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# Attenuation of cavity internal pressure oscillations by shear layer forcing with pulsed micro-jets

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**Abstract**

Experimental results concerning the pressure oscillations induced by a grazing flow over a deep cavity like a Helmholtz resonator are presented. The study deals with the forcing of the neck shear layer instability in an opened-loop control scheme by means of pulsed micro-jets. The effects of the frequency and amplitude are investigated. It is found that efficient attenuation of the pressure oscillations can be reached when the forcing frequency is larger than the cavity resonance frequency. Then the shear layer is locked with the forcing and resonance with the cavity is lost, inducing a significant decrease of the acoustic pressure level in the cavity. Effects of the jet amplitude are weak, a very small amplitude being capable of forcing the shear layer. By contrast, when the forcing frequency is lower than the cavity resonance frequency (the forcing wave length is greater than twice the neck length) the forcing is ineffective.


*Keywords:* Cavity; Shear layer; Aeroacoustics; Control

## 0. Introduction

Flows over cavities are well known for their capabilities to generate pressure oscillations inside the cavity. A number of flow regimes are concerned: high speed flows at compressible Mach numbers are mainly encountered in aeronautics and low speed flows are common in ground transportation systems. In all these cases, the attenuation or the active control of the pressure oscillations remains a challenge which has been studied by many authors, for instance with piezo-electric actuators by Cattafesta et al. [1] and by Kikushi and Fukunishi [2], or with an oscillated spoiler actuator by Kook et al. [3].

We deal in this paper with low speed flow over a deep cavity which is akin to a Helmholtz resonator. Road vehicles with open sunroof constitute a typical application. The shear layer generated is usually unstable and is bounded by the lips of the resonator. This results in the periodic impingement of the vortices generated by the shear layer instability. This periodic excitation can resonate with the volume of the cavity, which is precisely the mechanism that we wish to study.

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**Nomenclature**

| | | | |
|---|---|---|---|
| $A$ | area of the cavity neck (0.00312 $m^2$) | $U_1$ | upper free-stream velocity of the shear layer . . . m/s |
| $c$ | sound velocity . . . m/s | $U_2$ | lower free-stream velocity of the shear layer . . . m/s |
| $f_j$ | pulsed micro-jet frequency . . . Hz | $V$ | volume of the cavity (0.003008 $m^3$) |
| $f_H$ | resonance frequency of the cavity . . . Hz | $x$, $z$ | streamwise and wall normal coordinates |
| $H$ | thickness of the cavity neck (3 mm) | $\delta_\omega$ | shear layer vorticity thickness at the neck middle . . . m |
| $L$ | length of the neck (19.5 mm) | $\gamma$ | empirical parameter in Rossiter's formula |
| $l$ | perimeter of the neck aperture (0.359 m) | $\lambda$ | wave length . . . m |
| $M$ | Mach number, $M = U_1/c$ | $\rho$ | air density . . . $kg/m^3$ |
| $St$ | Strouhal number | | |
| $St_\omega$ | shear layer Strouhal number | | |
| $U_{ref}$ | reference velocity . . . m/s | | |
| $U_c$ | convection velocity . . . m/s | | |

This paper is a continuation of the research which was previously conducted by the authors [4,5]. In the first of these papers it was shown that pulsed micro-jets were capable of controlling the pressure oscillations when they are integrated in an open or closed-loop scheme. However the open-loop solution remains an interesting challenge due to its applicability in various situations. This implies however to know under which conditions the shear layer can be forced to oscillate. The previous study presented in [5] was partially devoted to this objective, but we were not capable of studying the effects of the forcing frequency and amplitude with the piezo-electric actuators which were used.

The present paper is therefore devoted to the experimental study of the shear layer forcing with pulsed micro-jets, in order to evaluate more accurately the potential of sound attenuation in an open loop scheme and to propose simple rules for the design of actuators.

## 1. Experimental setup

The experimental investigation concerning the control of acoustic oscillations generated by a flow over a deep cavity was carried out in the Laboratory of Aerodynamics of Warsaw University of Technology.

### 1.1. Cavity

The cavity is installed on the upper wall of a small wind tunnel driven by an aspirating centrifugal fan. The cavity dimensions are presented in Fig. 1. The neck is 3 mm thick and its length is 19.5 mm. The spanwise dimension of the cavity is 160 mm. The volume surrounding the neck is 0.003008 $m^3$. The formula giving the resonance frequency of such a Helmholtz resonator was developed in a previous paper [5]. It is given by

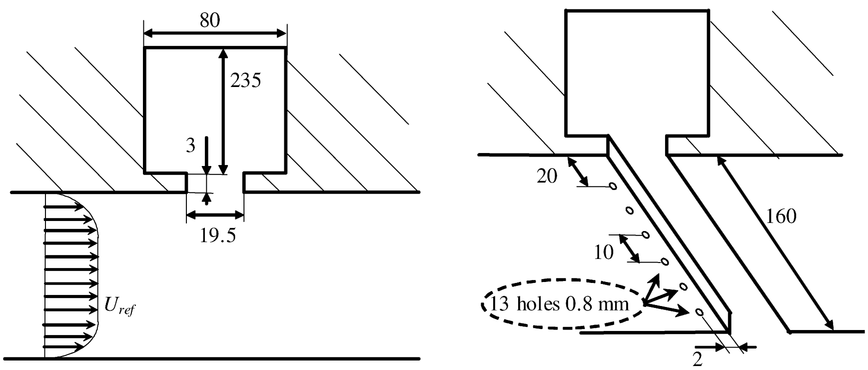


Fig. 1. Sketch of the cavity model showing the geometrical dimensions (mm).

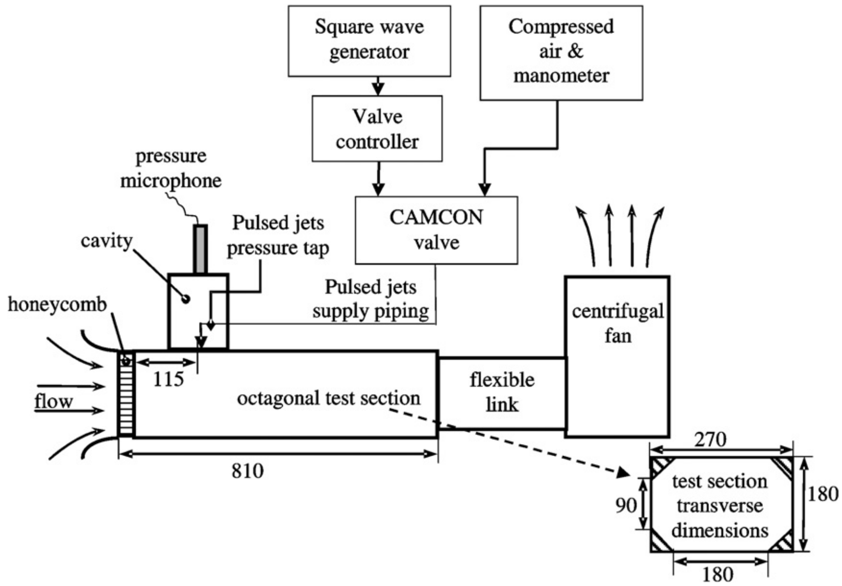


Fig. 2. Principle of the experimental setup.

$$f_H = \frac{c}{2\pi}\sqrt{\frac{A}{V(H + 1.7A^{0.75}/\sqrt{l})}} \tag{1}$$

and it leads here to a frequency $f_H = 276.4$ Hz, which is a reliable value as we will see later.

The experimental set-up is shown in Fig. 2. The test section is octagonal in order to reduce turbulence level. The wind velocity can be varied in the range 0 to 30 m/s with a frequency controller that sets the fan rotation speed. The reference velocity is measured with a Pitot tube mounted in the test section.

A short verification was conducted in order to check the possible existence of an acoustic resonance between a mode of the wind tunnel and the shear layer, or with the fan blades. No significant interaction was detected.

### *1.2. Pulsed micro-jets*

The pressure impulses are generated by the electromagnetic binary valve provided by CamCon Ltd. This valve is built as a magnetic circuit closed by a steel spring tongue which can take one of two stable positions. A short, low energy electric impulse applied to the coil can change the spring position to the opposite one, thereby clearing or closing the output opening.

The valve controller is stimulated by a square wave generator furnishing a wavy train of variable frequency in the range 100–1000 Hz. The energy of the pressure impulse can be varied by simply changing the pressure supply level. The pressure chopped by the valve is fed to a rectangular tube $3 \times 3$ mm (external dimensions) installed on the upwind edge of the cavity lip; from there the micro-jets enter normally to the grazing flow (see Fig. 1) in the form of a series of pulsating micro-jets through 13 holes, 0.8 mm diameter and spaced 10 mm apart in the spanwise direction.

A typical time history of the pressure measured inside the supply piping just before the rectangular tube is given in Fig. 3. The input pressure level is 1 bar which is the level used in most of the cases presented hereafter. The resulting mean value is 1832 Pa, minimum 1076, maximum 2605 and root mean square (RMS) value 454 Pa. Note that the curve is periodic but not sinusoidal due to the valve technology. It was not possible to measure the resulting velocity in the jets due to their very small size. However, considering that the output velocity follows the square root of the pressure, we can deduce that the pulsed micro-jets deliver a peak to peak value of $\pm 20\%$ of their mean velocity.

### *1.3. Measurement system*

The pressure oscillation in the cavity is measured by a 1/2 inch pressure microphone flush mounted on top of it. The microphone signal is sent to an acquisition and processing system PAK provided by Müller-BBM. The acquisition card

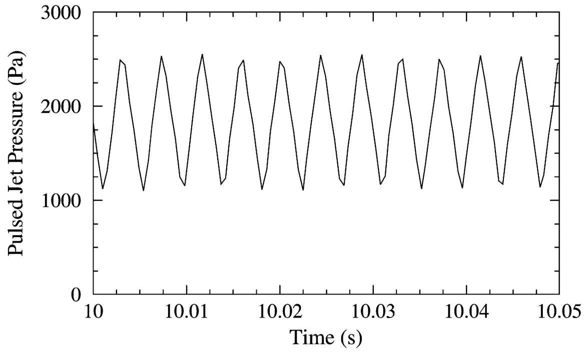


Fig. 3. Sample of time history of the pulsed jets pressure for a mean forcing pressure of 1 bar.

is a 24 bits A/D converter equipped with anti-aliasing filters and direct signal processors for Fast Fourier Transform measurements. The frequency resolution is chosen to be 0.25 Hz. Acquisition time of a single measurement is 30 s at a sampling frequency of 2048 Hz. The acoustic pressure accuracy is typically better than 1 dB. Calibration was performed using a Bruel & Kjaer calibrator delivering 94 dB at 1000 Hz.

In this paper, all acoustic pressure levels are given in the form of Spectral Density (SD) in $\mathrm{Pa}/\sqrt{\mathrm{Hz}}$ units. The peak levels extracted from these spectra are then independent of the acquisition sampling frequency. We shall distinguish the peak level which is related to the cavity resonance, referred as “Cavity Acoustic Pressure”, and the peak level due to the pulsed micro jets, referred as “Forcing Acoustic Pressure”.

The mean pressure level input of the micro-jets is measured with a standard manometer.

### *1.4. Velocity profiles of the shear layer*

A constant temperature hot wire anemometer was also used in order to measure the velocity profiles in the middle of the cavity neck for two situations: unperturbed flow and the flow with the optimal action of the micro-jets as defined later. Both results are reported in Fig. 4 in dimensionless coordinates. Mean values and root mean square values (RMS) are provided. The dimensionless coordinates are chosen so as to fit with the hyperbolic tangent mean velocity profile studied by Michalke [6,7] and recently reviewed by Huerre [8]. It is written as

$$\overline{U} = U_1\big[1 + R\tanh(2z/\delta_\omega)\big]/2, \tag{2}$$

where the velocity ratio $R$ is by definition

$$R = (U_1 - U_2)/(U_1 + U_2) \tag{3}$$

and the vorticity thickness $\delta_\omega$ is defined as

$$\delta_\omega = (U_1 - U_2)/(\partial U/\partial z)_{\max}. \tag{4}$$

A best nonlinear fit with the measured mean velocity profile leads to $\delta_\omega = 9.1$ mm, a shear layer upper velocity $U_1 = 19.6$ m/s and a velocity ratio $R = 1$, which implies that the lower velocity $U_2 = 0$. The origin of the vertical coordinate $z$ is chosen as the upper wall of the wind tunnel. Note that the wind tunnel reference velocity is $U_{\mathrm{ref}} = 19.8$ m/s, marginally different from $U_1$ due to confinement of the flow. The turbulence intensity in the upper region of the shear flow is quite uniform and is 1.85%.

The influence of the micro-jets on these profiles is more or less negligible. A small perturbation occurs in the upper part of the shear layer, but we observed that this perturbation is not uniform along the span due to the discrete positions of the micro-jets, spaced every 10 mm.

## 2. Results and discussion

### *2.1. Cavity internal pressure oscillations*

We identify first the behaviour of the cavity without perturbation by the pulsed micro-jets. The frequency and level of the pressure peaks are represented as a function of the reference velocity in Figs. 5 and 6 respectively. Different

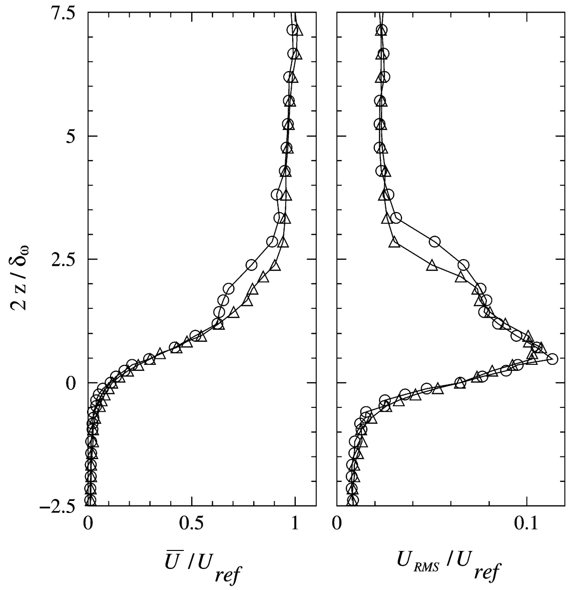


Fig. 4. Velocity profiles in the middle of the cavity neck at resonance ($U_{\mathrm{ref}} = 19.8$ m/s), Δ: without forcing; ○: with optimal forcing ($f_j = 316$ Hz).

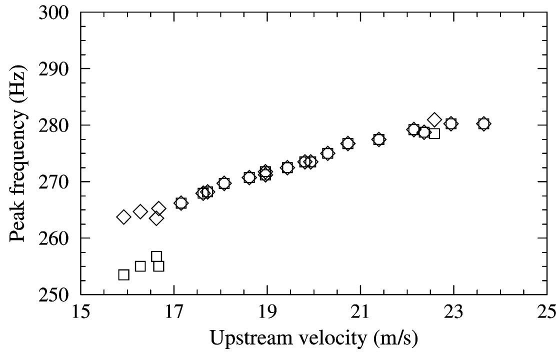


Fig. 5. Frequency of the pressure peak versus upstream reference velocity.

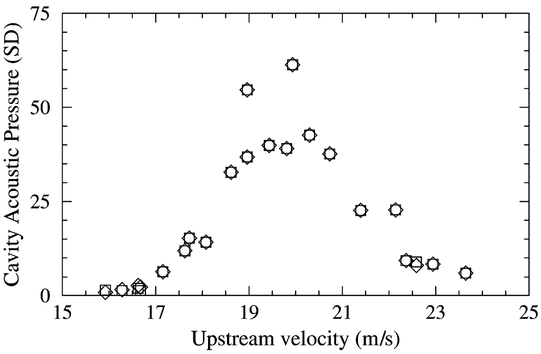


Fig. 6. Pressure peak level versus upstream reference velocity.

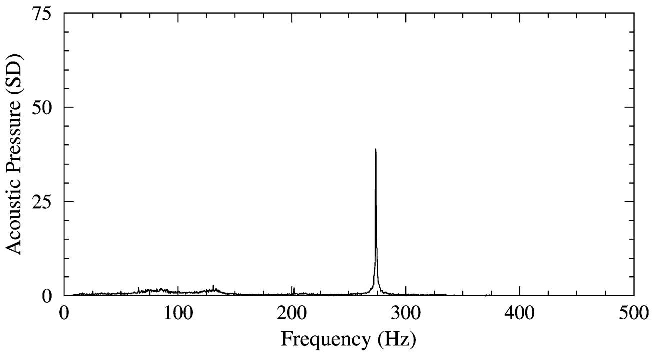


Fig. 7. Typical spectral density of the cavity acoustic pressure at resonance ($U_{\mathrm{ref}} = 19.8$ m/s).

symbols correspond to different peaks extracted from the spectral density curves: in most cases, only one peak is present in the spectrum. All these results are independent of each others, which means that hysteretic behaviour is not represented in the experiments.

A resonance peak is detected, centred at 274 Hz for $U_{\mathrm{ref}} = 19.8$ m/s. The measured resonance frequency matches well with the one obtained by formula (1), the difference being less than 1%.

The corresponding pressure level reaches more than 50 $\mathrm{Pa}/\sqrt{\mathrm{Hz}}$, which at 1 Hz resolution is equivalent to 128 dB, a very high sound level indeed. A typical spectral density is presented in Fig. 7 where the resonance peak is shown to completely dominate the level of the signal.

The resonance is not concentrated within a thin velocity band as it should for a standard linear resonance between the shear layer and the cavity: it occurs in a wide band around the central wind velocity given above. The width of the lock-in range spreads to ±2 m/s around the resonance velocity, corresponding to ±10% of the central resonance velocity. It is important to notice that simultaneously the frequency, instead of being constant, evolves linearly versus velocity with a positive slope of 2.75 $\mathrm{m}^{-1}$.

We can now compute the shear layer Strouhal number $St_\omega$ at the neck middle along the streamwise axis, which can be reasonably considered as a spatial mean value. By definition

$$St_\omega = f\delta_\omega/2U_1 \tag{5}$$

which gives $St_\omega = 0.064$. This value is obviously in the unstable range of the shear layer, as determined by Michalke [6,7]. In this configuration, we have also shown in previous work [5] that the convection velocity predicted by linear instability theory is indeed observed and hence can be used here. From Michalke we obtain $U_c/U_1 = 0.48$.

Rossiter's formula [9] is also commonly used in order to obtain the frequencies generated in a shear layer developing in a neck. It is based on the existence of a feed-back mechanism in which the impingement of a vortex at the downstream edge creates an acoustic pulse travelling upstream and thus triggering the shedding of a new synchronized vortex at the upstream edge. Rossiter's formula includes the feed-back mechanism between the two edges of the neck but not the interaction with the cavity volume. It is given by

$$St = \frac{fL}{U_1} = \frac{n-\gamma}{M + U_1/U_c}, \tag{6}$$

where $n$ is an integer characterizing the order of the mode. In this paper we have $n = 1$ due to the physical dimensions of the set-up. The empirical parameter $\gamma$, linked to the shape of the neck lips and the cavity depth, represents a part of the phase lag in the feed-back loop. Rossiter proposed $\gamma = 0.25$. From this point of view, the Rossiter formula includes the time delay due to the sum of the times taken for the impingement of a vortex at the trailing edge, emission of an acoustic pulse, arrival of the pulse at the leading edge and finally shedding of a new vortex.

The application of this formula with $St = 0.273$ and the very low Mach number $M = 0.057$ yields $\gamma = 0.41$, which differs significantly from Rossiter's value. However our configuration differs significantly from Rossiter's cavity which was simply rectangular without a neck. Hence it is not too surprising to obtain such a difference in the phase delay.

### 2.2. Attenuation of the pressure oscillations

We now activate the pulsed micro-jets with a supply pressure level of 1 bar and we set the wind velocity at resonance ($U_{\text{ref}} = 19.8$ m/s). The forcing frequency of the micro-jets $f_j$ is varied from 160 Hz to 450 Hz in a series of independent measurements. The results are reported in Fig. 8 where the pressure level in the cavity extracted from the spectral density peaks is plotted versus the forcing frequency $f_j$.

The explored range is divided into 3 regions:

- When the forcing frequency is lower than the cavity resonance frequency 274 Hz, the pulsed micro-jets have no effects and the pressure level remains the same as without jets.
- When the forcing frequency coincides with the cavity resonance frequency, the pressure level is strongly amplified, up to 150 $\text{Pa}/\sqrt{\text{Hz}}$ (137 dB at 1 Hz resolution).
- For a forcing frequency just larger than the cavity resonance frequency, the pressure level is well attenuated. It gradually recovers its original level as the forcing frequency differs more and more from the cavity resonance frequency.

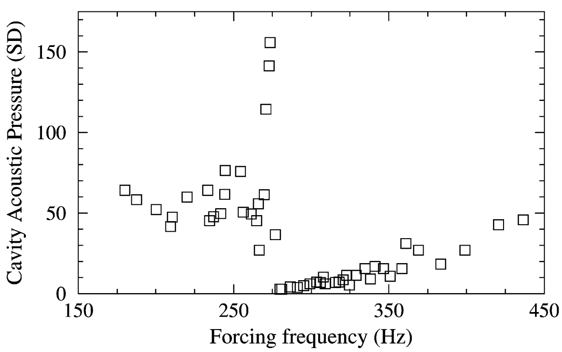


Fig. 8. Cavity pressure peak level versus forcing frequency at resonance ($U_{\text{ref}} = 19.8$ m/s).

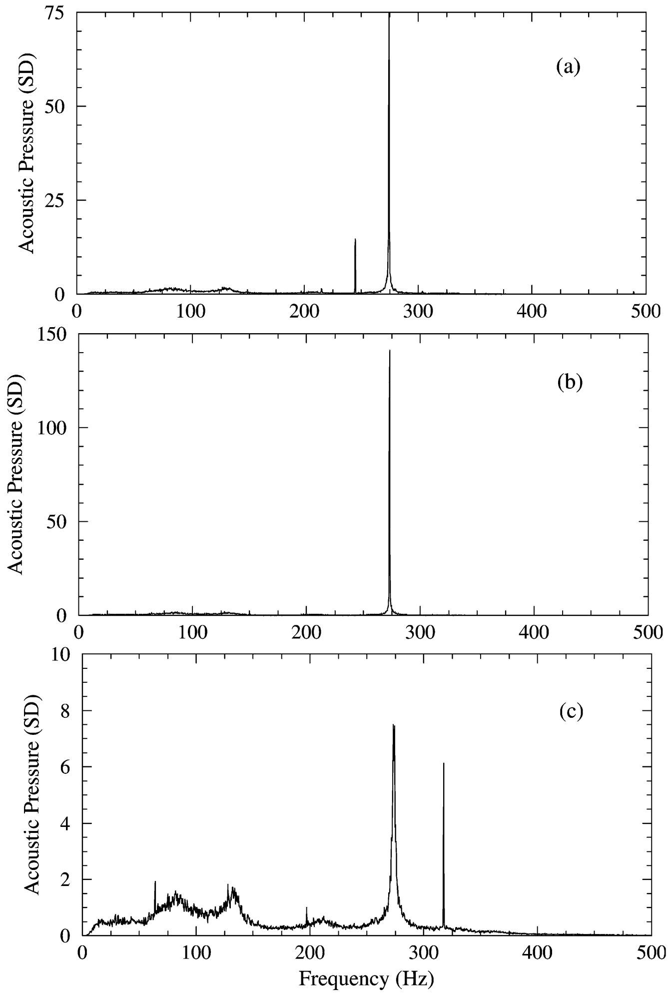


Fig. 9. Typical spectral densities of the acoustic pressure for three different forcing frequencies at resonance ($U_{\mathrm{ref}} = 19.8$ m/s). (a) $f_j = 245$ Hz; (b) $f_j = 272$ Hz; (c) $f_j = 317.5$ Hz.

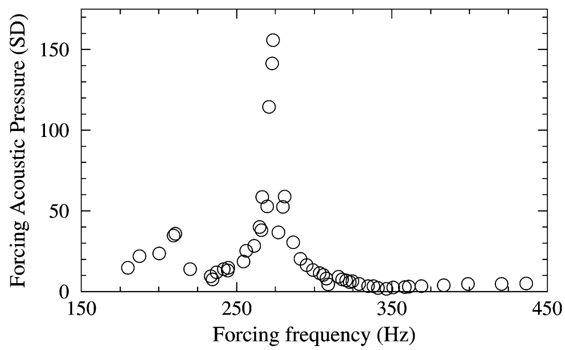


Fig. 10. Pressure peak level due to the actuators versus forcing frequency at resonant velocity ($U_{\mathrm{ref}} = 19.8$ m/s).

Typical spectral densities are shown in Fig. 9 for these 3 cases. In the first (a) and the third (c), the two peaks correspond to the cavity resonance frequency and the pulsed micro-jet frequency. Note that different scales for the pressure levels are used in the 3 plots. In the "controlled" case (c), the pressure level due to cavity resonance is less than 8 $\mathrm{Pa}/\sqrt{\mathrm{Hz}}$, more or less the same level as the sound produced by the pulsed micro-jets.

We arbitrarily define the optimal forcing frequency as the frequency which results in the minimum total level of acoustic pressure measured by the cavity microphone, including both peaks present in the spectral density, from the actuators and from the cavity. It is found here to be in the range 310 to 325 Hz i.e. 13% to 19% above the resonance frequency. This is explained in Fig. 10 where the acoustic pressure level due to the pulsed micro-jets is plotted versus forcing frequency in the same wind conditions as in the previous figure. Around synchronization there is only one peak because the pressure levels from the cavity and the micro-jets are identical.

In the range of optimal forcing and without wind, the pressure level due to the micro-jets is small, not interacting with the cavity. The level they produce in this situation is more or less the same as when there is no flow, as shown in Fig. 11 which is the same figure as Fig. 10 but without flow in the tunnel. We obviously detect the cavity Helmholtz mode because the micro-jets play the role of acoustic excitation. The single peak at 210 Hz is considered as an experimental artifact, probably generated by interaction with one of the wind tunnel components.

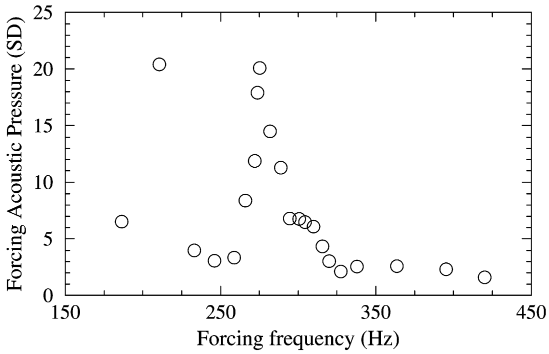


Fig. 11. Pressure peak level due to the actuators versus forcing frequency without wind ($U_{\mathrm{ref}} = 0$).

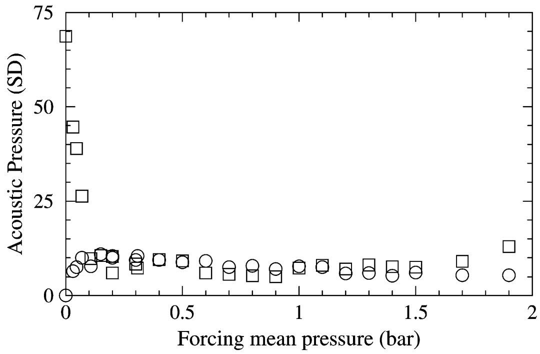


Fig. 12. Pressure peak level versus forcing pressure at resonant velocity ($U_{\mathrm{ref}} = 19.8$ m/s) and optimal forcing frequency ($f_j = 316$ Hz). □, cavity; ○, actuators.

### 2.3. *Effect of the micro-jet amplitude*

The effect of the micro-jets amplitude was rapidly observed by varying the mean pressure supply from 0 to 2 bars. The tests were carried out at resonance wind velocity and a pulsating frequency of 316 Hz, which is in the optimal range of efficiency for cavity pressure oscillations attenuation. The results are shown in Fig. 12. The pressure levels, at the cavity frequency (274 Hz) and at the forcing frequency (316 Hz) are plotted versus forcing pressure. Note that for pressures larger than 1.5 bar, there is saturation of the binary valve and results are not very reliable.

This figure shows that the pulsed micro-jets behave practically like binary actuators, with efficiency independent of their amplitude. Their efficiency is lost only for very low pressure supply, lower than 0.1 bar. It shows furthermore that the shear layer is very receptive to such forcing in these conditions. It must be noticed also that the acoustic pressure generated by the micro-jets is more or less independent of the pressure supply, except for very low amplitudes.

Note that a test was performed by increasing the micro-jets amplitude up to 2 bars in the range of frequencies below the cavity resonance frequency: this was in order to check if larger amplitudes could result in a forcing of the shear layer as for frequencies greater than the cavity resonance frequency. No effect was detected, the behaviour remained the same as for lower amplitudes.

## 3. Conclusion

An experimental study of the attenuation of cavity pressure oscillations by means of pulsed micro-jets has been conducted. We deal here with an open loop scheme, and the technique should be considered as a forcing technique rather than active control. These micro-jets, mounted normal to the main flow at the upstream edge of the cavity neck, are capable of considerably decreasing the pressure oscillations when their forcing frequency is just larger than the cavity resonance frequency. But when the forcing frequency is lower, these micro-jets are unable to force the shear layer.

These conclusions can be interpreted in terms of aerodynamic wavelengths of the forcing, compared to the cavity neck length. Assuming that the convection velocity in the shear layer is the pertinent velocity to characterize the waves due to forcing, we find that the wavelength at resonance $\lambda = U_{\mathrm{c}}/f_H$ (37 mm) is equal to about twice the neck length $L$. Hence the synchronization with the cavity neck occurs when $L \approx \lambda/2$. Experiments have shown that the micro-jets are efficient in forcing the shear layer only when the forcing wavelength $\lambda = U_{\mathrm{c}}/f_j$ is smaller than $2L$. On the other hand, when the forcing wavelength is greater than $2L$, the shear layer bounded by the neck edges cannot be perturbed.

Our point of view is that the forcing waves have a length that cannot “fit in the neck”, which is compatible with geometry. But other interpretations exist which require further investigations. These remarks are limited to the range explored in our experiments, i.e. a forcing wavelength between $1.16L$ and $3.5L$.

## References

[1] L.N. Cattafesta III, S. Garg, M. Choudhari, F. Li, Active control of flow-induced cavity resonance, AIAA paper 97-1804, 1997.
[2] S. Kikushi, Y. Fukunishi, Active flow control technique using piezo-film actuators applied to the sound generation by a cavity, ASME paper FEDSM99-7232, 1999.

[3] H. Kook, L. Mongeau, M.A. Franchek, Active control of pressure fluctuations due to flow over Helmholtz resonators, J. Sound Vibr. 255 (1) (2002) 61–76.
[4] J. Wojciechowski, Active control of the acoustic oscillations generated by flow over deep cavity, in: E. de Langre, F. Axisa (Eds.), Flow-Induced Vibrations, Paris, 6–9 July 2004.
[5] P. Hémon, F. Santi, X. Amandolèse, On the pressure oscillations inside a deep cavity excited by a grazing air flow, Eur. J. Mech. B Fluids 23 (2004) 617–632.
[6] A. Michalke, On the inviscid instability of the hyperbolic-tangent velocity profile, J. Fluid Mech. 19 (1964) (2004) 543–556.
[7] A. Michalke, On spatially growing disturbances in an inviscid shear layer, J. Fluid Mech. 23 (1965) (2004) 521–544.
[8] P. Huerre, Open shear flow instabilities, in: G.K. Batchelor, H.K. Moffat, M.G. Worster (Eds.), Perspectives in Fluid Dynamics, Cambridge University Press, 2000, pp. 159–229.
[9] J.E. Rossiter, Wind tunnel experiments on the flow over rectangular cavities at subsonic and transonic speeds, Aero. Research Council Reports and Memoranda, Technical report 3438, 1964.