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EXPERIMENTAL INVESTIGATION OF THE SOURCE LOCATIONS FOR WHISTLING SHORT CORRUGATED PIPES

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ABSTRACT

The goal of this study is to investigate the issue of the aeroacoustic source location within corrugated pipes. A configuration with a short pipe and well defined boundary conditions has been chosen, in order to have a precise knowledge of the distribution of the acoustic velocity and pressure within the pipe. The source locations have been investigated methodologically by using straight pipe segments to replace the corrugated section near the acoustic velocity nodes or near the acoustic velocity antinodes. The main locations of the sound sources have been identified to be the sections of the corrugated pipe near the acoustic velocity antinodes.

INTRODUCTION

Corrugated pipes are employed in many technical applications such as domestic appliances, LNG storage systems, risers for offshore natural gas production or cooling systems. The purpose of the corrugations is to make the structure of the pipes substantially stronger, while keeping their ability to move and deflect under load without structural damage. Under certain conditions, the flow through these corrugated pipes causes severe noise and vibration problems. In extreme cases these can lead to loss of integrity of high pressure gas installations [13].

Initial research on the whistling behavior of corrugated pipes has been started by Burstyn [2] and Cermak [5]. Those early investigations identified the flow-acoustic coupling as the mechanism of sound production.

Some characteristics of the whistling behavior of corrugated pipes are commonly agreed upon in almost all the studies present in the literature [1, 3, 5, 6, 9, 11]. These characteristics are the fact that the fundamental tone is difficult to excite, the stepwise increase of the whistling frequency f as function of the flow velocity U and the fact that the whistling frequencies are always related to the flow velocity by a critical Strouhal numbers $Sr_L = (fL)/U$ based on a length scale L.

The determination of the most suitable length scale to be used in the definition of the Strouhal number related to the whistling of corrugated pipes, is a matter of current debate. Some researchers [12] proposed to use the pitch, p, others [9] the corrugation cavity width, W. Furthermore, it appears that a proper length scale should take the edge geometry into account when the edges are not sharp [3].

The identification of the regions within the corrugated pipes where the sound is mainly produced is a major matter of debate. Kristiansen and Wiik [9] concluded that the energy generation occurs in the regions of acoustic velocity nodes. They observed, however, that a short section of corrugations will only produce sound effectively when placed at the inflow end of a long smooth pipe. This position corresponds to an acoustic velocity antinode, which is in contradiction with their own conclusions.

More recently, Tonon et al. [14] used a multiple side branch system as a model for corrugated pipes. The experiments on this system, and successive experiments by Nakiboglu et al. [10] on the same system, show that the multiple side branch system is a reasonable model for corrugated pipes. The versatility of the system to geometrical modifications was used to identify the acoustic velocity antinodes of the acoustic standing wave along the main pipe as the regions where sound is mainly produced. This contradicts the results obtained by Kristiansen and Wiik [9].

The debate on the source location promoted the present study, in which the main goal is to investigate the issue of the acoustic source locations within short corrugated pipes.

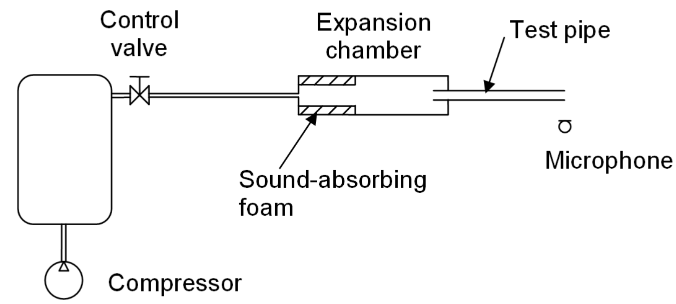

FIGURE 1. Experimental setup

MECHANISM OF FLOW-INDUCED TONAL NOISE IN CORRUGATED PIPES

When air is blown through a corrugated pipe, sound is generated by the instability of the shear layers separating the main flow from the stagnant fluid in the corrugations. These instabilities are triggered by the acoustic oscillation and result into the formation of discrete vortices. The acoustic oscillation frequencies correspond to acoustic resonances, which depend on the geometry and on the acoustic boundary conditions of the system. One general condition for acoustic oscillations to occur is that a resonance frequency of the corrugated pipe should coincide with a frequency range of energy production of the flow instabilities.

For long corrugated pipes, the modal density is so large that the boundary conditions do not affect the acoustic resonances. However, they affect the dissipation of acoustic energy at the ends of the system. In this case, the acoustic oscillations almost always occur, provided there is more acoustic energy generated by the flow instabilities than dissipated in the system and radiated at its ends [3, 4].

In the case of a relatively short corrugated pipe (when only a few wavelengths fit in the length of the pipe), distinct tones are observed close to the resonance frequencies of the pipe. These pulsations are furthermore observed to collapse around certain optimal Strouhal numbers $Sr_W = fW/U$ based on the cavity width W as discussed by Tonon et al. [14] and Nakiboglu et al. [10]. In this case, a modification of the boundary conditions implies a modification of the standing wave patterns within the pipe. We therefore pay special attention to the boundary conditions in our experiments.

EXPERIMENTAL SETUP

The pipes used in our experiments are flexible corrugated pipes of inner diameter of 24 mm and length 0.82 m, sold as toys. In their natural use, they are swung around at arms length with a rotational velocity of the order of 1 revolution per second. The rotation induces a centrifugal force and a corresponding gradient of pressure. Due to flow separation the pressure at the outlet of the pipe is close to the surrounding atmospheric pressure. The end of the pipe close to the hand of the operator is quasi immobile and will be at a lower pressure. This will suck air from the surrounding, creating a flow through the pipe. At certain rotation speeds, the pipe will sing, for the pleasure of the operator and the despair of their parents.

A preliminary analysis showed that the first acoustic mode possibly excited by the flow corresponds to a wavelength equal to the length of the corrugated pipe $\lambda = L_p$. Subsequent whistling modes correspond to $\lambda = 2L_p/n$, with $n = 2, 3, 4, \ldots$. The impossibility to get tones for the first acoustic mode ($\lambda = 2L_p$) is an interesting feature of corrugated pipes that was already observed in the early study of Cermak [5].

The objective of our experiments is to reproduce the tones observed by rotation of the pipes at arms length, but with controlled experimental parameters. Particularly of importance are the flow velocity and the acoustical boundary conditions.

FLOW SUPPLY AND INSTALLATION OF THE TESTED PIPES

The experimental setup is sketched in figure 1. The flow through the corrugated pipe is maintained by a high pressure supply system. The pressure in the pipe is atmospheric and the flow is controlled by a regulation valve. An expansion chamber muffler, of inner diameter 120 mm and length 1 m, is located upstream of the corrugated pipe. Damping material is installed in the upstream part of the muffler in order to avoid cavity resonances. The tested pipes are inserted 55 mm in the end-flange of the muffler. This configuration was found to reproduce an open unflanged boundary condition for the upstream end of the tested pipe. The other end of the tested pipe is open to the laboratory.

INSTRUMENTATION AND DATA PROCESSING

The sound generated by the corrugated pipe is measured with a microphone located at 100 mm from the downstream end of the pipe, in a direction perpendicular to the pipe. The microphone is pressure-field type B&K 4192 and has been calibrated prior to the measurements. The flow rate of the control valve

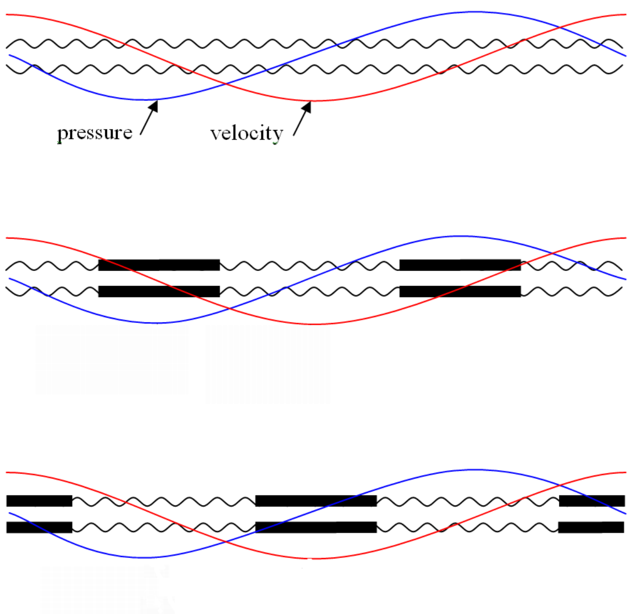

FIGURE 2. Sketches of the three pipes tested and of the acoustic pressure (blue lines) and velocity (red lines) distributions for the $\lambda = L_p$ mode. Top: Reference pipe **conf-a**; Middle: Pipe **conf-b**; Bottom: Pipe **conf-c**

is controlled by a computer. Both the microphone signal and the flow rate are monitored and recorded by a Dewetron analyser and recorder. The flow velocity along the pipe outlet is obtained from the recorded flow rate.

When whistling is observed, at the resonances of the corrugated pipe, standing waves are present in the pipe. The amplitude of these standing waves is computed from the amplitude of the pressure measured by the microphone [8].

TESTED CORRUGATED PIPES

The corrugated pipes employed in our experiments are built-up by means of flexible corrugated sections and rigid smooth sections, of which the characteristics are summarized below:

- The flexible corrugated sections are made of soft plastic with a wall thickness of $t = 0.5$ mm. They have a minimum inner diameter $D_i = 24$ mm and a maximum outer diameter $D_o = 32$ mm. The corrugations have a pitch $p = 5.5$ mm, a depth $d = 3.5$ mm and a cavity width $W = 4.0$ mm.
- The rigid smooth PVC sections have inner diameter $D_i = 24$ mm and outer diameter $D_o = 32$ mm.

The combination of the two types of piping allowed us to build up a series of corrugated pipes of equal length and constant cross section with corrugated and smooth parts in different regions. The following configurations (as sketched in figure 2) were built up:

- **conf-a** – A fully corrugated pipe of length $L_p = 820$ mm. This is considered as the reference pipe.
- **conf-b** – A pipe of length $L_p = 820$ mm with corrugations along the whole pipe except two smooth segments at positions near $L_p/4$ and $3L_p/4$. For the first whistling mode ($\lambda = L_p$), these positions correspond to the regions of the pipe close to velocity nodes (pressure antinodes) of the standing wave. Two pipes have been built-up for this configuration:
  - **conf-b1** with two smooth sections of 50 mm. In this case, 12% of the wavelength is smooth.
  - **conf-b2** with two smooth sections of 100 mm. In this case, 24% of the wavelength is smooth.
- **conf-c** – A pipe of length $L_p = 820$ mm with corrugations along the whole pipe except three smooth segments at positions near $L_p/2$ and near the inlet and the outlet of the pipe. For the first whistling mode ($\lambda = L_p$), these positions correspond to the regions of the pipe close to acoustic velocity antinodes (pressure nodes) of the standing wave. Two pipes have been built-up for this configuration:
  - **conf-c1** with one smooth section of 50 mm around $L_p/2$ and two smooth sections of 25 mm at the ends of the pipe. In this case, 12% of the wavelength is smooth.
  - **conf-c2** with one smooth section of 100 mm around $L_p/2$ and two smooth sections of 50 mm at the ends of the pipe. In this case, 24% of the wavelength is smooth.

Note that all pipes have the same total length $L_p = 820$ mm and that **conf-b1** (resp. **conf-b2**) has the same proportion of corrugated and smooth parts as **conf-c1** (resp. **conf-c2**). Special care has been taken to ensure flawless transition between the two kinds of piping elements and to avoid fluid and acoustic leakage at the connections.

The effective speed of sound c_{eff} in a corrugated pipe (or corrugated section) is lower than the speed of sound c_0 in a smooth pipe (or smooth section) due to the extra compressibility induced by the cavity [7]. The speed of sound can be evaluated as $c_{eff} = c_0/\sqrt{1+V_c/(S_p p)}$, where V_c is the volume of each corrugation, p is the pitch length and S_p is the cross sectional area of the pipe.

EXPERIMENTAL RESULTS

Results for the first whistling mode

The dimensionless amplitudes of the tone corresponding to the first whistling mode for each configuration tested are plotted in figure 3 as function of the flow velocity.

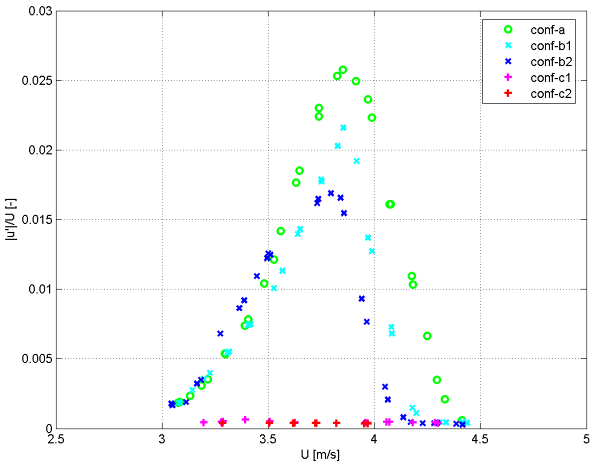

FIGURE 3. Amplitude of the tones corresponding to the first whistling mode versus flow velocity.

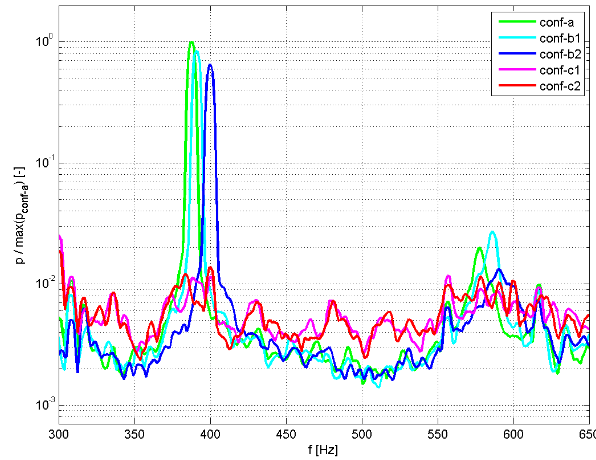

FIGURE 4. Sound power spectra measured at 100 mm from the end of the tested pipes. Amplitude is made non-dimensional with the amplitude of tone for **conf-a**.

For the reference corrugated pipe **conf-a**, the first tone was obtained at flow speeds between 3.2 m/s and 4.3 m/s, with the maximum at 3.85 m/s. The frequency of the tone is 388 Hz. Given the corrugation cavity width $W = 4\ mm$, this corresponds to a Strouhal number $Sr_W = 0.40$.

For the pipes **conf-b1** and **conf-b2** with smooth sections at the acoustic velocity nodes, the first tone was observed at the same flow speed as for the reference corrugated pipe **conf-a** (between 3.2 m/s and 4.2 m/s, with the maximum at 3.85 m/s for **conf-b1** and between 3.2 m/s and 4.1 m/s, with the maximum at 3.80 m/s for **conf-b2**). The frequency of the tones at the maximum pulsation amplitude was larger (391 Hz for **conf-b1** and 399 Hz for **conf-b2**) than for **conf-a**. The difference in resonance frequency of the pipes can be explained by the fact that the effective speed of sound c_{eff} is lower in the corrugated sections than in the smooth sections [14]. The frequency and the amplitude of the tone for each configuration is summarized in table 1.

TABLE 1. Summary of maximum pulsation amplitudes (peaks) for the different configurations.

		f_{tone}	Ampl.
conf-a	Fully corrugated	388 Hz	100%
conf-b1	Smooth on 3% of λ around velocity nodes	391 Hz	84%
conf-b2	Smooth on 6% of λ around velocity nodes	400 Hz	65%
conf-c1	Smooth on 3% of λ around velocity antinodes	400 Hz	1.4%
conf-c2	Smooth on 6% of λ around velocity antinodes	400 Hz	1.1%

(Amplitude of tones is given as a percentage of the amplitude of the tone of corrugated pipe **conf-a**)

For the pipes **conf-c1** and **conf-c2** with smooth sections at the acoustic velocity antinodes, it was not possible to observe a clear tone for the acoustic mode $\lambda = L_p$. The frequency and amplitude of the maximum (broadband) peak observed are reported in table 1.

The spectra measured for the different configurations at the same flow velocity $U = 3.85$ m/s are plotted in figure 4. For all the pipes, the broadband noise is similar and shows peaks around $\lambda = nL_p/2$ but tones are only observed for the pipe with corrugations on the full length **conf-a** and for the pipes with smooth sections at the acoustic velocity nodes **conf-b**. When the pipe is smooth around the acoustic velocity antinodes **conf-c**, no tone is observed. This behavior is similar to the behavior of a multiple side-branch system as model for corrugated pipes [14].

Results for the higher whistling modes

When the flow velocity is monotonically increased, a stepwise behaviour of the whistling frequencies is observed. This results in consequent jumps from one acoustic mode to another, as can be seen in figure 5 for **conf-a**. While the system is mainly observed to whistle at an hydrodynamic mode corresponding to $Sr_W = 0.4$, a higher mode ($Sr_W = 0.7$) is observed around $U \approx 4.2$ m/s.

The non-dimensional acoustic amplitude of the different

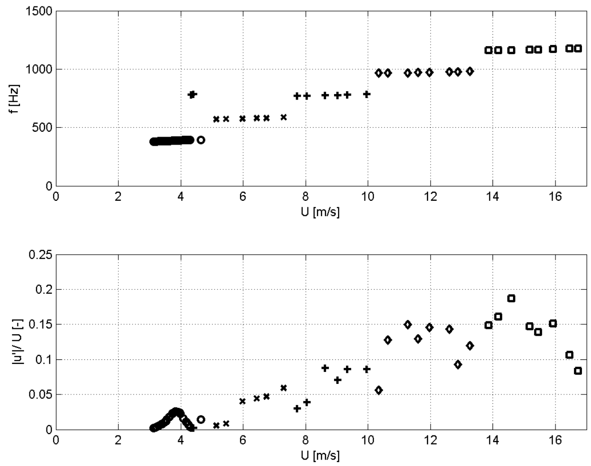

FIGURE 5. Frequency (top) and non-dimensional amplitude (bottom) of dominant tones plotted versus flow velocity of reference corrugated pipe **conf-a**. The different symbols correspond to the different acoustic modes $\lambda = nL_p/2$ of the pipe. o: n =2; x: n =3; +:n =4; $\diamond$:n =5; $\square$:n =6.

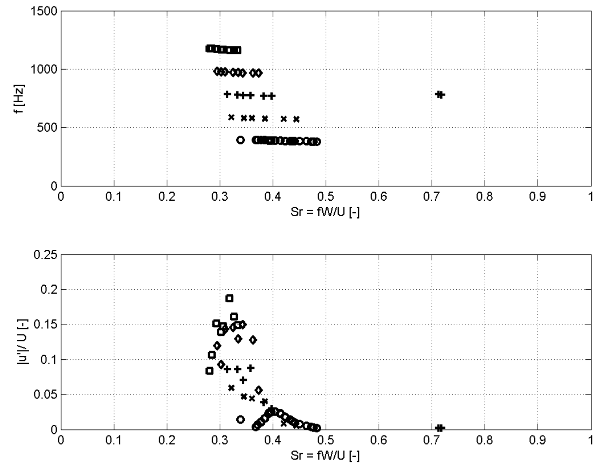

FIGURE 6. Frequency (top) and non-dimensional amplitude (bottom) of dominant tones plotted versus Strouhal number of reference corrugated pipe **conf-a**. The different symbols correspond to the different acoustic modes $\lambda = nL_p/2$ of the pipe. o: n =2; x: n =3; +:n =4; $\diamond$:n =5; $\square$:n =6.

whistling modes increases as the flow velocity increases. This feature has been explained by Tonon et al. [14] and Nakiboglu et al. [10] by means of an energy balance model.

An interesting aspect is that the increase of the acoustic amplitude in the corrugated pipe of configuration **conf-a** leads to a shift of the maximum pulsation condition towards lower Strouhal numbers (figure 6). It is also typically observed in side branch systems displaying moderate and high pulsations [15].

The results of the experiments carried out by monotonically increasing the flow velocity U for the three extreme configurations tested are presented in figure 7.

CONCLUSIONS

In this paper an experimental investigation of the tonal noise generated by air flow through short corrugated pipes is presented. Pipes with different corrugated and smooth sections are tested. The most interesting results are obtained in the case of the second acoustic mode of the pipe, for which the smooth sections were carefully located at the velocity nodes or at the velocity antinodes for the acoustic standing waves. In this case, clear tones are only observed for the pipe with corrugations on the full length and for the pipes with smooth sections at the acoustic velocity nodes. When the pipe is smooth around the velocity antinodes, the tone is strongly reduces or disappears completely.

This behavior contradicts the conclusions of Kristiansen *et al.* [9] that the acoustic energy generation occurs close to the acoustic velocity nodes. The results shown here are similar to that obtained on multiple side-branch systems [10, 14] which were used to identify the acoustic velocity antinodes of the standing wave in the main pipe as the regions where sound is mainly produced.

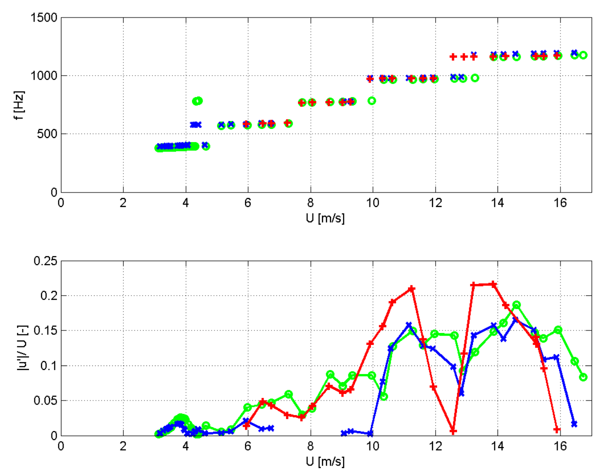

FIGURE 7. Frequency (top) and non-dimensional amplitude (bottom) of dominant tones plotted versus flow velocity of pipes **conf-a** (green markers), **conf-b2** (blue markers) and **conf-c2** (red markers).

ACKNOWLEDGMENTS

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