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Use flow to achieve an unidirectional acoustic propagation in a duct

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A mean flow in a waveguide can cause significant changes in wave propagation. Among the effects of flow (possibility of creating an acoustic gain, changes in the characteristics of the metamaterials located in the waveguide, etc.), the flow can be used as a vectorial field that break reciprocity in order to make a broadband acoustic diode. In this context, we demonstrate theoretically and experimentally that an acoustic diode can be manufactured in a flow duct by slowing down the acoustic wave. In the slow sound region, the effective sound velocity can be so low that no waves can propagate against the flow while propagation is still possible in the direction of flow. Sound is slowed down by putting locally reacting porous chamber around a cylindrical duct. This phenomenon can occur over a wide range of frequencies that can be extended to very low frequencies.

Diode effect in slow sound with flow.— We consider the sound propagation in a cylindrical waveguide in the presence of an air flow, see Fig. 1. Over a length l, this tube is surrounded by annular cavities in order to reduce the effective speed of sound. Such a structure has been extensively studied in the two-dimensional (2D) case in [1]. In the absence of losses in the waveguide and considering the flow as uniform, the acoustic propagation in the waveguide, supposed azimuthally uniform, can be described by the following convected wave equation and boundary conditions:

$$\begin{cases} D_t^2\phi - \nabla^2\phi & \text{for } \ 0 < r < 1 \\ \partial_r\phi = 0 & \text{for } \ r = 0 \\ \partial_r\phi = -D_t(CD_t\phi) & \text{for } \ r = 1 \end{cases} . \qquad (1)$$

Here $\phi(x, r, t)$ is the normalized acoustic velocity potential in the duct, $D_t = \partial_t + M\partial_x$ is convective derivative and M is the Mach number. Neglecting the thickness of the plates separating the cavities in front of the thickness of the cavities, the normalized compliance of the wall at $r = 1$ is given by

$$C = \omega\,\frac{Y_1(\omega b)J_1(\omega) - J_1(\omega b)Y_1(\omega)}{Y_1(\omega b)J_0(\omega) - J_1(\omega b)Y_0(\omega)}$$

where $J_{0,1}$ and $Y_{0,1}$ are the Bessel function of the first or second kind of order 0 and 1. This compliance reduces to $C = (b^2-1)/2$ when the reduced frequency ω goes to 0. The parameter b is the ratio between the outer radius of the cavities and the radius of the tube

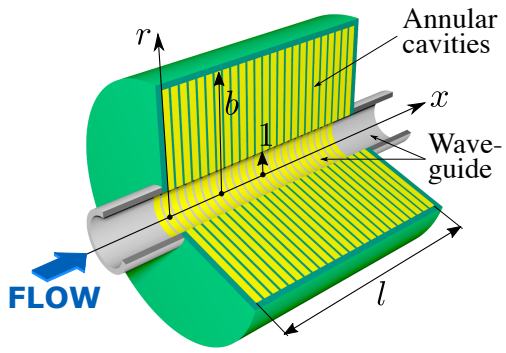

FIG. 1: Schematic of the waveguide loaded with annular cavities of radius b. The flow in this case is considered to be in the positive axial direction.

(see Fig. 1) and is a key parameter for this problem. Looking for solutions propagating in the x direction in the form $\exp(i(-\omega t + kx))$, leads to the dispersion equation expressed as a function of the frequency in the moving frame $\Omega = \omega - Mk$:

$$\mathcal{D}(\omega, k) = \alpha J_1(\alpha) + C\Omega^2 J_0(\alpha) = 0, \qquad (2)$$

where $\alpha^2 = \Omega^2 - k^2$.

To better understand the diode behavior of this setup, it is instructive to study in detail the solutions of Eq. (2) We start with the case of no flow ($M = 0$) for which the dispersion relation is shown in Fig. 2(a) where the outer radius is $b = 5$. We first note that the effect of the liner is to introduce a polaritonic dispersion relation with a resonance depending on b, i.e. the radius of the cavities.

Note that in the reciprocal system without flow we obtain two propagative modes for each frequency with a wavenumber $\pm k$. The dispersion relation for low frequencies can be approximated by $\omega = k/b$, leading to acoustic waves with a phase velocity $c_b = 1/b$ which is always smaller than the free space normalized velocity $c_0 = 1$. In addition, we notice that, under the resonance frequency, the phase velocity is always smaller than $1/b$

When a flow is introduced, it is therefore useful to distinguish between the case where this flow is slower than the maximum speed of the sound waves ($M < M_c = 1/b$) and the case where it is faster ($M > M_c = 1/b$). The dispersion relation when $M = 0.12 < M_c$ is shown in Fig. 2(b) and exhibits a richer structure than without flow (see also [1]). Starting from the low frequency regime, we find that Eq. (2) has four real solutions corresponding to four propagating modes. Two of them, which we call acoustic, approach $k = 0$ as $\omega \to 0$, and they propagate in both directions with the speed of sound c_b corrected by the convective effects. The other two modes do not exist without flow and we further on refer to them as hydrodynamic modes. They correspond to waves more concentrated against the wall than acoustic waves which are closer to plane waves, Fig. 2(d). In this low frequency limit both the hydrodynamic modes are traveling in the direction of the mean flow because the group velocity $c_g = \partial_k\omega$ is positive. The sign of the slope changes when $\omega > \omega_2$ for the hydrodynamic mode with $k > 0$. Beyond a critical frequency $\omega > \omega_1$, the two solutions with $k < 0$ collide and disappear. For

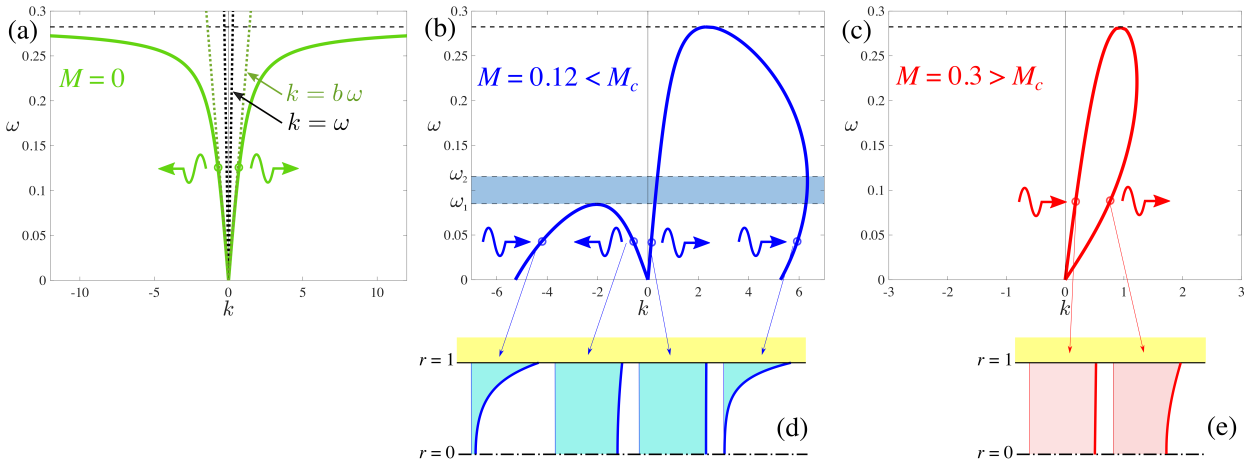

FIG. 2: Dispersion relation in the tube with annular cavities when $b = 5$. (a) Case without flow. (b) Case where the flow is smaller than the critical Mach number $M_c = 1/b$. (c) Case with a flow larger than the critical value ($M > M_c$). (d) Shape of the modes for $M < M_c$, (e) Shape of the modes for $M > M_c$

$\omega > \omega_1$, the system supports only two modes and, for $\omega_1 < \omega < \omega_2$, bluish zone in Fig. 2(b), those two modes are going in the same direction. In other words, for these frequencies only waves traveling in the same directions as the mean flow are allowed. This is the mechanism that we employ here in order to build an acoustic diode.

The dispersion relation is highly dependent on the flow velocity M, particularly the merging frequency ω_1 decreases when the flow increases and reaches 0 for $M = M_c$. The dispersion relation when $M = 0.3 > M_c$ is shown in Fig. 2(b). In this case, only two propagative waves remain and from the zero frequency and for all low frequencies, these two waves propagate only in the direction of flow. This produces a diode that works in principle from very low frequencies and over a wide frequency band.

Experimental set-up.— To experimentally test this diode concept, a cylindrical expansion chamber is divided by means of a partition walls as sketched in Fig. 1. The radius of the pipes upstream and downstream as well as the radius of the perforations in the partition walls are 15 mm. The radius of the expansion chamber is 75 mm leading to a value of $b = 5$. This chamber is divided into 30 cavities with a thickness of 5 mm. The length, normalized by the radius of the tube, is therefore $l = 10$.

In a first attempt, the annular cavities were empty but, when a flow is generated in the tube, a very loud whistling appears. To solve this problem, perforated discs made of open cell polyurethane foam were put into the cavities (yellow parts in Fig. 1). The use of this porous material has eliminated whistling. Nevertheless, due to the flexibility of the foam and partition walls, an acoustic transmission by structural vibration was observed. To overcome this last issue, discs cut from metal foam have been made and are shown in Fig. 3(a). With this rigid porous material, the partition walls can be made with very thin plastic discs.

The diode is mounted between two measurement sections, upstream and downstream. Each of them consists of a hard-walled steel tube (radius 15 mm) where four microphones are mounted. This enables

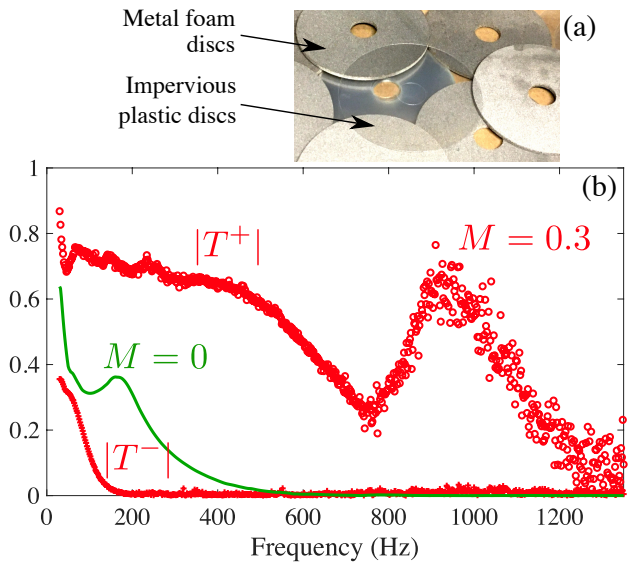

FIG. 3: (a) Picture of the porous metal foam and separation discs. (b) Modulus of transmission coefficients as a function of the frequency. The green line corresponds to the no-flow case ($M = 0$) while the red symbols correspond to the case with a flow $M = 0.3$. T^+ is the transmission in the flow direction and T^- is the transmission against the flow

an over-determination of the incoming and outgoing plane waves on both sides of the device. Two acoustic sources on both sides of the system give two different acoustic states and the four elements of the scattering matrix (transmission and reflection coefficient on both directions) for plane waves can be evaluated. A more detail description of the measurement technique can be found in [2]. The measured modulus of the transmission coefficients are plotted in Fig. 3(b) in the no-flow case and in the case of a grazing flow with a mean Mach number equal to M = 0.3. The phases of the transmission coefficients are given in Fig. 4 and their slopes are indicative of the propagation speed of the waves in the diode. We can observe that when the flow is present the wave transmitted against the flow

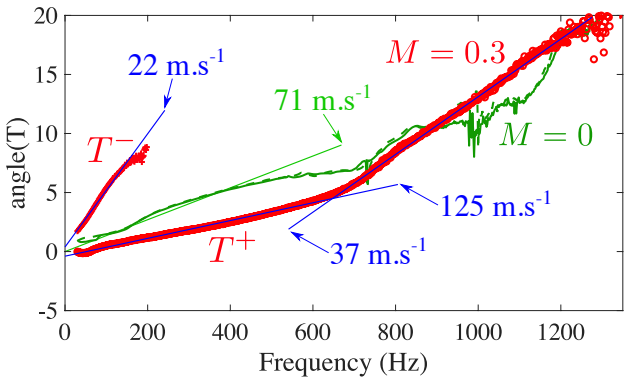

FIG. 4: Phase of transmission coefficients as a function of frequency. The lines and symbols are the same as in Fig. 3. The straight lines correspond to a linear fitting of the curves from which a phase velocity can be extracted.

is so small for $f > 200$ Hz that only the background noise from turbulent flow fluctuations is measured upstream.

Experimental results.— Without flow, the modulus of the transmission coefficient $|T|$ displays an oscillation at low frequencies that is due to standing waves along the length l of the material. Due to the dissipation in the porous material, $|T|$ decreases exponentially from 200 Hz up to the resonance frequency of the cavities that is around 1000 Hz. At low frequency, the phase velocity is well approximated by the theoretical value which is c_0/b. This means that the porous material as a small influence on the slowdown of sound due to cavities.

With flow, the diode effect can be clearly see by considering the difference in the transmission coefficients according to the direction of the wave propagation. In the flow direction, the transmission is much larger than without flow but against the flow the transmission is substantially reduced. As already noted, this attenuation is masked when it is greater than 100 by the background noise of the flow. The phase velocity in the flow direction ($\simeq 0.37\,c_0$) is of the same order as that predicted from the slope of the curve in Fig. 2(c) which is $0.46\,c_0$. We can observe that above 800 Hz, i. e. near the resonance frequency of the cavities, a second phenomenon occurs with a hump in the module and a reduced phase velocity of $0.4\,M$. This phenomenon must be related to a convective instability (see for example [3]) whose amplitude is limited by the presence of porous material. In the direction against flow, over the small frequency range where the phase velocity measurement is significant, this one is extremely low $0.0647\,c_0$.

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