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EXPERIMENTAL EVIDENCE OF SOUND AMPLIFICATION BY STABLE SHEAR LAYERS IN A CORRUGATED PIPE

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Flow through a corrugated pipe can cause whistling in favorable conditions. This can be a nuisance for domestic appliances or create vibrations in high-tech devices where corrugated pipes are used for cooling. The whistling can even be a safety issue in industrial applications where flexible pipes with corrugated inner walls are used for transport of high-pressure gas. In such applications, the goal is now to have non-whistling pipes. That is, a pipe which is potentially singing will be operated in a range of flow velocities range below the onset of possible whistling. The other approach is to have a geometry of the corrugations as close as possible to a smooth-bore pipe in order to eliminate the potentiality of singing.

The mechanism generating whistling involves the shear layers over the cavities, which act as amplifiers of sound waves at certain frequencies. If the losses in the system (radiation losses and visco-thermal losses) are not larger than this amplification at a given frequency, a sound wave of this frequency propagating in the pipe will be amplified until non-linear phenomena limit its amplitude. This causes whistling (self-sustained oscillations) in the pipe. The analysis performed to predict if whistling can occur has long been based on whistling tests, where information is only gained once the self-sustained oscillations are initiated, and thus when the shear-layers behave non-linearly. Recently, methods were developed to measure directly the amplification (or attenuation) factor of acoustic waves traveling through the corrugated pipe. This allows the evaluation of pipes with much lower singing potentiality, which would not sing at atmospheric conditions, but which might give problems when used in more extreme pressure conditions. In any case, the first step to decide if a pipe can sing is to evaluate if the shear layer developing over the cavities can act as amplifiers, and if yes, with what strength.

To act as an amplifier, it is generally considered that the shear layer should be unstable, that is, that a Kelvin-Helmholtz (K-H) instability should be present in the shear layer. Such an instability is only possible for small shear-layer thicknesses. Indeed, a stability analysis of the shear layer shows that the growth factor becomes negative for Strouhal number based on the momentum thickness θ larger than a value of 0.04 [1]. That is, at a certain frequency f and flow velocity U , the shear should not develop Kelvin-Helmholtz instability if its momentum thickness is greater than $0.04 U/f$. On the other hand, a shear

layer acts as an amplifier for a grazing acoustic field at a Strouhal number based on the cavity width W typically between 0.2 and 0.5. Taking a typical (mid-range) value of 0.4, this means that amplification occurs for $U/f \sim 0.4$. This means that, if the K-H instability is required to obtain amplification, it is only possible for thin shear layers compared to the cavity width ($\theta/l_c \lesssim 0.1$). Earlier studies on closed side branches [2] and corrugated pipes [3] indeed indicate that whistling disappears (or becomes negligible) for a given θ/l_c which depends on the geometry.

However, recent computational work [4, 5] shows that a shear-layer does not need to be unstable in order to act as an amplifier. This work is based on a multi-modal description of the inviscid flow-acoustic interaction in ducts with cavities or orifices.

In this presentation, we will discuss measurements of sound propagation in three corrugated pipes of inner diameter of 30 mm. The geometry of the corrugations, as illustrated in Figure 1(a) varies with cavity widths L_c of 0.2 mm, 0.6 mm and 1.2 mm. The momentum thickness in these very rough pipes is of the order of 0.15 mm, that is, $\theta/l_c \sim 1$ for the narrowest cavities.

The experimental setup is similar to the one described in [6]. The corrugated tube is mounted in a flow-rig between two measurement sections (see Figure 1(b)). A mean flow is provided by a centrifugal fan, and the flow rate can be continuously varied in order to provide a mean

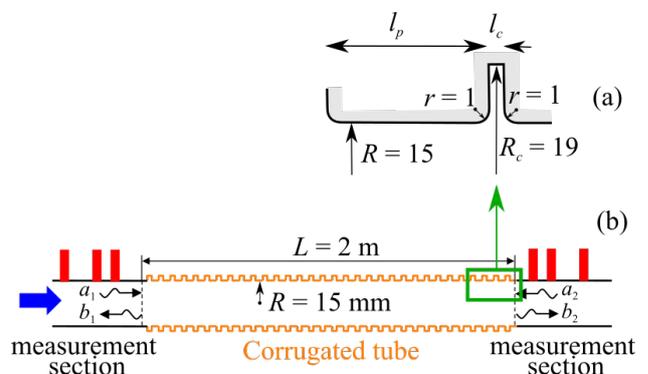


Figure 1. (a) Dimensions of a cavity of the corrugated tube. (b) Experimental setup with the corrugated tube subjected to a mean flow and placed between measuring sections equipped with microphones.

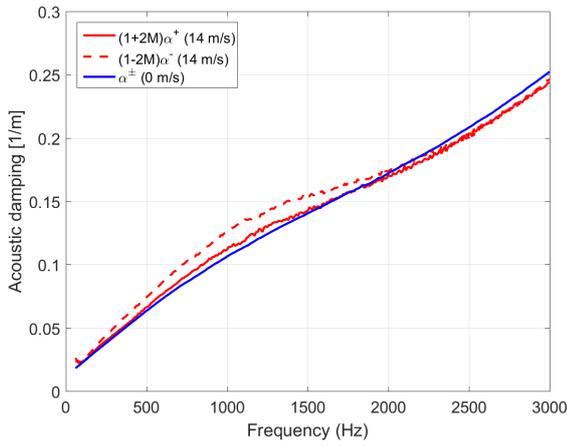


Figure 2. Equivalent wavenumber for propagation in the corrugated pipe with small gaps ($L_c = 0.2$ mm) measured without flow (blue line) and with flow at 14 m/s (red lines).

flow velocity up to 20 m/s in the corrugated tube.

Each of the measurement sections consists in a hard walled steel duct of radius $R = 15$ mm where four 1/4-in microphones B&K 4136 are mounted. An overdetermined measurement of the incoming and outgoing waves can thus be performed on both sides of the measured system from 100 Hz to 4000 Hz in steps of 5 Hz. In this frequency range, only plane waves propagate. The overdetermination of the system to be solved is used to adjust the speed of sound by an optimization process.

Two acoustic sources, mounted on both sides of the system, give for each frequency two different acoustic states. During the experiments, it is ensured that the incident waves (from either the upstream source or the downstream source) have a controlled and constant amplitude. It has then been verified that the coefficients of the scattering matrix are independent on the amplitude of the incident field.

By performing two measurements, one with the upstream source on (downstream side with low reflections), one with the downstream source on (upstream side with low reflections), the scattering matrix for the corrugated pipe as a whole is computed. A further step in the analysis suggested in [6] is to describe the corrugated pipe as an equivalent homogeneous medium and to compute, from this scattering matrix, the wavenumber k_e^\pm for the acoustic propagation in this equivalent medium. Without flow, $k_{e0}^+ = k_{e0}^-$, but in presence of a mean flow in the pipe, k_e^+ does not generally equals to k_e^- . A part of this difference is well known as it is due to the convection. However, once this convection effect is discounted, a frequency-dependent difference between k_{e0}^\pm , k_e^+ and k_e^- is observed. As an example, some results obtained for a 1980 mm long pipe with the smallest cavity width $L_c = 0.2$ mm are presented in the following. Figure 2 displays the imaginary part of the equivalent wavenumber (the amplification coefficient of the propagating waves) for this pipe, measured without flow and with a flow of 14 m/s ($M = 0.029$). This quantity, corrected by the Mach number to remove the convection effect, represents the attenuation of the acous-

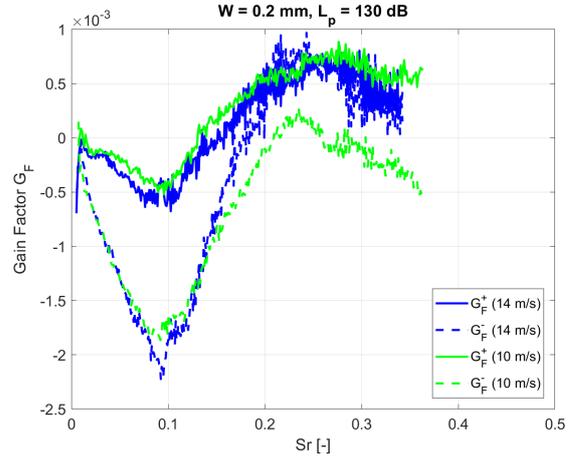


Figure 3. Gain factor for propagation in the corrugated pipe with small gaps ($L_c = 0.2$ mm).

tic waves. It is clear that, at low frequencies, the attenuation is increased by the flow. However, at frequencies above 2000 Hz, the attenuation is actually decreased by the flow. This is even more clear when a gain factor G_F^\pm is defined as $G_F^+ = \text{Im}(k_e^+/k_0)_M - \text{Im}(k_e^+/k_0)_{M=0}$ for forward-traveling waves and $G_F^- = -\text{Im}(k_e^-/k_0)_M + \text{Im}(k_e^-/k_0)_{M=0}$ for backward-traveling waves. One can then see, as in Figure 3, that the effect is Strouhal-number dependent and is identified as due to the interaction of the shear layers and the acoustic waves.

This shows that the an acoustic gain due to the shear layers is possible even for a very thick shear layer (compared to the gap width) as is the case for $l_c = 0.2$ mm.

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