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CONTROL OF DEEP CAVITY TONES USING A SPANWISE CYLINDER AT LOW-SUBSONIC SPEEDS

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ABSTRACT

Deep cavity configuration at subsonic velocity could be found in many industrial processes, ranging from windows and sunroofs in automobiles and over space between two consecutive train vehicles. These cavities may induce aeroacoustic couplings between the cavity shear layer oscillations and the acoustic modes of the installation. This aero-acoustic coupling can leads to serious damages of vehicles due to resonance of high pressure fluctuation level around the cavity. The study of deep cavity at low velocity presents a great practical interest to suppress acoustic noise. In spite of numerous studies devoted to the cavity and its control, very few of them relate to the deep cavity configuration at low velocity. The focus of the present study is to apply a passive control to the case of the deep cavity flow at relatively low velocities. A Detailed Experimental study of flow over a deep cavity was conducted towards understanding the attenuation of tones using a spanwise cylinder. The cavity length-to-depth aspect ratio is $L/H = 0.2$. Single hot-wire measurements characterized the incident turbulent boundary. A "no control" cavity was compared with a similar configuration using a cylinder on the leading edge of the cavity. Parametric changes of the spanwise cylinder such as the distance from the wall are studied. Maximum control across the range of studied velocities occurs for a particular position of the spanwise cylinder. Reductions in sound pressure levels (SPL) of up to *36 dB* were obtained. Moreover, a shaped cylinder was also studied and shows that the attenuation of tones is not due to high frequency pulsing as suggested in literature, but to an increase of the cavity shear layer thickness due to change in the mean axial velocity profiles.

INTRODUCTION

Cavity flows have been the subject of research since the 1950's. Although geometrically simple, the fluid dynamics in such flows are complicated, involving shear layer instability, flow-induced resonance and turbulence. Consequently, research on cavity flow has been ongoing for a number of decades. Some of the first detailed studies were conducted in the 1950's by Krishnamurty [15]. In the early sixties, Rossiter [34] developed a semi-empirical relationship to predict resonance frequencies based on the feedback mechanism. Subsequently, much research has been focused on determining the mechanisms responsible for such generation of sound and on predicting the oscillation frequency of the tonal component of the noise ([38], [39], [40], [36], [32], [29], [24]).

Much of the flow physics governing cavity behaviour remains unclear ([30], [23], [22], [21]). Low frequencies induced by shear layer cavity resonance are characterized by large dynamic pressure loads and represent an important problem in many aeronautical applications ([41], [37], [35], [33], [31]). Indeed, it is of interest from a practical standpoint, due to its presence in many flow configurations.

Two 'classes' of cavities are generally studied. Shallow cavities with aspect ratios $L/H > 1$ (length to depth), and deep cavities, with aspect ratios of less than one, induce acoustic resonance through the interaction of depth mode standing waves and vortices shed at the cavity leading edge lip. However few studies are devoted to the deep cavity because the majority of the studies were mainly focused on large cavities in the military field such as in aircraft landing gear bays or in internal weapon bays. Particularly deep cavities ($L/H = 0.2$ and 0.41) are studied in this paper. El Hassan et al. [3] have founded that such cavity configuration has different quantitative influence on the skin friction comparing with square cavity cases. El Hassan et al. [4] also showed how this particular deep cavity could affect the shear layer oscillations. The objective here is to eliminate the resonance produced by these cavities. Passive and active control methodologies were employed for the suppression of cavity-flow tones in past studies. Feedback flow control, however, has only recently been applied to the problem using piezoelectric bimorph actuator [9] and loudspeaker [8] coupling to pressure transducers. An overview of the various control methodologies used is given in the review paper by Cattafesta et al. [42]. Some research programs have investigated active acoustic noise suppression using pulsed blowing or oscillating devices. Some recent experiments have shown that efficient amplitude reduction of these oscillations can be produced by a cylindrical rod parallel to the leading edge of the cavity. Cylindrical rods placed at the leading edge of a cavity were first suggested as a passive acoustic suppression device by McGrath and Shaw [16]. McGrath and Shaw demonstrated significant reduction of tone peak for a rod with a diameter approximately half the boundary layer thickness. Shaw [5] suggested two mechanisms of suppression. The rod either displaces the boundary layer to break the acoustic feedback loop, or the high frequency vortex shedding in the rod wake acts to extract energy from the larger oscillating structures. Results from this study were inconclusive in identifying the suppression mechanism. Acoustic control of weapons bays (Shallow cavity, high velocity) using cylindrical rod in cross flow are widely investigated ([20], [16], [17], [18], [19]). Stanek et al. studied the vertical position of the rod in the boundary layer, its relative size d/δ_0, installation issues, and end conditions. They recommended an optimal position as centered at the edge of the boundary layer and an optimal size of $d/\delta_0 = 2/3$. They argued that their results conclusively demonstrate that the suppression is due to high frequency rod shedding. At the same time, the study of Smith et al. [10], also based on parameterizing the optimum cylinder geometry and location, concluded that the cylinder should have a diameter approximately one third of the boundary layer thickness ($d/\delta_0 = 1/3$). Again, while the cylinder clearly affects the mean flow and its stability characteristics, there are other important factors that cannot be ignored, including experimental evidence presented by Ukeiley et al. [14] and the numerical simulation of Arunajatesan et al. [11], [12], [13] that the cylinder lifts the shear layer and causes the impingement region to be altered. If the shear layer impingement location is altered, then the source strength is presumably affected. Fairly few authors have studied deep cavity control by cylindrical rod in cross flow compared to the shallow cavity. All of these investigations are conducted at very high velocity and in many civil applications such as cars and railways. The study of deep cavity at low velocity presents a great practical interest to suppress acoustic noise. So, in spite of numerous studies devoted to the cavity and its control, very few of them relate to the deep cavity configuration at low velocity. The focus of the present study is to apply this passive control to the case of the deep cavity flow at relatively low velocity ($M \approx 0.17$). Experiments were conducted in two deep cavity configurations for different distances between the rod and the wall.

APPARATUS AND EXPERIMENTAL PROCEDURES

Flow parameters

The experimental measurements have been conducted in the closed circuit low speed wind tunnel. The test section is $2 \times 2\ m^2$ in cross-section and 10 m long. The relative turbulence level, in the middle of the test section at 30 m/s, is about 0.5%. figure 1 shows a two-dimensional schematic view of the cavity and the spanwise cylinder location. Two cavity configurations were studied. The dimensions of the first cavity configuration were L = 104 mm in length, H = 520 mm in depth and W = 2000 mm in width. Aspect ratios were L/H = 0.2 and L/W = 0.052. The second cavity configuration had the same H and W as the first one, with L = 213 mm. Its ratios were L/H = 0.41 and L/W = 0.107. Each cavity was installed on the lateral wall of the test section, with the leading edge located 8 m downstream from the test section inlet. Hot-wire measurements were done just upstream from the cavity leading edge to characterize the incident boundary layer. Velocity profiles at this location showed that for a low free stream velocity ($U_0 = 2$ m/s) the boundary layer was fully developed. The spanwise cylinder is located 30 mm upstream from the cavity leading edge. A 6 mm diameter was used for the cylinder, and the vertical position of the cylinder to the wall (measured at mid-diameter) was varied above the lateral test section ($z_c/d = 0.5$ to 6.5). The rod was tested for the cavity aspect ratio of 0.2 and 0.41. This type of device induces a wake of vortices at a frequency dependent on its diameter and freestream velocity. Over a large range of Reynolds numbers the Strouhal number for the wake shedding is approximately constant and equal to 0.2. The calculated shedding frequencies were 900 Hz and 1000 Hz respectively for 43 m/s and 50 m/s. Note that the calculate valued is not based on the tunnel freestream velocity, but on that within the boundary layer. The measured shedding frequencies were obtained from hot-wire measurements near the cylinder wake.

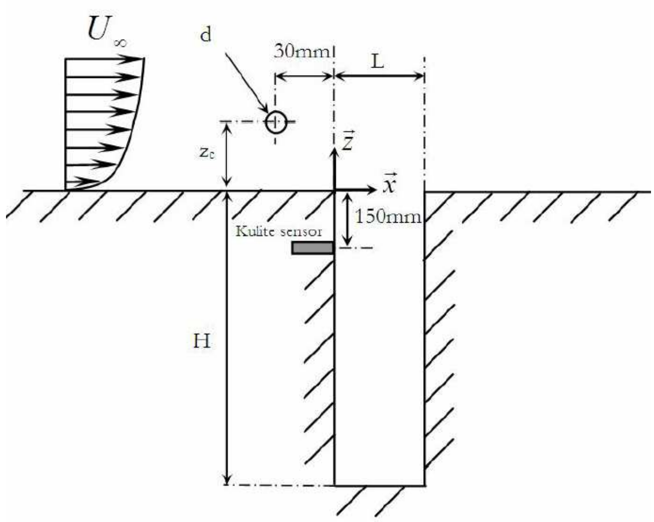

Figure 1 Schematic view of the cavity with a spanwise cylinder

Pressure measurements

A Kulite pressure transducer was employed, with a nominal sensitivity of 275 mV/bar. The output from the transducer was connected to a multi-channel signal conditioner. Data acquisition of pressure signals was accomplished using an A/D board with 12 −bit resolution. A gain adjustment was used in order to meet the required voltage input levels of the A/D board. Data were sampled at 6 kHz typically for 180000 samples. Location of the sensor is indicated in figure 1.

Hot-wire measurements

Experiments were carried out using a DANTEC 90C10 constant temperature hot-wire anemometry (CTA) system. The output signal was transferred by an A/D digital card connected to a PC. The STREAMLINE software supplied by DANTEC was used to acquire and store data. Measurements were obtained using single hot-wire sensors (DANTEC 55P 15) placed in the shear layer at x/L = 0.1 from the leading edge of the cavity in the streamwise direction for the two cavity configurations. A traversing system was used to move the probes in the normal direction (z). A traverse grid was defined for each cavity configuration. For each free stream velocity, data are acquired along the shear layer. The signals from the C.T.A. were filtered and amplified to give signals that covered most of the ±10 V range of the A/D converter.

RESULTS AND DISCUSSION

Results with "no control" cavities

Acoustic resonance is an important mechanism presents in deep cavity flow and leads to a high pressure level around the cavity. This resonance occurs when the frequency of the shear layer oscillation and that of acoustic phenomena coincide. At the cavity upstream corner, instability waves are produced and grow as they are convected downstream along the shear layer. The pressure disturbances, resulting from structures impingement at the cavity downstream corner, propagate upstream to affect the instability process near the separation region (upstream corner). A semi-empirical formula of this feedback loop was proposed by Rossiter [34]:

$$f_n = \frac{n - \alpha}{\tau_c + \dfrac{L}{c_0}}$$

Where n is the cavity mode, f_n its frequency, L the length of the cavity, c_0 = 340 m/s is the sound speed inside the cavity and $\tau_c = u_c/U_0$ (u_c is the structure convection velocity).

The aero-acoustic coupling for both configurations (L/H = 0.2 and L/H = 0.41) is clearly shown in the spectrograms (Fig. 2 and 3). The depth mode is a mechanism related to deep cavities and leads to resonance generation. The frequency values of 137 Hz and 123 Hz correspond to the depth mode of the cavity for L/H = 0.2 and 0.41 respectively. Around these frequencies, the amplitude of the DSP becomes significantly high and a cavity tone occurs. This is related to the excitation of the depth mode of the cavity by the oscillation of the shear layer. Moreover, the oscillation mode of the shear layer excites the acoustic mode generated by the trailing corner of the cavity around f = 169 Hz. Around this frequency and for both cavity configurations, high pressure amplitudes are discernible and characterize the aero-acoustic lock-in. More details concerning the aero-acoustic couplings are given by El Hassan et al.[4].

For L/H = 0.2, the amplitude evolution of sound pressure level with the free stream velocity shows that the first hydrodynamic mode (mode 1) is dominant for all studied velocities where a cavity oscillation occurs. The highly energetic peaks observed for L/H = 0.41 illustrate the existence of mode 1 and mode 2 for this configuration.

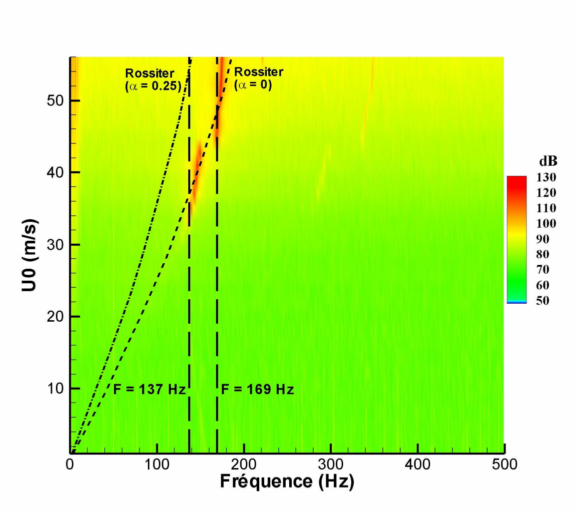

Figure 2 Spectrogram for L/H = 0.2

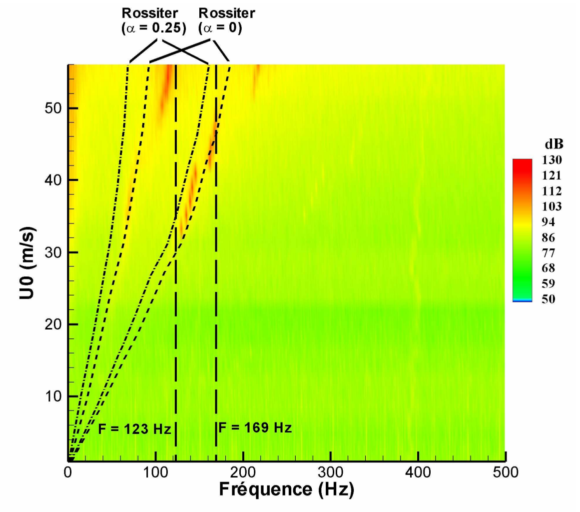

Figure 3 Spectrogram for L/H = 0.41

Parametric control study

In the case of a spanwise cylinder control, the same measurements are done on the cavity flow. Solid cylinders are used to induce a wake of vortices at a high frequency (depending on the diameter of the cylinder, the velocity and the density of the flow). The Strouhal number for the range of the Reynolds numbers used for the present study is about 0.2. The 6 mm diameter cylinder was used for both configurations and the corresponding shedding frequencies are on the order of 1 - 2 kHz. Figures 4 and 5 show “no control” and “control” sound pressure level plots for a cavity aspect ratio of 0.2 and 0.41 and for a velocity of 43 m/s. The rod was set at z_c/d = 1.67 to the wall and at 30 mm upstream from the cavity leading edge. This was the optimal configuration for SPL reduction for both flow speeds tested. A drop of over 36 dB in the dominant frequency SPL is noted between the ”control” and the ”no control” cases for a cavity aspect ratio of 0.2 and a drop of over 23 dB for a cavity aspect ratio of 0.41.

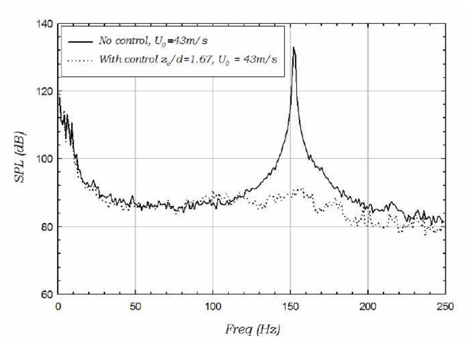

Figure 4 Sound pressure level with and without control for L/H = 0.2

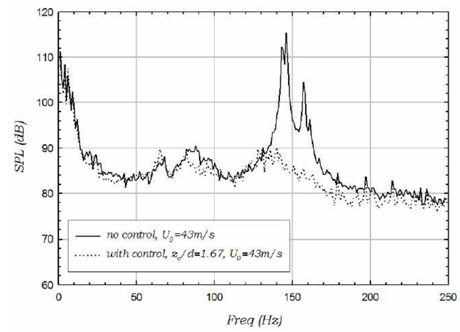

Figure 5 Sound pressure level with and without control for L/H = 0.41

The spanwise cylinder is an efficient device to control the cavity resonance over an entire range of velocity. Such a system is able to optimize suppression levels for each flow regime encountered (0 to 54 m/s) as it is shown in figures 6 and 7 for both configurations. Each configuration parameter such as cylinder height was varied. The parametric variations were performed to determine optimum control configurations for a given cavity configuration. Reductions in peak sound levels (SPL) as high as 36 dB can be achieved using a spanwise cylinder. Optimal control was achieved across the entire velocity range by using a 6 mm cylinder diameter at z_c/d of 0.83 to 2.67 for both configurations (L/H = 0.2 and 0.41).

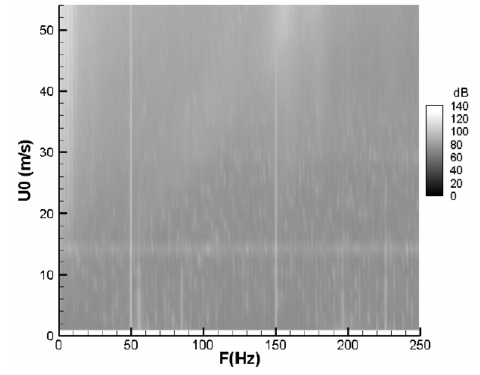

Figure 6 Spectrogram with control (z_c/d = 1.67) for L/H = 0.2

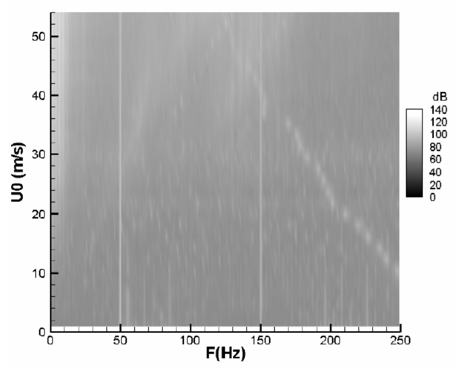

Figure 7 Spectrogram with control (z_c/d = 1.67) for L/H = 0.41

Mean flow field

This part presents results of velocity measurements based on the optimized control position (z_c/d = 1.67) found in the previous part of the paper. Mean velocity profiles, measured at x = L/2, for the ”no control” and optimized controlled cavity cases are shown in figure 8. The ”no control” cavity behaves in good agreement with expectations for a deep cavity configuration. The velocity deficit results from the wake behind the cylinder and contributes to thicken and therefore to stabilize the cavity shear layer.

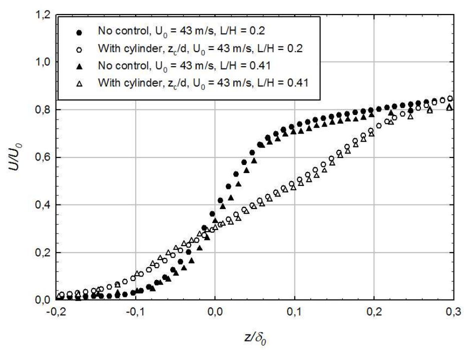

Figure 8 Mean velocity profile

Velocity fluctuations in the shear layer of the cavity are presented in figure 9. It appears that the cylinder is responsible of strong fluctuating events in this part of the cavity shear layer. These results are in close agreement with those obtained from wind tunnel data, initially proposed by McGrath and Shaw [16], and reported earlier by Illy et al. [6], [7].

Stanek [17] suggested that the effect of the cylinder could be due to turbulence mechanism and particulary consists in an increase of the energy transfer rate within the inertial range of turbulence scales separating the cavity modes from dissipation scales. Earlier work on the receptivity of free shear flows to external excitation, suggests that these flows are typically not receptive to low-level excitation at frequencies above a relatively narrow band around the natural frequency. Thus, it might be expected that high frequency disturbances induced by the cylinder device would be rapidly attenuated as they are advected by the flow.

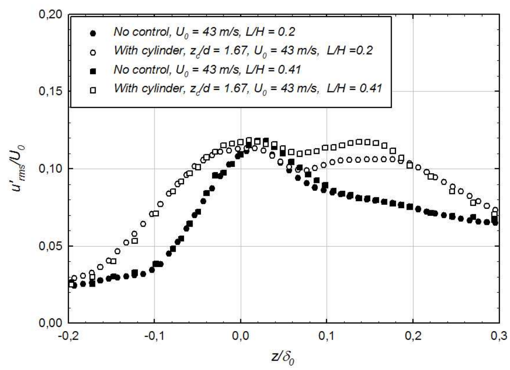

Figure 9 Root-mean-square velocity profile

The effect of the energy transfer is shown in normalized velocity spectra (fig. 10). The most prominent feature in the spectra of the controlled flow is the sharp increase in the amplitude of spectral components within frequency band around the excitation frequency. A comparison of normalized velocity spectra of the flow with and without control reveals a notable difference. Indeed, the normalized velocity spectra components with the cylinder at all frequencies above 300 Hz are higher than in the no control flow. The reduction in the magnitude of spectral components at low frequencies suggests that the cylinder induces coupling between small and large scales within the flow and thus leads to an accelerated energy cascade from the large scales. Wiltse and Glezer [1] have measured velocity spectra, and showed the wholescale transfer of energy from low frequencies to high frequencies. In addition, these authors computed turbulent dissipation rates based upon their hot wire measurements. Based upon their calculations and hot wire data, the high frequencies forcing increased the turbulent dissipation in the jet by more than an order of magnitude.

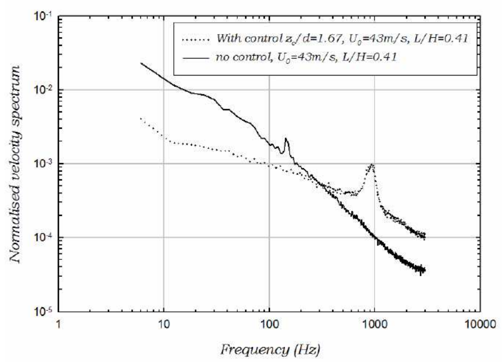

Figure 10 Normalized velocity spectrum for L/H = 0.41

The turbulent dissipation and Taylor's length scales were estimated using time series of the stream-wise velocity assuming isotropic turbulence and Taylor's hypothesis :

$$\varepsilon = 15\upsilon \frac{1}{u_c^2(z)} \overline{(\frac{\partial u}{\partial t})^2}$$

As it may be observed in figures 11 and 12, most of dissipation happens in the shear layer region in the small scale eddies. The larger coherent structures should disappear at the expense of an increase in the population of very small structures. R. Deron et al. [2] showed with Schlieren pictures that the shear layer large scale vortices disappear and are replaced by small scales of the cylinder wake.

It seems that it is the wake that interacts with the shear layer above the cavity, thereby altering it in a manner that it reduces the fluctuating pressure inside the cavity.

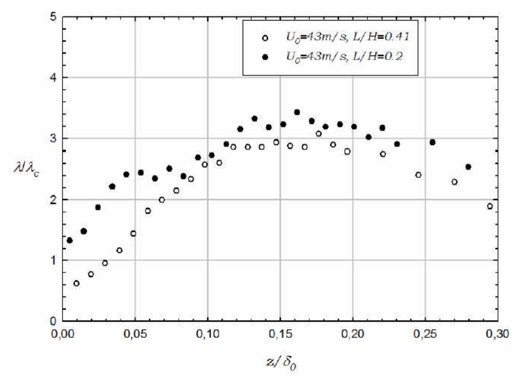

Figure 11 Relative Taylor's microscale (no control/control)

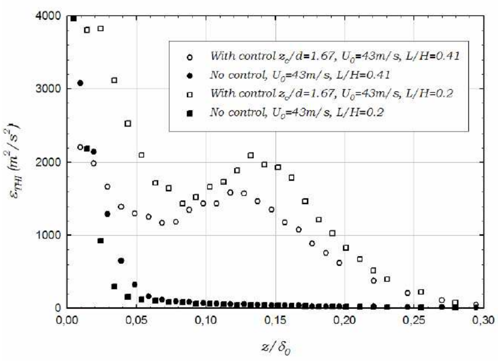

Figure 12 Turbulent dissipation with and without control

High frequency pulsing effect

The cylinder in cross flow was shown to be an effective device for suppressing acoustic resonance in low speed deep cavity flows. The rod configuration is a simple cylinder in cross flow, located at the leading edge of the cavity. Variation on this configuration was investigated in an attempt to isolate the mechanism of acoustic suppression. The performance of this device according to Stanek (2003) was primarily due to the pulsing (and not simply due to mass addition).

In order to estimate the pulsing effects on the attenuation of tones, experiments where the cylinder shedding can be either disrupted or eliminated entirely, were performed. This was made using a shaped cylinder design (Fig.13) for which the shedding was strongly disrupted. This modified rod was selected to minimize the shedding process.

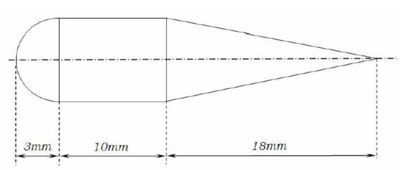

Figure 13 Shaped cylinder

Figures 14 and 15 show sound pressure levels and normalized velocity spectra for ”no control”, cylinder ”control” cases and with a shaped cylinder for L/H = 0.2 with respect to the optimal cylinder position (z_c/d = 1.67), and permitted to compare ”shedding on” performance with ”shedding off” performance. In the ”no control” case, the first Rossiter mode clearly appears and when rod control was applied, the shedding frequency of the cylinder was definitely visible. In the case of the shaped cylinder, the normalized velocity spectrum exhibited no sharp peak resulting from shedding frequency breakdown. The corresponding sound pressure levels show the efficiency of the shaped cylinder as for the attenuation of tones. Consequently, the link between pulsing high frequency and the acoustic resonance suppression is not proved. To obtain a significant sound reduction, the pulsing effects of the cylinder are not necessary, only the presence of a body wake seems to be required.

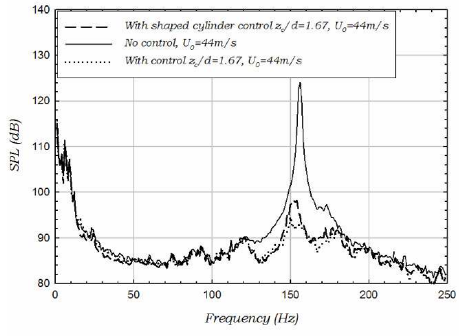

Figure 14 Sound pressure level for L/H = 0.41

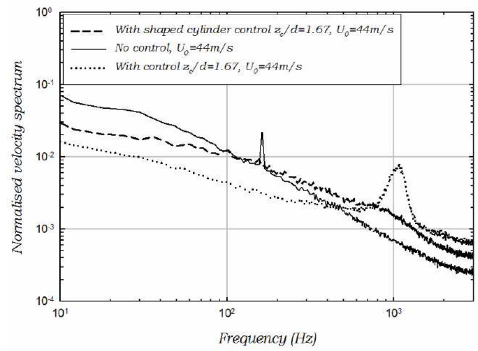

Figure 15 Normalized velocity spectrum for L/H = 0.2

Conclusion

The effects of cylinder suppression device were studied to develop an understanding of how they reduce the fluctuating pressure loads inside a deep cavity. ”No control” cavities measurements (respectively with length-to-depth aspect ratios of 0.2 and 0.41.) with no suppression device showed strong peak frequencies corresponding to the Rossiter modes. With rod control, pressure fluctuations were clearly attenuated, but optimized position of the spanwise cylinder with regard to the leading edge of the cavity is required to obtain the best suppression of tones. This optimized position is around zc/d = 1.67 for both configurations. The velocity analysis clearly showed strong fluctuating activities in a large region including the shear layer to the cylinder wake. Due to the rod control, the larger coherent structures in the shear layer should disappear at the expense of an increase in the small scale eddies. The results presented in this work suggest that the effectiveness of the cylinder to reduce the pressure loads inside the cavity is likely to be due to the thickening of the mixing layer resulting from the interaction between the cylinder wake and the cavity shear layer. The control of cavity resonance with the shaped cylinder failed the hypothesis concerning the link between high frequency pulsing and the acoustic suppression.

References

[1] Wiltse J.M. and Glezer A. (1998) Direct excitation of small-scale motions in free shear flows. Phys.Fluids, Vol. 10, No. 8, pp.2026-2036

[2] Deron R., Illy H., Geffroy P., Mendez F. and Corbel B. (2005) Effects of a cavity flow passive control on optical phase degradations. AIAA Paper 2005-4659, 36th AIAA Plasmadynamics and laser conference, Toronto, Ontorio Canada, June

[3] El Hassan M., Labraga, L., Keirsbulck L (2007) Turbulent boundary layer over a deep cavity: friction coefficient and streamwise velocity components. Can. J. Phys./Rev. can. phys. 85(12): 1447-1457

[4] El Hassan M., Labraga L., Keirsbulck L (2007) Aero-acoustic oscillations inside large deep cavities. 16th Australasian Fluid Mechanics Conference, 421-428.

[5] Shaw L. (1998) Active control for cavity acoustics. AIAA-98-2347, 19th AIAA Aeroacoustics conference, Toulouse, France, June

[6] Illy H., Geffroy P., Jacquin L. (2004) Control of Flow Oscillations over a Cavity by Means of a Spanwise Cylinder. XXI International Congress of Theoretical and Applied Mechanics Warsaw, Poland, August 1521

[7] Illy H., Geffroy P., Jacquin L. (2005) Contrôle des oscillations de cavité au moyen d'un cylindre placé transversalement `a l'´ecoulement. 17ème Congrès Français de mécanique, Troyes, Septembre

[8] Rowley C.W., Williams D.R., Colonius T, Murray R.M., MacMartin D.G., Fabris D. (2002) Model-based control of cavity oscillations, PartII: System identification and analysis. AIAA Paper 2002-0972

[9] Kegerise M.A. and Cambell R.H. (2004) Real-time adaptative control of flow-induced cavity tones (invited). AIAA Paper 2002-0572

[10] Smith B., Welteren T., Maines B., Shaw L., Stanek M., Grove J. (2002) Weapons bay acoustic suppression from rod spoilers. AIAA Paper 2002-0662

[11] Arunajatesan S., Shipman J., Sinha N. (2002) Hybrid Rans-LES Simulation of cavity flow fields with control. AIAA Paper 2002-1130

[12] Sinha N., Arunajatesan S., Seiner J.M. (2002) Computational and experimental investigations of cavity attenuation using high frequency control. AIAA Paper 2002-2403

[13] Arunajatesan S., Shipman J., Sinha N. (2003) Mechanisms in high frequency control of cavity flows. AIAA Paper 2003-0005

[14] Ukeiley L.S., Ponton M.K., Seiner J.M., Jansen B. (2004) Suppression of pressure loads in cavity flows. AIAA Journal Vol. 42, No. 1:70-79

[15] Krishnamurty K. (1955) Acoustic Radiation from two-dimensional rectangular cutouts in aerodynamic surfaces. NACA TN 3487

[16] McGrath S.F. and Shaw L.L. (1996) Active control of shallow cavity acoustic resonance. AIAA Paper 96-1949

[17] Stanek M.J.,Raman G., Kibens V., Ross J.A., Odredra J., Peto J.W. (2000) Control of cavity resonance through very high frequency forcing. AIAA Paper 2000-1905

[18] Stanek M.J., Ross J.A., Odredra J., Peto J.W. (2003) The mystery of the rod-in-crossflow revealed. AIAA Paper 2003-0007

[19] Stanek M.J.,Raman G., Ross J.A., Odredra J., Peto J.W., Alvi F., Kibens V. (2002) High frequency acoustic suppression-The role of mass flow, the notion of superposition, and the role of inviscid instability - a new model (part II). AIAA Paper 2003-0007

[20] Shaw L.L., Clark R., Talmadge D. (1988) Generic weapons bay acoustic environment. Journal of Aircraft Vol. 25,No. 2:147-153

[21] Bergmann D, Kaiser U, Wagner S (2003) Reduction of low-frequency pressure fluctuations in wind tunnels. Journal of Wind Engineering and Industrial Aerodynamics 91:543-550

[22] Camussi R, Guj G, Ragni A (2006) Wall pressure fluctuations induced by turbulent boundary layers over surface discontinuities. Journal of Sound and Vibration 294:177-204

[23] Chatellier L (2002) Modélisation et contrôle actif des instabilités aéroacoustiques en cavité sous écoulement affleurant. Université de Poitiers, thèse

[24] East L.F. (1966) Aerodynamically induced resonance in rectangular cavities. Journal of Sound and Vibration 3:277-287

[25] Forestier N, Jacquin L, Geffroy P (2003) The mixing layer over a deep cavity at high-subsonic speed. J. Fluid Mech. 475:101-145

[26] Gharib M, Roshko A (1987) The effect of flow oscillations on cavity drag. Journal of Fluid Mechanics 177:501-530

[27] Hirahara H, Kawahashi M, Uddin Khan M, Hourigan K (2007) Experimental investigation of fluid dynamic instability in a transonic cavity flow. Experimental Thermal and Fluid Science 31:333-347

[28] Kegerise MA, Spina EF, Garg S, Cattafesta LN (2004) Mode-Switching and Nonlinear Effects in Compressible Flow Over a Cavity. Physics of Fluids 16:678-687

[29] Knisely C, Rockwell D (1982) Self-sustained low-frequency components in an impinging shear layer. J. Fluid Mech. 116:157-186

[30] Larchevêque L, Sagaut P, Ivan M, Labbé O (2003) Large-eddy simulation of a compressible flow past a deep cavity. Physics of fluids 15:193-210

[31] Ricot D (2002) Simulation numérique d'un écoulement affleurant une cavité par la méthode Boltzmann sur réseau et application au toit ouvrant de vehicules automobiles. Thèse, Ecole Centrale de Lyon

[32] Rockwell D, Knisely C (1980) Vortex-edge interactions: mechanism for generating low frequency components. Physics of fluids 23:239-240

[33] Rockwell D, Lin J-C, Oshkai P, Reiss M, Pollack M (2003) Shallow cavity flow tone experiments: onset of locked-on states. journal of fluids and structures 17:381-414

[34] Rossiter JE (1964) Wind tunnel experiments on the flow over rectangular cavities at subsonic and transonic speeds. Aeronautical Research Council Reports and Memo No. 3438

[35] Rowley CW, Colonius T, Basu AJ (2002) On self-sustained oscillations in two-dimensional compressible flow over rectangular cavities. J. Fluid Mech. 455:315-346

[36] Sarohia V (1975) Experimental and analytical investigation of oscillations in flows over cavities. PhD Thesis,

California Institute of Technology
[37] Schachenmann A, Rockwell D (1980) Self-sustained oscillations of turbulent pipe flow terminated by an axisymmetric cavity. Journal of sound and vibration 73:61-72
[38] Tam C.K.W., Block P.J.W. (1978) On the tones and pressure oscillations induced by flow over rectangular cavities. J.Fluid Mech. 89:373-399
[39] Block P.J.W., Heller H.H. (1975) Measurements of Farfield sound generation from a flow-excited cavity. NASA TM X-3292
[40] Block P.J.W. (1976) Noise response of cavities of varying dimensions at subsonic speeds. NASA TM D-8351
[41] Williams JF (1992) Modern Methods in Analytical Acoustics Lecture Notes. The Journal of the Acoustical Society of America 92:313-354
[42] Cattafesta L.N., Williams D.R., Rowley C.W., Alvi F.S. (2003) Review of active control of flow-induced cavity resonance. AIAA Paper 2003-3567