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Engineering Notes

Effect of Captive Stores on Internal Weapons Bay Floor Pressure Distributions

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Introduction

THE new generation of stores to be used on the F-22 and joint strike fighter (JSF) are designed as efficiently packaged, small, highly lethal minimissiles. Because of their lighter weights and smaller moments of inertia, these small smart bombs (SSB) are more easily perturbed by flowfield effects than heavier stores carried externally in older aircraft. This can result in unsafe separations and targeting inaccuracies. For this reason, the majority of studies on internal weapons bays are focused on the stores' separation problem. A recent investigation on wind-tunnel and flight-test comparisons is given by Grove et al. [1]. However, aircraft weapons bays exposed to high subsonic or supersonic flows are subjected to an intense aeroacoustic field inside the bay. The M219 cavity [2] is often used as a test case for computational fluid dynamic (CFD) and wind-tunnel test comparisons. For a length-to-depth ratio of 5, Lee et al. [3] measured the frequency of the pressure oscillations on the cavity floor. The frequency for the first three modes at a Mach number of $M = 1.11$ when scaled to a typical weapons bay of 13 ft length gives values for $f_1 = 23$ Hz, $f_2 = 56$ Hz, and $f_3 = 90$ Hz, respectively. The large pressure oscillations at these low frequencies can lead to structural fatigue of the weapons bay walls and damages to the stores and electronic equipment. Data on the effect of small stores typical of the dimensions of the SSB on the unsteady pressure inside a weapons bay are lacking. This paper presents some preliminary results on the floor pressure measurements of a generic weapons bay for small stores at forward- and aft-release positions. The perturbations introduced by the stores are found to cause significant changes in the acoustic wave intensities inside the M219 cavity.

Experimental Setup and Instrumentation

We conducted our investigation using the M219 [2] deep cavity configuration. The dimensions of the cavity were as follows: 3.75 in. length L, 0.75 in. span W, and 0.75 in. deep D, giving a ratio of 5 for both L/D and L/W. The test assembly consisted of a 13.45 in. boundary-layer development plate, which spanned the full width of one side of the working section of the wind tunnel. When installed, the test plate assembly replaced one of the perforated walls and was held 0.5 in. above the nominal floor position to ensure the test plate was outside of the oncoming boundary layer. The front wall of the cavity was located at 5.8 in. from the leading edge of the development plate. The boundary layer was tripped at 1 in. downstream of the flat plate leading edge to promote a turbulent boundary-layer development at the cavity location. The displacement thickness δ^*/D measured by a pitot probe was 0.0213. The tests were conducted in the 5-in. trisonic wind tunnel at the Institute for Aerospace Research, National Research Council, Canada at a test Mach number of 0.861 and $Re_D = 1.72 \times 10^5$. The Reynolds number is defined as $Re_D = UD/\nu$, where U is the freestream velocity and ν is the viscosity. Mach number was controlled through adjustment of a control value where total pressure could be set to an accuracy of 0.01 psi. Test section flow was measured with the cavity closed by moving the floor up to flush with the development plate. The Mach number was repeatable within ± 0.0018 based on a 95% confidence level. A detailed description of the model, test facility, and instrumentation is given in [3].

Figure 1 shows the locations of the fast-response pressure transducers inside the cavity. Only floor pressure measurements along the cavity centerline from transducers 2–13 are presented in this paper. Transducer 2 was located at $x/L = 0.05$ from the cavity front vertical wall. The spacing between transducers was $x/L = 0.08$ except for transducers 5 and 11 where the spacing was $x/L = 0.09$. The frequency response of the transducers was about 20 kHz and calibration showed a practically flat response up to a test frequency of 6 kHz. Data from the pressure transducers were sampled at 15 kHz for 5 s following low-pass filtering at 5 kHz using an eighth-order Butterworth filter. The measured pressure $p(t)$ was expressed in coefficient form as $C_p(t) = [p(t) - p_\infty]/q$, where $q = 1/2\rho U^2$ and ρ is the air density The pressure fluctuations on the development plate centerline were measured by transducers 2–13 with the cavity closed. The maximum difference in $C_{p_{\rm rms}}$ for two identical runs at $M = 0.861$ was less than 0.4%.

The stores were represented by 0.125 in diameter rods ($d = 0.167D$) of lengths $l = 0.286L$ and $0.43L$ giving $l/d = 8.6$ and 12.9, respectively. These values of l/d were close to those for the Mk83 bomb and the SSB tested by Grove et al. [1]. The rods were 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 rods. This is a crude approximation for actual stores released in the front and rear section of a weapons bay.

Figure 2a shows two rods of length $0.43L$ attached to the cavity front wall with their centers located at $0.25W$ on either side of the centerline. The rods were positioned so that they were inside the cavity (centerlines at $y/D = 0.36$). Figure 2b shows the rods attached at the rear. These two configurations are useful in separating the effect of forward- and aft-mounted stores in perturbing the flow inside the cavity. Figure 2c shows four rods of length $0.43L$ attached to the cavity front and rear walls.

Time-averaged statistical analyses were carried out on the instantaneous C_p time series using a fast Fourier transform (FFT) algorithm from LabVIEW. In computing the modal frequencies and the amplitude of the pressure, 4.2325 s of data were analyzed and there were 63,488 samples. A Hanning window was applied to the time series and the frequency resolution was 7.32 Hz. The FFT block size was 2048, and using an overlap of 50%, the number of averages in the FFT was 61. At the open cavity resonant frequencies, the maximum spectral values for the closed cavity were less than 1% of those for the open cavity.

At $L/W = 5$, the flow inside the cavity is three-dimensional. Centerline pressures still give a very good indication of the cavity characteristics. Plentovich [4] showed for a cavity with $L/W = L/D = 4.4$ at $M = 0.95$, the spanwise variations in pressure were small. Even the pressures on the sidewalls were close to those on the cavity floor.

Results and Discussion

Existing theories on cavity flows [5,6] can predict modal frequencies quite accurately. However, the amplitude of the acoustic

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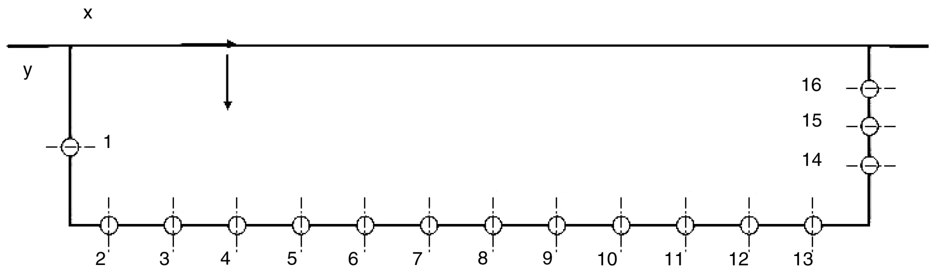

Fig. 1 Location of transducers.

waves cannot be determined. A drawback of these early studies is that the flow inside the cavity was not included in the analysis. Investigations by Lin and Rockwell [7] and Pereira and Sousa [8] showed that for low-speed flows there is strong evidence that the recirculating vortices inside a cavity and the shear layer are coupled. At high-speed flows, perturbing the flow inside the cavity disturbs the shear layer, which in turn will affect the acoustic waves generation.

Figure 3 shows the steady pressure distributions C_p on the cavity floor at $M = 0.861$ for the two stores lengths and locations shown in Fig. 2. The empty cavity results are included for reference. We see that forward positioning of the stores has a smaller effect on the C_p distributions than aft-positioned stores. For aft-mounted stores, the pressures on the cavity floor for $x/L > 0.6$ are substantially smaller than the empty cavity case. Previous studies by Dunn et al. [9] on the same cavity configuration at low-speed flows showed the existence of two recirculating vortices with the rear one being larger and more dominant. The results from Pereira and Sousa [8] also showed two vortices inside the cavity. The effects of stores are mostly felt at the rear section of the cavity where the velocity of the inflow at the rear corner of the cavity from shear-layer impingement is much higher than the velocity induced by the front vortex. We note that the flow blockage was 33.3% for the two stores' configuration.

Stallings et al. [10] carried out wind-tunnel tests for shallow and deep cavities at a Mach number range from 0.2 to 0.95. For a cavity with $L/D = 5.42$ close to our case, but with $W/D = 2$, they measured steady floor pressures for a long store with $l/d = 20.1$. The store model was a generic missile consisted of a body of revolution with an ogive nose and cylindrical afterbody mounted on a blade-strut assembly attached to the cavity floor. The nose of the store was located at $x/L = .0461$ from the cavity front wall, and the base at $x/L = 0.974$. Thus, we see that the store practically filled the length of the cavity. With the centerline of the store inside the cavity at $y/D = 0.625$, they found the store altered the C_p distributions only slightly compared with those where the store was place outside of the cavity ($y/D = -0.48$). This is quite different from our observations with shorter stores, which have a much larger effect on perturbing the rear recirculating vortex and hence the velocity and pressure. We note that the blockage due to a single store for a wider cavity in Stallings et al. [10] experiments was only 12.5%, and hence the influence on the mean C_p distributions was smaller.

Figure 4 shows $C_{p_{\mathrm{rms}}} = p_{\mathrm{rms}}/q$ for the forward- and aft-mounted stores. The effect of l/d is not large, but the pressure oscillations are greatly enhanced by the forward stores. The increase in $C_{p_{\mathrm{rms}}}$ at transducer 13 ($x/L = 0.95$) is 10 and 12.9% above the empty cavity values for the front-mounted stores with $l/d = 12.9$ and 8.6, respectively. For the rear- mounted stores, there is a decrease of about 20% for both stores. We note there is hump in the $C_{p_{\mathrm{rms}}}$ curves centered about midcavity at transducer 7 ($x/L = 0.459$). The front-mounted stores show, again, an increase in the pressure oscillation's intensity, and the increase above the empty cavity measurements is 15.2 and 19.5% for $l/d = 12.9$ and 8.6, respectively. The corresponding decrease in $C_{p_{\mathrm{rms}}}$ for the same two stores mounted at the rear is 12.1 and 13.8%, respectively.

The hump in the $C_{p_{\mathrm{rms}}}$ curves shown in Fig. 4 is due to pressure oscillations from the acoustic waves. FFT analysis of the C_p time series showed four distinct acoustic modes at frequencies $f_1 = 725$ Hz, $f_2 = 1950$ Hz, $f_3 = 3200$ Hz, and $f_4 = 4420$ Hz, which are close to those calculated using Rossiter's [5] empirical formula. The amplitudes of modes 1 and 4 are very small compared with the

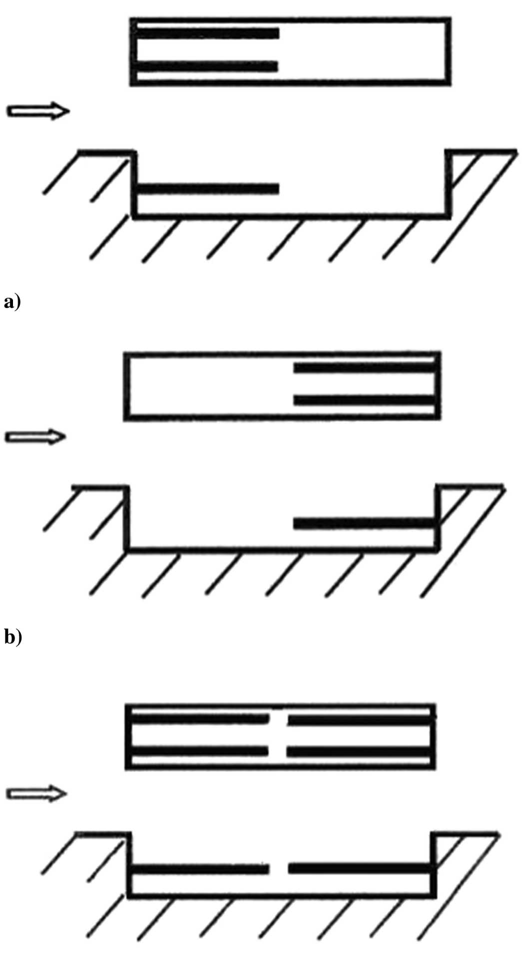

Fig. 2 Arrangement of stores inside cavity.

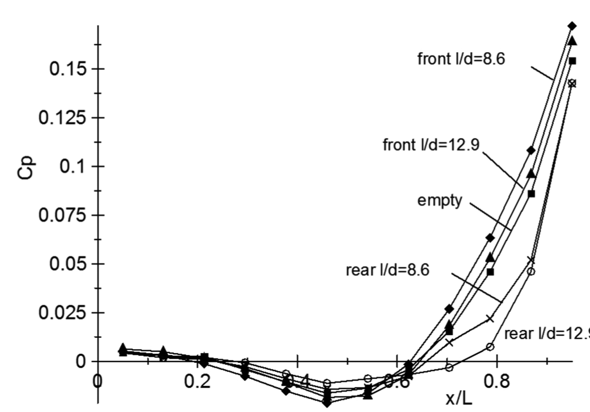

Fig. 3 C_p distributions on cavity floor at $M = 0.861$.

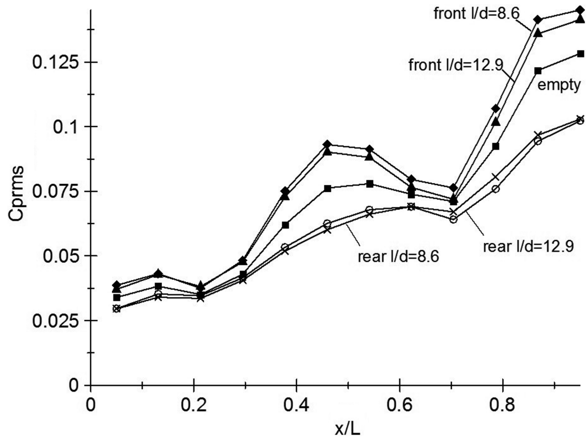

Fig. 4 $C_{p_{\rm rms}}$ distributions on cavity floor at $M = 0.861$.

dominant mode 2, and we only show the standing wave mode shape for modes 2 and 3 in Fig. 5. The C_p amplitude was obtained from FFT transform of the C_p time series. We see there is a hump centered around midcavity for mode 2, and the acoustic waves contribute significantly to the $C_{p_{\rm rms}}$ shown in Fig. 4. The effect of l/d is not large, but the positions of the stores have a large effect on changing the acoustic wave intensity of mode 2. Front-mounted stores increase the amplitude for mode 2, whereas rear-mounted stores decrease the amplitude. For mode 3 the opposite is true, though the front-mounted stores have only a very small influence on the mode amplitude. It appears that the front-mounted stores are more effective in perturbing the flow at the cavity leading edge, so that the development of shear-layer vortices is favorable to the excitation of mode 2. On the other hand, the rear stores disturb the shear flow downstream closer to the cavity rear wall, and this may be more effective in exciting the third mode. Similar to rear-mounted stores, the impingement edge geometry can also affect cavity flow oscillations by altering the flow at the rear wall [11].

Shaw et al. [12] tested advanced medium range air-to-air missiles (AMRAAMs) inside a generic cavity installed on a 4.9% model of the F-111. A deep cavity with $L/D = 6.79$ was instrumented with four unsteady transducers at $x/L = 0.07$, 0.52, 0.74, and 0.97 to measure the acoustic spectra. The diameter of the missiles was not given in the paper, but we estimated it from their sketch of the missile and deduced an l/d ratio of between 17 and 20. The l/L ratio of the AMRAAM was 0.925. As in Stallings et al.'s [10] model, the store nearly filled up the length of the cavity. Only very limited results were given for the unsteady pressures. For two side-by-side AMRAAM stores in the bay, but with only one being moved, the halfway outstore position resulted in the lowest pressure level. The highest level occurred when the store was out of the bay and not interacting with

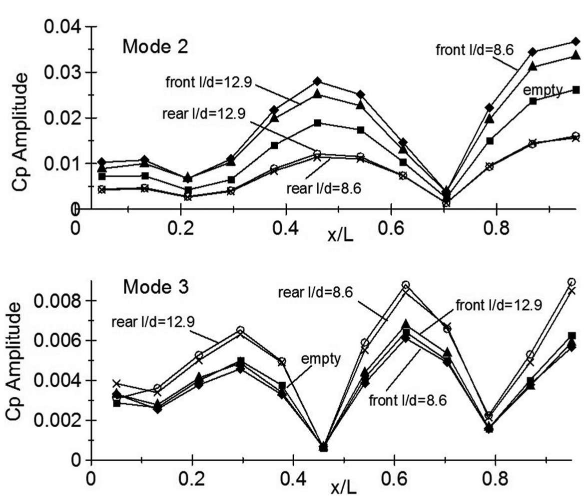

Fig. 5 Amplitude of modes 2 and 3 on cavity floor for $M = 0.861$.

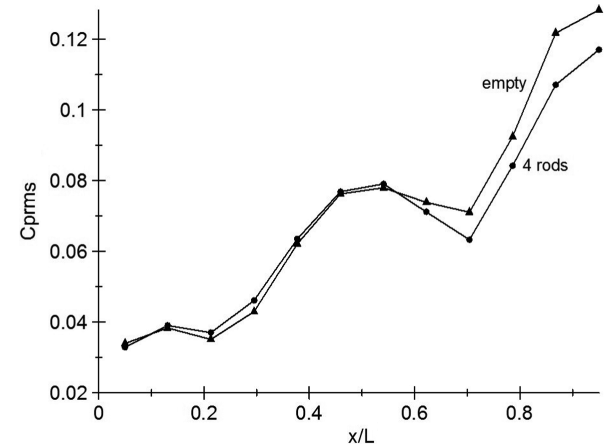

Fig. 6 Comparison of $C_{p_{\rm rms}}$ distributions on cavity floor between empty cavity and configuration *c*.

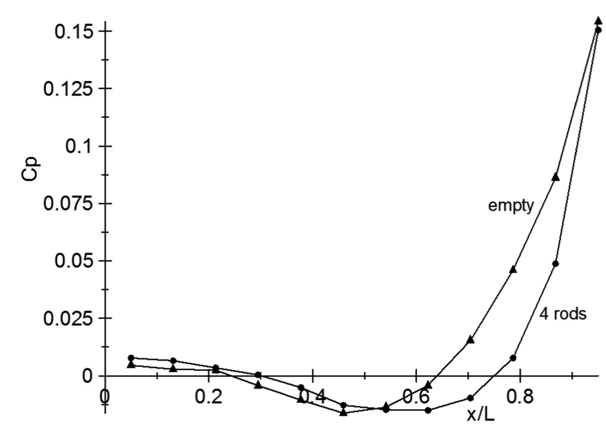

Fig. 7 Comparison of C_p distributions on cavity floor between empty cavity and configuration *c*.

the shear layer. Shaw et al. [12] attributed this observation to the ability of the half-out position store in suppressing the shear-layer instability. We carried out a test by mounting four $l/d = 12.9$ stores on the front and rear cavity walls at $y/D = 0.36$. This is somewhat similar to the two AMRAAM missiles in the Shaw et al. [12] investigation, except for a gap in the middle with spacing of $0.16L$. The $C_{p_{\rm rms}}$ distributions along the floor are shown in Fig. 6. The results were much closer to the empty cavity case than when only two stores were placed either at the forward or aft positions. We found the ability of the forward- and aft-mounted stores in increasing or decreasing $C_{p_{\rm rms}}$ cancelled each other. The $C_{p_{\rm rms}}$ for the four stores' configuration was practically similar to the empty cavity values for $x/L < 0.54$. For $0.54 < x/L < 0.95$, $C_{p_{\rm rms}}$ was lower with a maximum decrease of 9% at $x/L = 0.95$. This has some similarities to the Shaw et al. [12] results. The steady C_p distributions are shown in Fig. 7. The rear-mounted stores exerted a dominant effect. The C_p values for two rear stores (Fig. 3) and four stores were very close except for x/L between 0.45 and 0.78, where the four stores gave lower C_p values than the two rear stores.

Conclusions

The results in this investigation showed that forward-mounted SSB affected the steady C_p on the cavity floor only slightly. However, the acoustic mode 2 was strongly amplified with a resulting large increase in $C_{p_{\rm rms}}$ values. Aft-mounted stores reduced the C_p on the rear portion of the cavity. The amplitude of mode 2 was significantly reduced at the expense of a small increase in mode 3 amplitude. The unsteady load on the cavity floor was decreased, especially at the middle of the cavity. When buffeting of a weapons bay is an issue, aft-mounted stores have an advantage in decreasing the unsteady loads.

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