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Engineering Notes

Effect of a Perturbed Shear Layer on Cavity Resonance

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I. Introduction

MODERN combat aircraft adopted the internal weapons bay concept for stores carriage in order to reduce drag, enhance maneuverability, and minimize radar cross section. This has revived interest in cavity flow studies that can be dated back to the early works of Krishnamurty [1] and Roshko [2]. The frequency of the acoustic tones generated inside the cavity can be predicted quite accurately using Rossiter's [3] empirical formula. Experiments [3] have shown that the shear layer rolls up to form large coherent turbulent structures or vortices, and hence Rossiter's [3] model is more realistic than the thin-shear-layer model proposed by Bilanin and Covert [4]. So far, no method has been advanced to estimate the amplitude of the acoustic waves. The strength of the acoustic waves depends on the intensity of the pressure generated at the downstream corner of the cavity upon impact of the shear-layer vortices. Tang and Rockwell [5] studied the pressure field associated with the impingement of a convected vortex at a sharp corner in low-speed flows and found that three types of interaction can occur, leading to time-dependent pressure amplitudes that are random. Thus, we have a situation in which we cannot predict which acoustic mode is present and what its amplitude will be. The usual statistical technique favored by many investigators is to compute the power spectra of pressure signals measured inside the cavity in order to determine the time-averaged properties of the acoustic waves. In this Note, we use a joint time–frequency analysis technique to determine the modes at any instant of time. Furthermore, we perturb the shear layer and alter the vortical structure to investigate the mode-switching phenomenon. This study was motivated by work performed for the Department of National Defence (Canada) in a program on stores release from an internal weapons bay. The effect on the acoustic wave intensities inside the weapons bay when stores traverse the shear layer is of interest from the point of view of stores integrity.

II. Experiments

The tests were conducted in the 5 in. trisonic wind tunnel at the Institute for Aerospace Research, National Research Council, Canada. The description of the model, test facility, and instrumentation is given in [6]. The cavity length L was 3.75 in., span W was 0.75 in., and depth D was 0.75 in., giving a ratio of 5 for both L/D and L/W. The cavity was instrumented with 16 fast-response pressure transducers, but only the one located on the rear wall along the centerline and at a distance of $0.73D$ from the cavity floor was analyzed. This transducer location was closest to the impact of the vortices on the rear corner and is shown in Fig. 1 by the symbol T. The frequency response of the transducer was about 20 kHz and calibration showed a practically flat response up to a test frequency of 6 kHz. Data from the pressure transducer was sampled at 15 kHz for 5 s following low-pass filtering at 5 kHz using an eighth-order Butterworth filter. The low-pass frequency was kept constant, and the highest acoustic frequency analyzed was slightly above 3 kHz at a test Mach number of 0.86. The corresponding Reynolds number was 2.75×10^6 per foot. The measured pressure $p(t)$ was expressed in coefficient form as $C_p(t) = [p(t) - p_\infty]/q$, where $q = 1/2\rho U^2$ with ρ and U being the air density and freestream velocity, respectively. The stores were represented by 0.125-in.-diam rods ($0.167D$) of various lengths attached to the cavity front and rear walls, thus eliminating the need for a mounting system that would cause interference to the flow around the cylinders. This is a very crude approximation for actual stores released in the front and rear sections of a weapons bay. Various combinations of stores installed at different locations inside the cavity were investigated, but in the present Note, only results for three configurations are presented. Configuration 1 represents the clean cavity. Configuration 2 shown in Fig. 1a shows two rods of length $0.43L$ attached to the cavity rear wall with their centers located at $0.25W$ on either side of the centerline. The rods were positioned so that they were just inside the cavity (centerlines at $0.0835D$). Configuration 3 shown in Fig. 1b is similar to configuration 2, except the rods were attached at the front wall. Configurations 2 and 3 are useful in separating the effect of the nose and base of a store in perturbing the shear layer, and the subsequent effect in altering the cavity resonance can be quite different.

III. Results

Joint time–frequency analyses were carried out on the instantaneous C_p time series using a short-time Fourier transform (STFT) algorithm from LabVIEW Signal Processing Toolset. The time series was 4.2325 s duration and there were 63,488 samples. A Hanning window of length 256 was used in the analysis. The frequency resolution was $\Delta f = 58.59$ Hz, and from the uncertainty principle, the time resolution $\Delta t \geq 1.358$ ms. The number of time steps in the output data was fixed by LabVIEW to be 508 for this case, giving a time step of 8.35 ms.

Figure 2 shows the spectrogram for the clean cavity (configuration 1) at $M = 0.86$. For clarity, only 25 equally spaced time steps are included. Two distinct modes at average frequencies of approximately 1950 and 3200 Hz are detected. These frequencies are very close to those determined from a modified form of Rossiter's [3] semi-empirical formula derived by Heller and Bliss [7], with the cavity speed of sound replaced by the freestream stagnation sound speed. The expression is given as

$$St_n = \frac{f_n L}{U} = \frac{(n - \alpha)}{M(1 + \frac{\gamma-1}{2}M^2)^{-1/2} + \frac{1}{k}} \tag{1}$$

In the above equation, n is the mode number; U and M are the freestream velocity and Mach number, respectively; and the constants α and k are given by Rossiter [3] for a cavity of $L/D = 4$ as 0.25 and 0.57, respectively. From a previous investigation [6], the values of α and k were found to give accurate frequency predictions for the L/D and M values used in this study. Only the second and third Rossiter [3] modes (f_n for $n = 2$, 3) are prominent and our analysis will focus only on these two modes.

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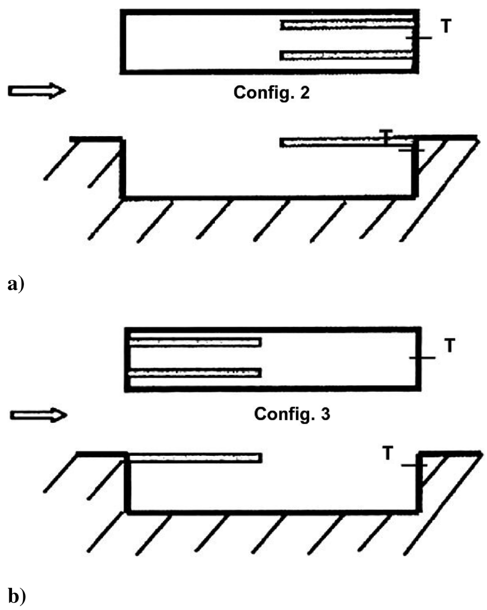

Fig. 1 Arrangement of rods inside cavity.

In Fig. 2 the frequencies of modes 2 and 3 at each time step deviate only slightly from Rossiter's [3] frequencies, and the differences are less than 1.5%. The magnitude of the spectrogram $\mathrm{SP}(t, f_n)$ of $C_p(t)$ is given in nondimensional units and shows large variations with time and has a random appearance. For mode 2 based on results for 25 time steps, $\mathrm{SP}(t, f_2)$ varies from a maximum of 0.013 to a minimum of 0.001. If we consider all 508 time steps, it is possible that higher and lower values of $\mathrm{SP}(t, f_2)$ may be detected. We note that Fig. 2 does not show mode 2 to completely vanish. Mode 3 is considerably weaker than mode 2, and $\mathrm{SP}(t, f_3)$ varies from a maximum of 0.0025 to approximately 0. There are at least five time steps out of the 25 shown for which, for all practical purposes, we can assume mode 3 to be absent.

The spacing of the vortices from Eq. (1) is $\lambda_n/L = k/St_n$. For configuration 1, $\lambda_2/L = 0.83$ and $\lambda_3/L = 0.53$ for modes 2 and 3, respectively. Rossiter's [3] model requires vortices to be spaced either at λ_2 or λ_3 apart, and hence only one mode is present at resonance conditions. Schlieren photographs [8] taken of the shear layer for a cavity with $L/D = 2$ at $M = 0.4$ clearly showed the large coherent structures (or vortices) with spacing corresponding to one value of the wavelength λ_n ($n = 1$, 2 or 3) at different instances of time. The mode-switching phenomenon was also observed by Kegerise et al. [8], who found from pressure measurements that multiple modes were present almost all the time. In our experiments we found that when either mode 2 or mode 3 was the dominant mode, the other mode was usually much weaker. Even though the shear-layer vortical structure allowed only one resonance mode at any instant of time, the presence of two simultaneous modes leads us to believe that the weaker mode cannot be sustained. It will eventually be dissipated and only one mode will be present, provided that the vortex spacing does not change.

When the shear layer is perturbed, for example, by the passage of a store when released from the weapons bay, the acoustic waves inside the cavity will be affected as well. In an approximate simulation, the stores were assumed to be stationary at the shear layer, for maximum perturbation. The rods were attached at the rear wall in configuration 2 and the lengths $(0.43L)$ were $0.51\lambda_2$ and $0.81\lambda_3$, respectively. Two other lengths of $0.143L$ and $0.286L$ were also tested, and the results were similar but less dramatic than those shown in Fig. 3.

The frequencies of modes 2 and 3 are nearly the same as those in configuration 1. However, the amplitude of $\mathrm{SP}(t, f_n)$ ($n = 2$, 3) is greatly affected. For the 25 time steps shown in Fig. 3, the frequency of occurrence when either mode dominated over the other is approximately equal. The maximum value of $\mathrm{SP}(t, f_2)$ is 0.0046 and 0.006 for $\mathrm{SP}(t, f_3)$. Most of the time one mode dominated over the other by a substantial amount in the $\mathrm{SP}(t, f_n)$ values, but there are a few occasions when both $\mathrm{SP}(t, f_2)$ and $\mathrm{SP}(t, f_3)$ are approximately of the same order of magnitude. The minimum values of $\mathrm{SP}(t, f_2)$ and $\mathrm{SP}(t, f_3)$ for the given 25 steps are approximately 0 and 0.00025, respectively. Comparison with configuration 1 shows that the maximum $\mathrm{SP}(t, f_2)$ is decreased by a factor of 0.35, whereas $\mathrm{SP}(t, f_3)$ is increased by a factor of 2.4. For stores carriage inside the weapons bay, it may be an advantage to transfer some energy to another mode while keeping the amplitude of both modes to be approximately the same but at a reduced value.

The $\mathrm{SP}(t, f_n)$ results for configuration 3 are shown in Fig. 4. The frequencies for modes 2 and 3 are approximately the same as the previous two configurations. Most of the time, the maximum $\mathrm{SP}(t, f_2)$ is at a level below 0.005, except for a spike at $t = 1.508$ s when the value of $\mathrm{SP}(t, f_2)$ is approximately 0.0105. Taking this value of $\mathrm{SP}(t, f_2)$ to be the maximum, $\mathrm{SP}(t, f_2)$ decreases by a factor of 0.8 relative to the same mode in configuration 1. By observing the full 508 time steps output from the computer code, it can be seen that this spike occurred about 10–15% in a period of 4.2325 s. The maximum $\mathrm{SP}(t, f_3)$ is larger by a factor of 1.5 than the corresponding mode in configuration 1. Comparing the results for configurations 2 and 3, we observe that configuration 2 is more effective at reducing the maximum strength of mode 2, but at the expense of a larger gain in mode 3.

The above deductions are based on observations of a very small sample of the STFT spectrogram. An alternative approach to estimate the effect of the rods is to compare time-averaged properties from the measured pressure signals. We applied a Hanning window to the

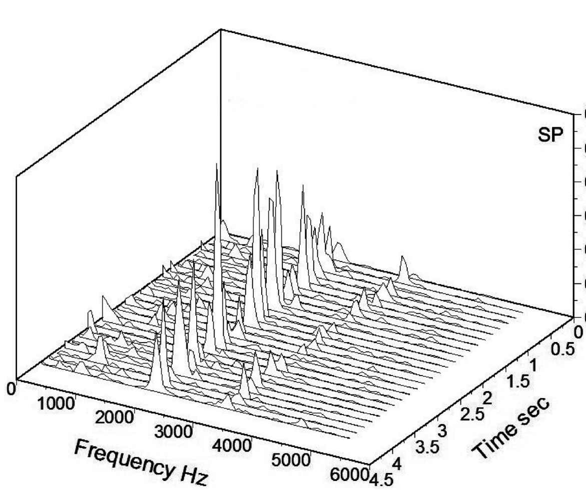

Fig. 2 Spectrogram for configuration 1 (clean cavity).

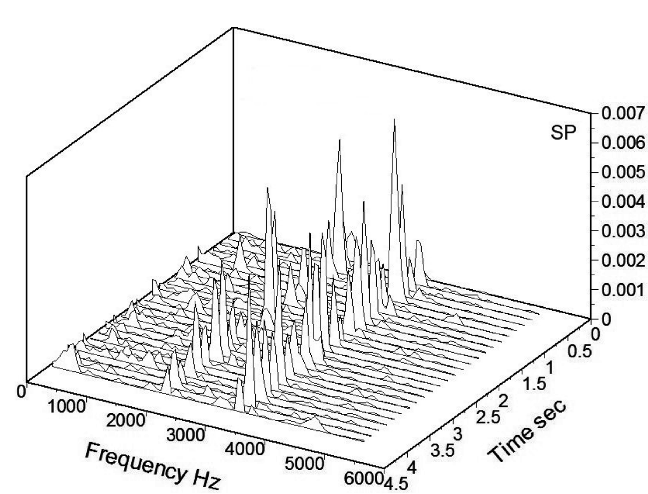

Fig. 3 Spectrogram for configuration 2 (rods attached to cavity rear wall).

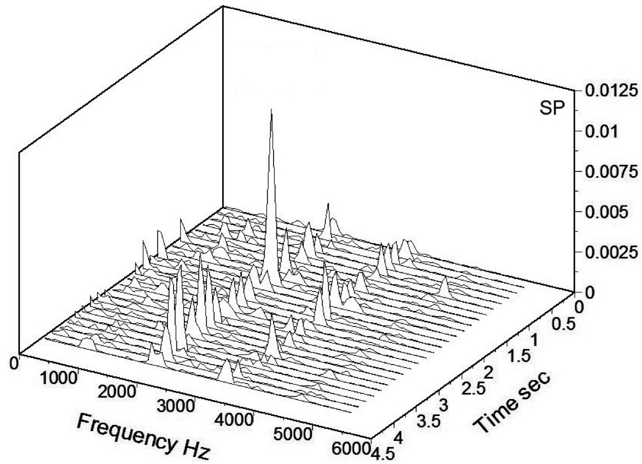

Fig. 4 Spectrogram for configuration 3 (rods attached to cavity front wall).

$C_p(t)$ time series and performed fast Fourier transform (FFT) using LabVIEW to compute the nondimensional modal pressure amplitude. The FFT block size used was 2048 with an overlap of 50%. The frequency resolution was 7.32 Hz. For configurations 1, 2, and 3, the nondimensional pressure amplitudes of mode 2 are 0.0409, 0.0196, and 0.0289, respectively; for mode 3, the amplitudes are 0.0153, 0.0287, and 0.0136, respectively. For rear-wall-mounted rods, the amplitude of mode 2 is reduced by a factor of 0.48, but mode 3 is increased by a factor of 1.87. For front-wall-mounted rods, modes 2 and 3 decrease by a factor of 0.7, and 0.88, respectively, compared with the clean-cavity values. Except for mode 3, the trend of the amplitude changes is consistent with observations from the STFT spectrograms.

IV. Conclusions

In conclusion, we find that perturbing the shear layer by placing rods at the front and rear walls of a rectangular cavity is an effective way to modify the intensity of the acoustic waves. For the clean cavity with L/D and L/W ratios of 5 and Mach number 0.86, mode 2 is the dominant mode with a much larger amplitude than mode 3. However, by disturbing the shear layer with rods approximately half of the cavity length, we find that attaching rods at the rear wall can reduce mode 2 amplitude at the expense of an increase in mode 3 amplitude. On the other hand, rods placed at the front wall reduce mode 2 amplitude by a lesser amount than in the configuration with rear-wall-attached rods, but mode 3 amplitude is smaller. Mode-switching occurs in all three configurations.

References

[1] Krishnamurty, K., "Acoustic Radiation from Two-Dimensional Rectangular Cutouts in Aerodynamic Surfaces," NACA TN-3487, 1955.

[2] Roshko, A., "Some Measurements of Flow in a Rectangular Cutout," NACA TN-3488, Aug. 1955.

[3] Rossiter, J., "Wind-Tunnel Experiments on the Flow Over Rectangular Cavities at Subsonic and Transonic Speeds," Aeronautical Research Council Reports and Memorandum No. 3438, London, Oct. 1964.

[4] Bilanin, A. J., and Covert, E. E., "Estimation of Possible Excitation Frequencies for Shallow Rectangular Cavities," *AIAA Journal*, Vol. 11, No. 3, 1973, pp. 347–351.
doi:10.2514/3.6747

[5] Tang, Y. P., and Rockwell, D., "Instantaneous Pressure Fields at a Corner Associated with Vortex Impingement," *Journal of Fluid Mechanics*, Vol. 126, Jan. 1983, pp. 187–204.
doi:10.1017/S0022112083000105

[6] Lee, B. H. K., Orchard, D. M., and Tang, F. C., "Flow Past a Yawed Rectangular Cavity in Transonic and Low Supersonic Flows," *Journal of Aircraft*, Vol. 46, No. 5, 2009, pp. 1577–1583.
doi:10.2514/1.40729

[7] Heller, H., and Bliss, D., "Aerodynamically Induced Pressure Oscillations in Cavities: Physical Mechanisms and Suppression Concepts," U.S. Air Force Flight Dynamics Lab. TR-74-133, Wright-Patterson AFB, OH, Feb. 1975.

[8] Kegerise, M. A., Spina, E. F., Garg, S., and Cattafesta, L. N., III., "Mode-Switching and Nonlinear Effects in Compressible Flow Over a Cavity," *Physics of Fluids*, Vol. 16, No. 3, 2004, pp. 678–687.
doi:10.1063/1.1643736