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Coupling Helmholtz resonators for sound manipulation

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Abstract - In this work, we discuss the interaction between Helmholtz resonators, using the finite element method. We show that the coupling between two spheres gives rise to two resonant modes at low frequencies. One is symmetric and corresponds to a mono-polar breathing mode, as currently observed. The second one is asymmetric and behaves as a dipole. We show that the first one generates an isotropic wave in the far pressure field while the second one gives rise to a directional propagative wave. We discuss the behavior in frequency of the two modes as a function of the geometrical parameters. By managing the two modes, we aim to create a multifunctional meta-surface operating at two different frequencies.

I. SIMULATIONS

A. Introduction:

The Helmholtz resonator (HR) is defined as a cavity linked to the environment by a neck, which is equivalent to a mechanical oscillator (a spring and a mass) or an LC circuit. The resonance is control by the geometrical parameters of the resonator. Ingard¹ et al. investigated deeply the effect of the neck and the cavity geometry on the resonance response by modify the radius of the section, the location and the length of the neck and the shape of the cavity.

This resonator has been widely used in acoustic due to its ability in controlling low frequencies sound. For that, many innovative structures called “acoustic metasurfaces” were built based on the HR as a sub-wavelength unit. As an example, the behavior of a spherical HR connected to the exterior by an orifice has been investigated by Ding et Al.². This unit was periodically repeated to construct a phase-shifts metasurface that can manipulate the sound. The control of this structure is based on changing the section of the orifices between the resonators to create a constant phase-shift on the surface. Several metasurfaces based on the HR with different functionalities were built (such as acoustic isolation³, anomalous transmission⁴, sound focusing⁵...)

Despite the large development, the multi-functionality in airborne meta-surfaces has not been fully demonstrated. In this work, we scope on the possibility of creating an innovative meta-surface for the manipulation of low frequencies acoustic waves, tunable, with double functionality. To reach this objective, we study here the interaction between two Helmholtz resonators.

B. Methods:

Fig. 1 (a) reports the 3D schematic view of a rigid spherical resonator that emerged in air and the corresponding section of the sphere along the equatorial plane. A planar acoustic wave of a pressure $|P_0| = 1$ Pa is driven perpendicularly to the axe of the opening and a probe was placed on the edge of the aperture to detect the complex pressure (see blue circle).

The resonator is represented by a spherical hollow cavity of constant radius $R = 11.8$ mm and thickness $e = 0.7$ mm. The cavity is connected to the surrounding air media by a circular opening of radius $r = 1.5$ mm as seen in Fig.1 (a). The calculation is done with the help of the finite element method, and the resonant curve recorded at the aperture of the resonator gives a resonant peak at the resonant frequency $f_0 = 1107$ Hz.

Fig. 1 (b) illustrates the 3D schematic view of two rigid spherical resonators with the same parameters as the previous one ($R = R_1 = R_2 = 11.8$ mm and $r = r_1 = r_2 = 1.5$ mm) where the resonators' edges are separated from each other by d_0 . In this case, a probe was placed on the edge of one opening to detect the complex pressure. In our study, we concentrate on changing the distance between the two resonators and the orientation α of the spheres to evaluate the coupling's effect.

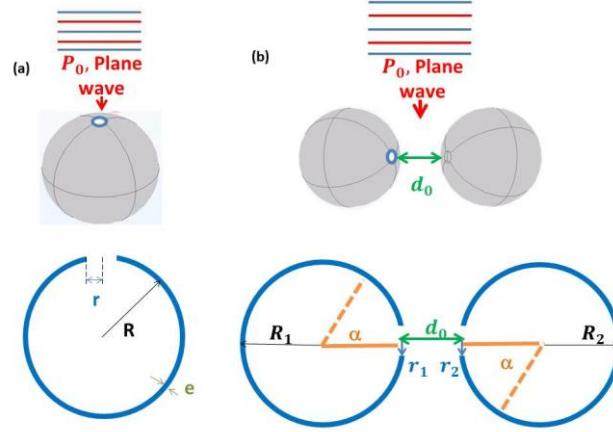


Fig. 1 (a) Three-dimensional representation and cross section of a single Helmholtz resonator. The blue circle indicates the position of the detector, where $R = 11.8$ mm is the cavity radius, $r = 1.5$ mm is the hole radius, $e = 0.7$ mm is the thickness of the sphere, (b) Three-dimensional representation of two Helmholtz resonators placed in a face-to-face position where $R_1 = R_2 = R$, $r_1 = r_2 = r$ and $d_0 = 1$ mm is the distance between the resonators, $|P_0|$ is the pressure's amplitude of the incident acoustic wave.

C. Results and Discussions:

The resonators are firstly placed in a face-to-face position, with $\alpha = 0$ deg. Fig. 2 (a) represents the evolution of the detected pressure as a function of frequency for several values of d_0 altered between 1 and 49 mm. At long distance, larger than $d_0 = 49$ mm, the peak of resonance is located at $f_0 = 1107$ Hz with a quality factor $Q = 81$ as obtained for the single sphere. But, as far as d_0 decreases, the resonant peak decreases in frequency attending 900 Hz at $d_0 = 1$ mm. It means that the two spheres coupled in the near field.

Next, we have modified the orientation between the two resonators by changing the angle α to 10 deg., as depicted in figure 1b. Fig. 2 (b) represents the variation of the detected pressure as a function of frequency for d_0 altered between 1 and 49 mm. For $d_0 = 49$ mm, the resonant peak is present at 1107 Hz. Once the distance is decreased, one can see the separation of the native mode in two following two effects: the displacement of the first mode to lower frequencies, and the delocalization of the second one to higher frequencies. The difference in the quality factor of the two peaks is remarkable. The first mode has a quality factor $Q = 120$ while the second one reaches 2941. The two quality factors are higher than the case of a single sphere. Therefore, the coupling between the two resonators has lifted the mode degeneration of the single mode into two separated peaks.

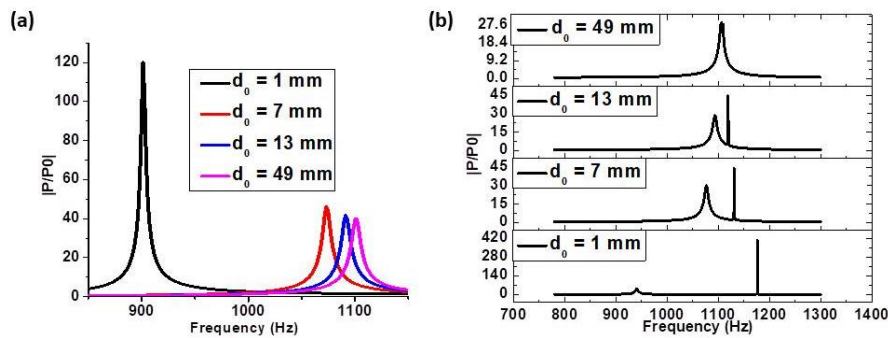


Fig. 2 Evolution of the detected pressure as a function of the frequency by changing the distance d_0 of (a) two face-to-face Helmholtz resonators, and (b) two oriented resonators with an angle $\alpha = 10$ deg.

Fig. 3 (a) represents the map of the pressure field of the two resonators placed at $d_0 = 1$ mm and oriented by $\alpha = 10$ deg. At the resonance frequency of the first mode, i.e. $f_0 = 940$ Hz one can see that the two spheres resonate in phase and the energy in the environment is negligible compared to the energy stored inside the resonators. Fig. 3 (a) describes the pressure in far-field at $f_0 = 940$ Hz. One can notice the isotropic distribution of the field in its environment, characterizing a mono-polar mode.

Next, the field map of the two resonators behaving at the resonance frequency of the second mode ($f_0 = 1176$ Hz) is presented in Fig 3 (b). As we can see, the resonators behave in phase opposite. At this frequency, the far-field

distribution is also illustrated in Fig. 3 (b) leading to an acoustic pressure propagating in a directional way, giving rise to a bipolar mode.

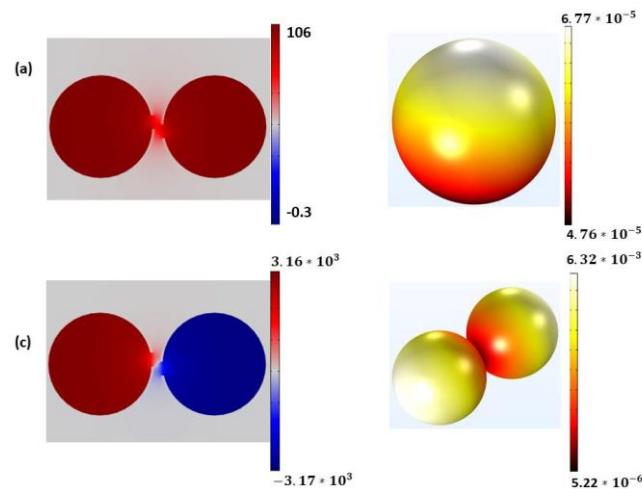


Fig. 3 (a) Distribution of the pressure inside the two resonators oriented by an angle $\alpha = 10$ deg., and (b) Far-field distribution of the diffused pressure in the (xOy) plane at $f_0 = 940$ Hz, (c) Distribution of the pressure inside the two resonators oriented by an angle $\alpha = 10$ deg., and (d) Far-field distribution of the diffused pressure in the (xOy) plane at $f_0 = 1176$ Hz.

II. CONCLUSION

In our work, two Helmholtz resonators were studied to evaluate the coupling effect. First, the resonators are placed in a face-to-face position and the behavior of the resonance peak studied by changing the distance. For distances lower than a critical threshold, the two resonators coupled and the frequency of the mode increases. Then, the orientation of the resonators is adjusted to have an angle of 20 deg. For low distances between the resonators (less than 13nm) the degeneracy of the resonance mode is raised into symmetric and anti-symmetric modes. At the resonance frequency of the first mode, the two spheres resonate in phase, and an isotropic propagation of the acoustic pressure in far-field is expected. At the resonance frequency of the anti-symmetric mode, the resonators vibrate in phase opposite and an anisotropic propagation in the far-field is obtained. To broaden this resonance response, we plan to take in consideration the solid material constituting the sphere and play on the absorption coefficient. Another solution considered would be to increase the number of openings in the rigid sphere to decrease the confinement and thus decrease the quality factor.

Giving the above, the dual Helmholtz resonator can serve as a sub-wavelength unit to create an innovative meta-material of double functionality to manipulate the acoustic waves of low frequencies and to create anomalous physical phenomena.

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