INFLUENCE OF CAPTIVE STORES ON THE UNSTEADY PRESSURE DISTRIBUTION WITHIN A RECTANGULAR CAVITY

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Keywords: *Cavity Flow, Store Release*

Abstract

Wind tunnel tests have been performed to examine the influence of stores positioned inside a rectangular cavity on the time-averaged fluctuating flow field. Tests performed with the baseline empty cavity at Mach numbers of 0.6, 0.85 and 1.11 show the first four acoustic tones, associated with cavity flows of this type, are present. The frequencies of these tones correspond to those predicted by established semi-empirical (Rossiter) formula. Acoustic tones are seen to become more distinct at the higher Mach Numbers.

Tests, repeated at Mach 0.85 with stores positioned in the cavity, show the unsteady pressure profiles along the cavity floor have been changed. Positioning stores either in the upstream or downstream region close to the top of the cavity is shown to reduce the overall unsteady pressure distribution. Examination of the acoustic tones demonstrates that, while all periodic pressure fluctuations have been altered, the reductions in unsteady pressure levels are attributable to the changes in the second mode of periodic fluctuations.

By positioning the stores lower in the cavity, only the second acoustic mode is seen to be changed. In some instances this leads to increases in the unsteady pressure levels when compared to the empty cavity.

1 Introduction

The new generation of military aircraft are adopting the concept of internal stores carriage to reduce drag, enhance maneuverability and minimize radar cross-section. Despite the advantages offered, however, the flow field associated with a cavity open to a high subsonic, transonic or supersonic freestream presents a number of challenges for the safe carriage and release of stores. These include the requirement for detailed knowledge of the interaction of stores with the shear flow spanning the cavity to enable estimation of the normal force and pitching moment on the stores during the early part of the release phase. These provide the initial conditions for computing the store's trajectory. Furthermore, the structural integrity of stores is of concern whenever conditions favor the generation of intense acoustic waves. In the present study, the influence of simulated captive stores on the unsteady flow profiles throughout a cavity are investigated. Various locations for positioning the stores have been chosen to examine their influence on the cavity flow field and the generation of acoustic tones.

The cavity used in this study has a Length to Depth (L/D) and Length to Width (L/W) ratio of 5 and was chosen to coincide with that given by Henshaw [1] for the M219 cavity. This represents an 'open cavity' configuration where the incoming boundary layer separates at the upstream lip resulting in a free shear layer, containing spanwise instabilities, that reattaches either downstream of, or on, the rear wall of the cavity. The interaction of the shear layer with rear wall acts as the primary acoustic source [2] and the generated oscillating pressure waves are fed upstream to the point of the original disturbance (the cavity lip). Here they force the shear layer, setting the initial amplitude and phase of the instability waves [2]. This feedback mechanism leads to an increase in the disturbance waves at frequencies dictated by the characteristic pressure patterns (mode shapes) within the cavity [3].

Numerous investigations have been performed into the characteristics of cavity flows to examine the parameters that affect the magnitude and frequencies of the acoustic tones. While, techniques have been developed to accurately predict the frequencies of the periodic pressure waves [4][5], methods of determining their magnitude are less satisfactory. These appear to be more dependant upon factors such as the condition of the incoming boundary layer, boundary layer thickness to cavity depth ratios, e.g., δ^*/D and the freestream Mach Number. For a comprehensive review of the many studies conducted into cavity flows and the parameters that affect the flow field, readers are referred to review papers of Rockwell and Naudascher [6] and Komerath *et al*. [7].

In the experimental study described here, the cavity was instrumented with 16 fast-response pressure transducers positioned on the fore and aft walls and along the length of the cavity floor. This enabled high-resolution measurements of the full unsteady pressure field within the cavity to be measured. Initial tests were performed using an empty cavity at freestream Mach numbers of 0.6, 0.85 and 1.11 to obtain mean and unsteady pressure distributions. Periodic pressure fluctuations associated with the first four acoustic tones were seen to exist in all cases. Magnitude of the tones was seen to be influenced by the freestream Mach number.

To examine the influence of stores positioned inside the cavity on the mean and unsteady flow fields, tests were repeated using four store/cavity configurations. For these cases, tests were performed at Mach 0.85 and results directly compared to those from the empty cavity. The configurations were chosen to simulate the conditions of 1) the stores just as they are about to be released from the cavity and 2) in a carriage position. The effect of positioning the stores in both the upstream and downstream sections of the cavity is provided. Analysis of the pressure signals is performed to examine the influence of the stores on the unsteady pressure field and how their inclusion in the cavity modifies the acoustic tones.

2 Experimental Set-up

The tests were conducted in the 5-inch tri-sonic wind tunnel at the Institute for Aerospace Research, National Research Council, Canada. This tunnel is blowdown facility with a Mach number range from 0.1 to 4.0. When air supply is provided by the main 50,430ft^3 storage tanks this tunnel is capable of almost continuous operation. For the present study, however, air supply was provided by the auxiliary high pressure system resulting in run times of approximately 10 seconds.

When operating in the transonic regime the 5” square working section is fitted with perforated walls. The test assembly used consisted of a 13.45” boundary layer development plate which spans the full width of one side of the working section. When installed, the test plate assembly replaces one of the perforated walls and is held 0.5” above the nominal floor position to ensure the test plate is outside of the oncoming boundary layer. Flow was allowed to pass underneath the test plate to ensure test section blockage was kept to a minimum. A schematic view of the test plate and cavity is given in Fig. 1.

Flow conditions are controlled through adjustment of the control value positioned upstream of the settling chamber in combination with diffuser entry flaps and throat settings downstream of the working section. Total pressure within the settling chamber was monitored by a Digiquartz pressure transducer with an accuracy of better than 0.01 psi. Working section static pressure was measured by a Sensym ASCX15 15psid pressure transducer attached to a static pressure tap installed 2” downstream from the leading edge of the boundary layer development plate. Static pressure measurement was calibrated against a Druck pressure unit.

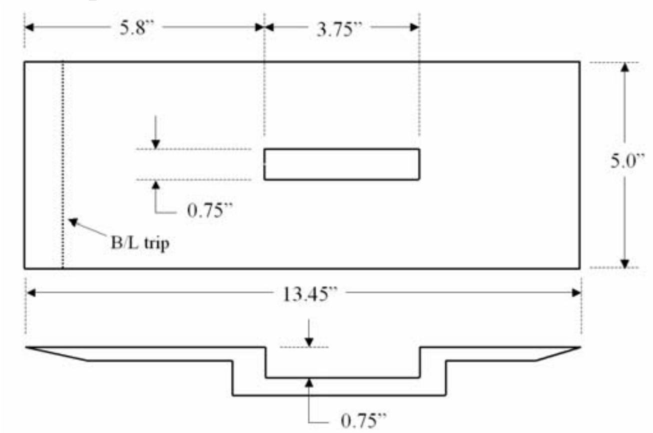

Fig. 1. Schematic of cavity test plate.

Prior to the start of the test program, test section flow (with cavity plate installed) was verified using the development plate static pressure measurement in combination with a total pressure probe installed in the working section. A series of 24 runs yielded a mean Mach number of 0.853 with a repeatability of ± 0.0018 based on a 95% confidence level. Similarly, above sonic conditions a mean Mach number 1.107 was attained with a repeatability of ±0.0053.

The cavity used during this study was 3.75” long, 0.75” wide and had its front lip 5.8” downstream from the leading edge of the development plate. An array of 0.002” turbulence trips spaced at 0.1” intervals was positioned 1” downstream from the leading edge to promote a turbulent boundary layer at the cavity location. Boundary layer thickness, δ, at Mach 0.85, obtained from a pitot probe traverses 0.25” upstream of the cavity front lip, was found to be 0.095” with a displacement thickness, δ*, of 0.016”.

The cavity base was adjustable to provide a range of L/D settings and was installed in a turntable assembly to allow yaw angles up to 25^o. For the present study, however, all tests were conducted at 0^o yaw with Length/Width (L/W) and Length/Depth (L/D) ratios chosen to coincide with those given by Henshaw for the M219 cavity, i.e., L/W = L/D = 5 cavity [1].

For dynamic pressure measurements 16 fast response 25psid XCQ-062 Kulite pressure transducers were placed inside the cavity. As shown in Fig. 2, twelve transducers were evenly spaced on the cavity floor with one on the forward wall and three on the aft wall. Locations of these transducers relative to the forward lip of the cavity are given in Table 1. Data from all pressure transducers was sampled at 15KHz for 5 seconds following low-pass filtering at 5KHz using an 8th order butterworth filter.

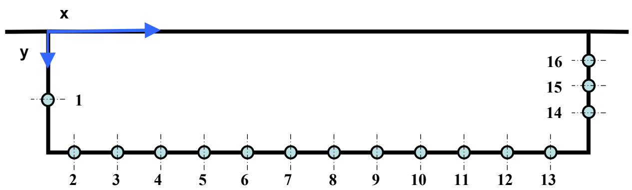

Fig. 2. Kulite pressure transducer locations within cavity (flow is from left to right)

Transducer	x/L	y/D	Location
1	0	0.63	Forward wall
2	0.05	1.0	Cavity floor
3	0.13	,,	,,
4	0.21	,,	,,
5	0.3	,,	,,
6	0.38	,,	,,
7	0.46	,,	,,
8	0.54	,,	,,
9	0.62	,,	,,
10	0.7	,,	,,
11	0.79	,,	,,
12	0.87	,,	,,
13	0.95	,,	,,
14	1.0	0.75	Aft wall
15	,,	0.5	Aft wall
16	,,	0.27	Aft wall

Table 1. Kulite pressure transducer positions

3 Test cases

Tests were conducted at three Mach numbers of 0.6, 0.85 and 1.11. In all cases, total pressure was adjusted to maintain a Reynolds number of 8.4×10^5 per foot. Tunnel settings yielded dynamic pressures, used to normalize all pressure data, of 6.8psi for Mach 0.6, 9.2psi for Mach 0.85 and 10.8psi for Mach 1.11.

Tests were conducted to investigate mean and fluctuating pressure distributions for various store/cavity configurations. Presented here are the results from the empty cavity case as well as the four store/cavity combinations given in Fig. 3.

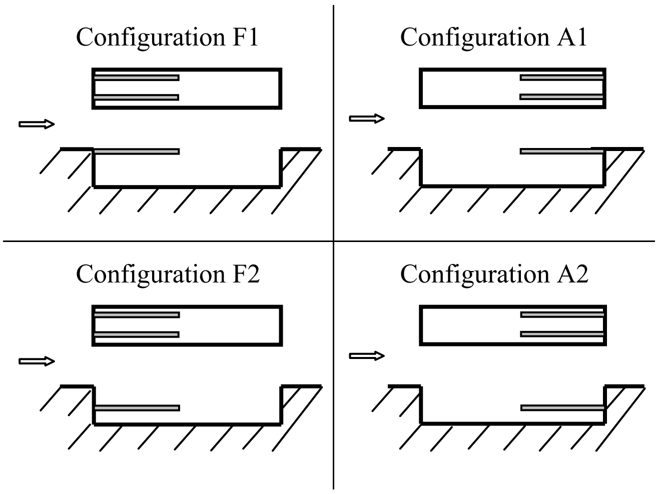

Fig. 3. Store / cavity configurations

The stores were represented by 0.125" diameter rods of length 0.43L attached directly to the cavity forward and aft walls, thus eliminating the need for a mounting system that would cause interference to the flow around the cylinders. While this is a very crude approximation for actual stores released in the fore- and aft-section of the weapons bay, it is useful in separating the effect of the nose and base of a store on the shear layer and the generation of discrete frequency acoustic waves inside the cavity. In all configurations two stores were mounted within the cavity with their centers located at 0.25W either side of the centerline. For configurations F1 and A1 the stores were positioned so that they were just inside the cavity (centerlines at 0.083D) on the forward and aft walls. For configurations F2 and A2 the store/cavity arrangement was repeated with store centerlines positioned lower in the cavity (at 0.36D).

4 Results and Discussion

4.1 Mach Number Effect

To examine the effect of freestream Mach number, tests were performed with the empty cavity at Mach 0.6, 0.85 and 1.11. The corresponding non-dimensionalised rms values of the unsteady pressures along the floor of the cavity, expressed as Cp_{RMS} (p_{RMS}/q), are given in Fig. 4. For Mach 0.6 the rms pressure distribution is seen to increase steadily with increasing streamwise distance. As the Mach number is increased to 0.85 and 1.11, however, a distinct 'hump' in the unsteady pressure distribution is visible between $0.3 < X/L < 0.7$. This is due to the contribution of the periodic frequency components increasing relative to the broadband rms levels as Mach number is increased [4].

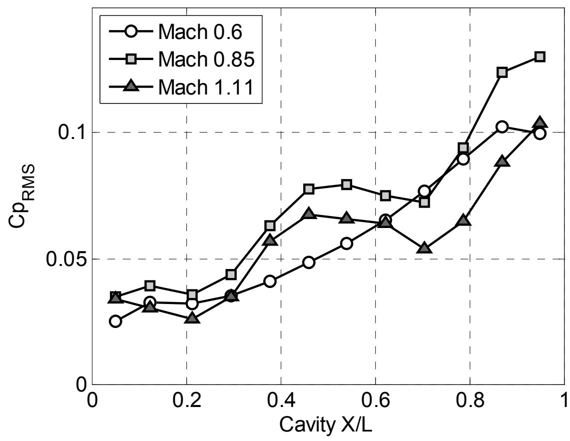

Fig. 4. Effect of Mach number on unsteady pressure distribution in cavity

The incoming boundary layer thickness was nearly constant for all Mach numbers tested yielding a thickness to cavity depth ratio (δ^*/D) of 0.021. This parameter is considered an important factor in the magnitude of the periodic frequencies [4][6][7] with increased amplitudes observed with decrease in boundary layer thickness. It is, therefore, considered that the relatively thin boundary layer in the present study, results in the large distinct periodic pressure fluctuations, relative to the random frequencies, and leads to mode shapes of the dominant frequncies (modes) being visible in the broadband rms pressure distribution.

The effect of increasing Mach number on the periodic components is shown in the spectra of the unsteady pressure fluctuations given in Fig. 5. The fluctuating pressure, non dimensionalised by freestream dynamic pressure (q), was used in the calculation of Power Spectral Densities and presented in terms of dB. MATLAB was used for the calculation of the PSD's, with blocks of 0.068s duration and a 50% overlap. This results in a frequency resolution of 14.6Hz.

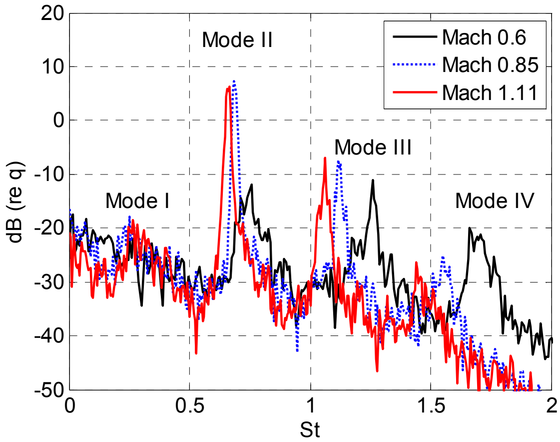

Fig. 5. Effect of Mach number on the amplitude spectra of unsteady pressures: Kulite 16

Clearly visible on Fig. 5 are the peaks corresponding to the periodic pressure fluctuations associated with modes II, III and IV. While mode I is seen, in some cases, this is not always clearly discernable against the random fluctuating signal. The frequencies at which these occur are given in Table 2 and are seen to closely match those provided by the modified Rossiter semi-empirical formula [1][5], i.e.,

$$St_n = \frac{f_n L}{U_\infty} = \frac{(n-\alpha)}{M_\infty\left(1+\frac{\gamma-1}{2}M_\infty^2\right)^{-1/2}+\frac{1}{k}} \qquad (1)$$

Where n is the mode number, M_∞ the freestream Mach number and the coefficients α and k were those reported by Rossiter for a cavity of L/D = 4 as 0.25 and 0.57 respectively.

	Mach Number		
Mode	0.6	0.85	1.11
I	0.27 *(0.32)*	0.25 *(0.29)*	0.26 *(0.27)*
II	0.76 *(0.75)*	0.69 *(0.69)*	0.67 *(0.64)*
III	1.26 *(1.18)*	1.12 *(1.08)*	1.04 *(1.00)*
IV	1.66 *(1.61)*	1.51 *(1.47)*	1.32 *(1.36)*

Table 2. Non-dimensional modal frequencies on cavity aft wall (Kulite 16). Terms in *brackets* relate to predicted frequencies given by Eq. 1

As shown, at Mach 0.6 spectra contain broad peaks and do not display a distinct dominance from one mode to another. As Mach number is increased, however, to 0.85 and 1.11 the peaks are seen to become more defined with increased contribution at the mode II and III periodic frequencies. For both Mach 0.85 and 1.11 mode II is seen to dominate.

4.2 Store / Cavity interactions

Tests were conducted using the four store configurations given in Fig. 3 with freestream Mach number held constant at 0.85. During the tests mean and fluctuating pressure distributions along the floor and on the fore and aft walls of the cavity were obtained.

Configurations F1 and A1

The non-dimensionalized mean pressure ($Cp = p - p_\infty / q$) distributions obtained along the cavity floor with stores positioned in configurations F1 and A1 are given in Fig. 6. For the empty cavity, the mean pressure remains relatively constant along the first half of the cavity floor, followed by a steady increase at X/L > 0.55. This is consistent with mean flow distribution within cavities of similar L/D ratios [4]. While the addition of stores in the configuration F1 did not affect the overall trend of the mean pressure distribution, slight increases in mean pressure for X/L<0.55 and a decrease for X/L>0.55 are observed.

The interaction of the stores with the flow spanning the cavity is seen to have more of an impact on the mean quantity when they are positioned on the rear face as in configuration A1. While the mean pressure distribution within the front region is seen to match closely with that of the empty cavity, as the aft wall is approached greater variation in absolute values are observed. In the region between 0.5 < X/L < 0.8, corresponding to the location of the front face of the stores, there is a localized increase in mean pressure, followed, at X/L > 0.8, by a decrease in pressure.

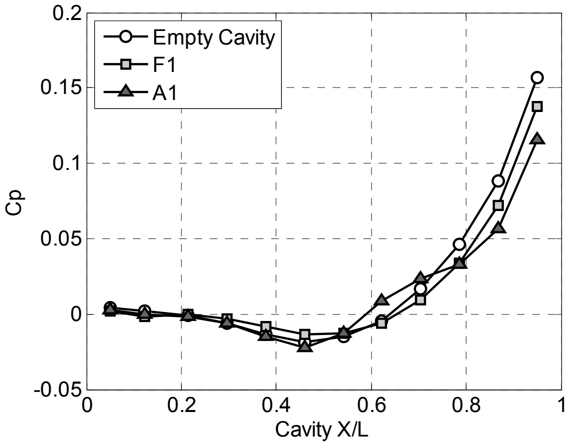

Fig. 6. Effect of store/cavity interaction on mean pressures along cavity floor (Configurations F1 and A1)

The influence of the stores positioned in configurations F1 and A1 on the unsteady pressure profiles is shown in Fig. 7. For both store configurations, unsteady pressure levels were reduced compared to the empty cavity. Although not shown on this figure, Cp_{RMS} levels measured on the rear cavity wall for the empty cavity case, ranged from 0.17 at a depth of 0.75D up to 0.22 close to the top of the cavity (at 0.27D). Similar trends in changes to unsteady pressure distributions due to the addition of stores was seen on the rear wall Cp_{RMS} levels.

More detailed examination of the effects of store location on the periodic fluctuations within the cavity can be obtained from the power spectra of the unsteady pressures as shown in Fig. 8. Here, spectra of the pressure fluctuations obtained on the aft cavity wall (Kulite 16) have been presented as they are representative of the overall pressure signals obtained throughout most of the cavity and provide some of the most distinct periodic fluctuations against the random signal.

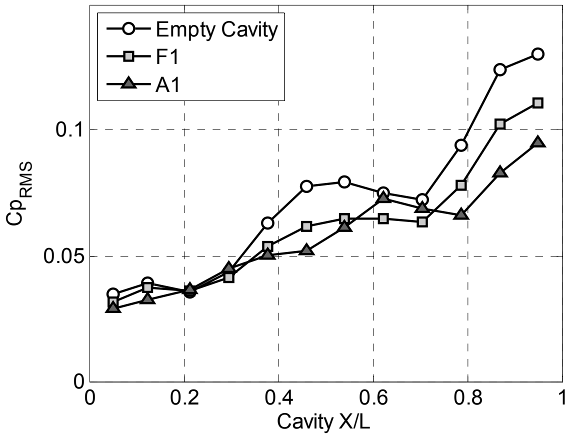

Fig. 7. Effect of stores positioned at top of cavity on unsteady pressure distribution

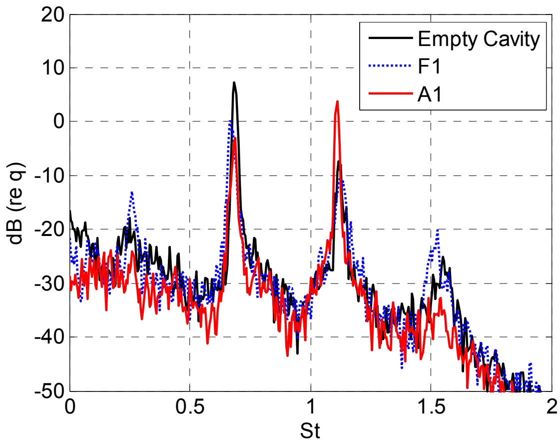

Fig. 8. Effect of stores positioned at top of cavity on amplitude spectra of unsteady pressures: Kulite 16

As shown, the position of the stores alters the contribution of different modes to the overall unsteady pressure levels. With stores positioned on the forward wall (configuration F1) the magnitude of the second mode, seen as the dominant frequency for the empty cavity case, is reduced by approximately 7dB. With only slight modification to the third mode, increases in the first and fourth modes and no changes in amplitude of the random fluctuating signal, the attenuation of the second mode is seen as the major contributing factor to the reduction of the unsteady pressure levels shown in Fig. 7.

For the stores positioned at the top of the aft wall (configuration A1), the amplitude of the second mode is reduced further by approximately 10dB compared to the empty cavity. In this case, however, the presence of the stores on the aft cavity wall, while suppressing mode II frequency components, tends to excite the third mode resulting in increases in amplitude at this periodic frequency of approximately 11dB. This represents a switching of the dominant frequency from mode II to III for this cavity/store configuration. Despite the increase of mode III, the reduction in mode II amplitude, further reductions at modes I and IV and an attenuation of the random signal, contribute to the decrease in the overall unsteady pressure signal shown in Fig. 7 for this case.

To examine the distribution of the periodic frequencies along the floor of the cavity, the pressure signals from each transducer were filtered using a fourth-order bandpass butterworth filter centered around the Rossiter frequencies, identified from Eq. 1, for the modes I to IV. PSD's of the filtered signals enabled acoustic mode shapes to be obtained. Shapes for modes I to III for stores positioned at the top of the fore and aft walls (configurations F1 and A1), compared to the empty cavity, are shown in Fig. 9.

Configurations F1 and A1 would result in a direct interaction of the stores with the shear layer spanning the cavity. As shown in the distribution of the acoustic mode shapes, this interaction influences all periodic frequency components throughout the cavity. Particularly evident is the increase in mode III for configuration A1 where, with the exception of the nodal locations, mode III is shown to be the dominant frequency along the full length of the cavity floor. Also shown, is the increase in Mode I amplitude with stores positioned at the top of the forward cavity wall (configuration F1).

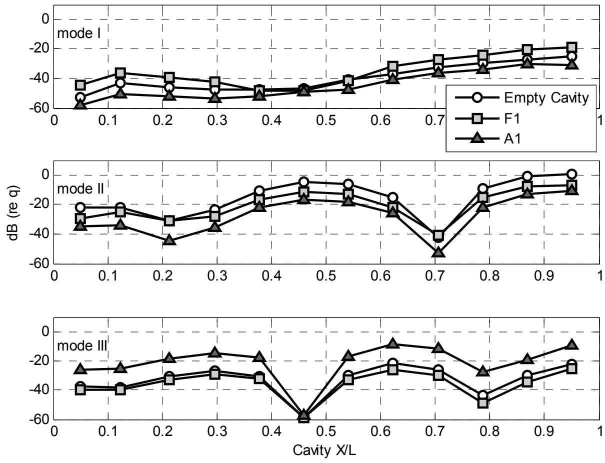

Fig. 9. Effect of store/cavity interaction on modes shapes for configuration F1 and A1.

Positioning the stores in configuration F1, would lead to modification of the upstream region of the shear layer. The effectiveness of this on reducing unsteady rms pressure distributions has been demonstrated through many studies using both passive and active devices. While these are too numerous to provide the full list of devices and studies here, these have included leading edge modification [8] [9], spoilers [1], leading edge blowing [10] and piezo-electric flapping surfaces[11]. A comprehensive survey on the various passive and active flow control techniques has been provided by Cattafesta *et al.* [2] .

For the present configuration, it is considered that the stores positioned in the upstream region would tend to suppress shear layer oscillation and reduce its receptivity to acoustic disturbances from within the cavity and lead to changes in the mass exchange mechanisms at the trailing edge associated with generation of periodic pressure fluctuations [6].

Perturbing the shear layer using stores placed at the top of the aft wall of the cavity (configuration A1), while enhancing mode III pressure fluctuations when compared to an empty cavity, provided the greatest overall reduction in rms pressure fluctuations observed for all cases. Here, the presence of the stores has directly affected the interaction of the shear layer with the trailing edge and, as with the shear modifications provided by configuration F1, has modified the mass exchange mechanism between the cavity and freestream. Directly suppressing these interactions, as with trailing edge geometry modifications examined by Franke [8], Zhang [9] and Heller [12], is seen as an important factor in the control of the periodic pressure fluctuations [6].

Configurations F2 and A2

The non-dimensionalized mean pressure distributions obtained along the cavity floor with stores positioned in configurations F2 and A2 are given in Fig. 10. Positioning stores lower on the forward wall (configuration F2) are shown to have little effect on the mean pressure distribution compared to the empty cavity case. Positioning stores lower on the aft wall however, as in configuration A2, appears to have more effect on the recirculation within the cavity resulting in a reduced length of the high pressure region upstream of the aft wall.

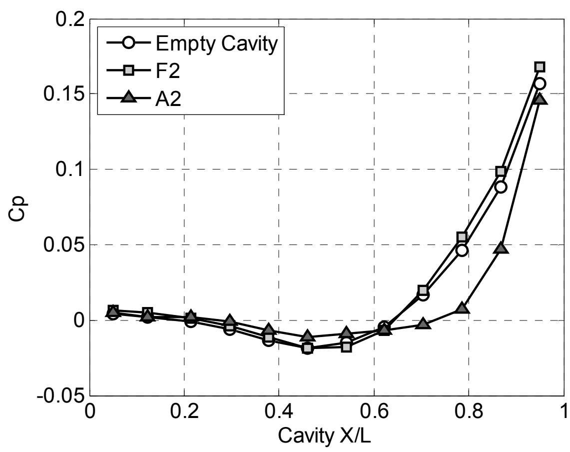

Fig. 10. Effect of store/cavity interaction on mean pressures in cavity

The influence of the stores positioned in configurations F2 and A2 on the unsteady pressure distribution is shown in Fig. 11. For configuration A2, the reduction in Cp_{RMS} levels throughout the cavity are similar to those observed for the configuration A1. For configuration F2, however, positioning the stores lower in the cavity on the forward wall significantly increases the unsteady pressures to above those observed for the empty cavity case.

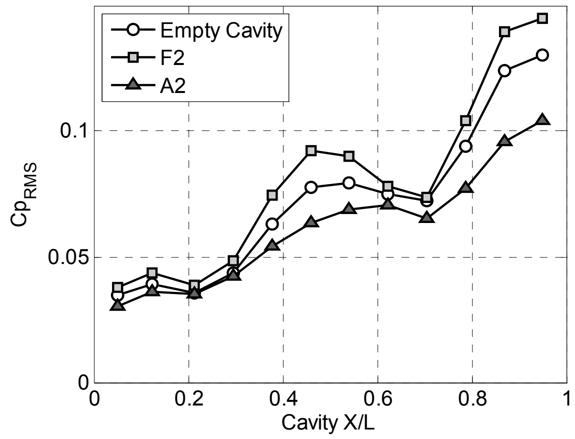

Fig. 11. Effect of stores positioned within cavity on unsteady pressure distribution

To examine the effect of these store locations on the periodic pressure fluctuations, power spectra on the aft wall of the cavity are given in Fig. 12. As shown, the second mode has been altered by the inclusion of stores inside the cavity. For configuration F2 this has been increased by 8dB when compared to the empty cavity case while for configuration A2 mode II has been reduced by 8dB. All other modes as well as the random signal are not effected by the addition of the stores.

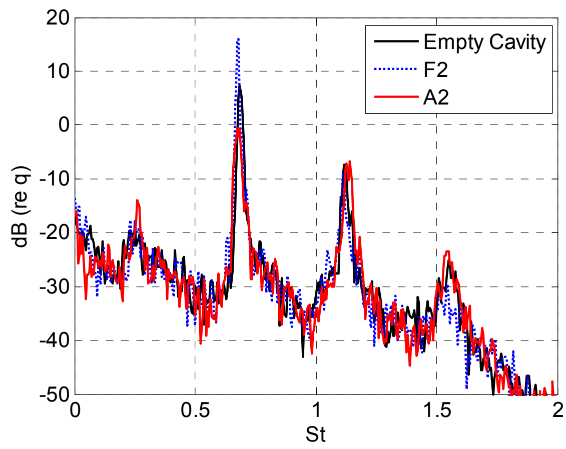

Fig. 12. Effect of stores positioned within the cavity on amplitude spectra of unsteady pressures: Kulite 16

The effect on the periodic frequencies is highlighted by the acoustic mode shapes given in Fig. 13. This shows that modes I and III have not been altered throughout the length of the cavity by the inclusion of the stores. For mode II, however, locating the stores lower in the cavity has resulted in large variations in this frequency component. These changes in mode II, therefore, are playing a major contribution to the observed alteration of overall unsteady pressure distributions given in Fig. 11.

Comparing the effect of the stores on the periodic frequencies for configuration F2 and A2 with those obtained for stores positioned at the top of the cavity (configuration F1 and A1), suggests the modes I and III are only influenced by direct interaction of the stores with the shear layer. Changes to the recirculation region inside the cavity, due to the addition of stores, do not appear to effect the feedback mechanisms associated with these modes. Hence, as the direct interaction of the stores with the shear layer is reduced the mode I and III periodic frequencies approach those of the empty cavity case. The alteration to the mode II, however, suggests this fluctuating frequency component is influenced by the changes to the flow field inside the cavity.

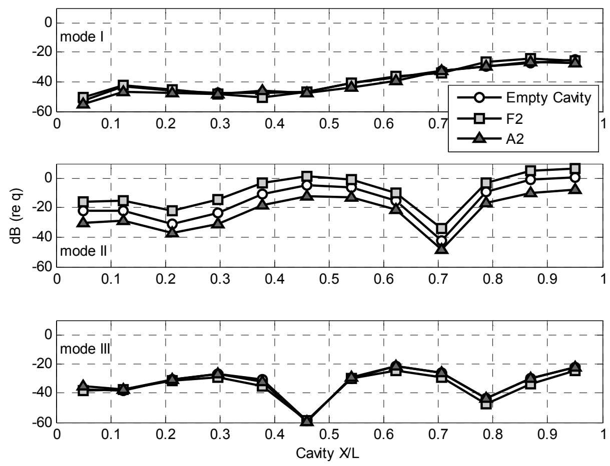

Fig. 13. Effect of store/cavity interaction on modes shapes for configuration F2 and A2

5 Conclusion

Tests have been performed to examine the influence of captive stores on the unsteady pressure distribution within a rectangular cavity.

Performing a series of baseline empty cavity measurements at Mach Numbers of 0.6, 0.85 and 1.11 has shown that the first four acoustic modes, characteristic of cavity flows of this type, are present. The frequencies of these tones are seen to closely match those predicted by the modified semi-empirical Rossiter formula.

The magnitude of the modes are seen to vary with Mach number. At Mach 0.6 spectra of the fluctuating pressure obtained at the rear cavity wall are shown to contain broad peaks and do not display a distinct dominance from one mode to another. These periodic pressure fluctuations are seen to become more distinct as the Mach Number is increased to 0.85 and 1.11. In these cases the pressure fluctuations associated with mode II are seen to dominate the unsteady flow field.

To examine the effect on the unsteady pressure distribution, the cavity/store interactions have been separated into two sections. Firstly, with stores positioned close to the top of the cavity and secondly with the stores positioned at a depth of 0.36D. For stores positioned at the top of the cavity more interaction between the stores and the shear layer would be expected. This interaction has led to a reduction in the overall rms pressure distribution along the cavity floor and walls when compared to the empty cavity case. Stores positioned in the downstream region of the cavity are seen to the be more effective in reducing unsteady pressure levels. The reductions are seen to be a result of the changes to the second mode of periodic pressure fluctuations. In this case, however, the mode III fluctuations are seen to be excited by the interaction of the stores with the shear layer resulting in a switching of the dominate acoustic mode from II to III. Even though the overall pressure levels were reduced the increase in amplitude of this higher frequency tone could be undesirable.

It is considered that positioning the stores close to the top of the cavity has altered the shear layer and made it less receptive to pressure waves traveling up and down stream along the length of the cavity. This has resulted in modification to the mass exchange mechanism between the cavity and freestream leading to the observed unsteady pressure reductions.

Positioning the stores lower in the cavity also resulted in changes to the unsteady pressure distributions. While similar pressure level reductions to those seen with the other store/cavity interactions were observed when positioning stores in the downstream region of the cavity, positioning the stores upstream led to an enhancement of the unsteady pressure levels.

Review of the acoustic mode shapes showed that, positioning stores at a depth of 0.36D did not change the mode I and III periodic fluctuations and that the changes to the unsteady pressure levels observed for these cases could be attributed to changes to the mode II acoustic waves alone.

Comparing the results from the differing store/cavity interactions suggests that the modes I and III are only influenced by direct interaction of the stores with the shear layer. Mode II, however, appears to be susceptible to changes in the recirculation region inside the cavity due to the addition of stores.

These results have suggested that changes to the cavity internal profile due to stores held in carriage locations could, potentially, increase the unsteady pressure levels.

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