frequency of the mechanical resonator. This assumption will also ease the presentation of the physical principle of acoustic energy containment. Under that assumption, the resonator imposes its mechanical resonance frequency to the acoustic standing wave within the acoustic cavity. The cavity design has hence to be designed accordingly to display an eigenmode exactly at that same frequency. A 2D principle schematic is presented in Fig. 1 for the case of a tuning fork vibrating on its fundamental flexural mode.

In order to couple efficiently the resonant acoustic field back into the resonator, phase considerations are essential. In the following, we only consider the case of tuning forks since they are one of the most popular and efficient geometry for sensing applications. However, our reasoning could be easily extended to any vibrating resonator which always radiates acoustic waves.

Pressure forces applied on the tuning fork must match its deformation profile denoted ϕ_n when vibrating on its nth mode of vibration. A simple analytical formula allows to understand the relevant design considerations. Indeed, the effective force acting on each prong can be expressed as follows [9]:

$$F_n = \int_0^L \left[P\left(x', \frac{g}{2}\right) - P\left(x', \frac{g}{2} + e\right) \right] \phi_n(x')dx' \qquad (2)$$

The typical variations of the pressure eigenmode distribution $P(x, y)$ are that of the acoustic wavelength, and depends on the boundary conditions (i.e. the shape and position of our reflector). The maximization of the effective pressure forces acting on the resonator is necessary to maximize the coupling. Since both the resonator and the acoustic cavity shape have to be determined simultaneously, the general problem is somewhat tricky since two fields are cross coupled by the vibroacoustics equations. The pressure distribution of the eigenmode has to match three major criteria:

- It has to match the mechanical eigenmode deformation profile ϕ_n in order to maximize the effective force F_n (Eq. (2)).
- It has to be excited efficiently by the radiated acoustic field from the resonator. The equivalent acoustic sources of the tuning fork, which can be seen as a linear quadrupole, need to be correctly localized to match the phase of the acoustic pressure distribution.
- Both the mechanical and the acoustic resonance frequencies have to be maintained identical in the process.

The problem is considerably simpler if the fundamental mode of vibration is considered for the resonator. In that case, the vibration direction is the same along the beam length L (ϕ_n keeps the same sign along the x dimension). According to our 2D representation in Fig. 1, and if e the width of the prongs along the displacement direction, the first and second criterion can be obtained if e equals to half the wavelength:

$$e = v/2f_0 \qquad (3)$$

A relevant choice for the distance from the reflector to the tuning fork can address the last criterion. Back conversion is not perfect in practise since acoustic waves suffers from losses along propagation [14], however those effects will be neglected in our approach.

3. Design of an optimal tuning fork

3.1. Resonator design

As an example, we will now design a custom tuning fork to overcome the physical limitation set in one of our previous work [11], to reach a maximal quality factor for a vibration in air at atmospheric pressure. In order to simplify the acoustic design of the cavity to come, we choose to operate the tuning fork on its fundamental flexural mode at frequency f_0.

The resonator can be designed considering only viscous damping as the main damping source, assuming that we will be able to