

Cavity Oscillation Mechanisms in High-Speed Flows

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An experimental study was conducted to investigate the physics underlying the oscillation cycle of high-Mach-number, turbulent, open-cavity flows. The specific aim was to investigate how the interaction between the cavity acoustics and the shear-layer dynamics is affected by increasing Mach number. In the experiments the freestream Mach numbers tested were 2 and 5, the cavity length-to-depth ratio was 6, and the primary measurements made were of fluctuating surface pressures. The shear-layer-acoustics coupling was investigated by testing the cavity both with and without a plate covering over 80% of the cavity. The cover plate isolated the cavity from the free shear layer above it. In the Mach 2 cavity flow, the uncovered-cavity resonance frequencies agree well with those predicted by Rossiter's model. On the other hand, the resonance frequencies measured in the covered cavity do not agree with Rossiter's model but instead are consistent with a model that is based on closed-box acoustics. At Mach 5, both the uncovered and covered cavities have resonance frequencies that agree equally well with both Rossiter's model and closed-box acoustics. The success of a pure acoustics model suggests that the coupling between the shear-layer dynamics and the cavity acoustics is greatly reduced at high Mach numbers. Based on a consideration of the physical mechanisms implicit in Rossiter's model, it is argued that its successful prediction of the resonance frequencies in high-Mach-number cavity flows is largely coincidental and likely does not reflect the correct modeling of the flow physics.

Nomenclature

a_c	=	sonic speed inside the cavity
f	=	frequency
H	=	cavity depth
k_c	=	ratio of vortex convection speed to freestream flow speed
L	=	cavity length
L_s	=	splitter plate length
M	=	Mach number
n	=	mode number
P	=	instantaneous pressure
P_{ref}	=	reference pressure, $2 \times 10^{-5} \text{ N/m}^2$
r	=	recovery factor
T	=	temperature
t	=	time
U	=	local mean velocity
U_c	=	convection velocity
W	=	cavity width
α	=	phase constant between the vortex shedding and the acoustic wave response in the cavity
γ	=	specific heat ratio of the gas
δ_0	=	boundary-layer velocity thickness, $0.99U_\infty$
λ	=	wavelength
$\Phi(f)$	=	power spectral density

Subscripts

A	=	closed-box acoustic quantity
a	=	Rossiter model acoustic quantity
c	=	cavity interior or convection condition

L	=	longitudinal
n	=	mode number
v	=	vortex
0	=	stagnation condition
∞	=	freestream condition

Introduction

PREDICTING the flow structure and magnitude of the pressure oscillations for turbulent airflow past cavities is one of the most challenging areas of aeroacoustics. A large volume of experimental and computational work has been devoted to investigating various aspects of cavity flow over a wide range of Mach numbers, from low subsonic to hypersonic. Reviews of the early work in the area can be found in Refs. 1 and 2; work through the mid-1990s is discussed in Ref. 3. The majority of applications that have driven most of this work have been largely at subsonic and transonic speeds and, accordingly, there are relatively few published data at high-supersonic or moderately hypersonic speeds. Because opening bay doors and releasing weapons at high speeds reduces time over target and, thus, enhances survivability, there is growing interest in supersonic cavity flows. This in turn is raising new questions related to physics, modeling, and control. For example, it is not clear if physical models that have been developed and validated for subsonic and transonic external flows, which involve a strong coupling between the cavity acoustics and shear-layer dynamics, are also applicable to higher Mach number flows.

This question stems in part from earlier work by the current authors^{4–6} in which it was suggested that cavity flow at Mach 5 was quite different from that at lower Mach numbers. Spectral and conditional sampling analyses of the fluctuating pressures on the cavity rear wall, together with planar laser scattering (PLS) imaging, showed that the pressure signal is dominated by nonperiodic, large-amplitude pressure fluctuations induced by intermittent shock waves. These shock-induced “events” are not tightly coupled to the cavity oscillation cycle and their duration was found to be independent of L/H and of the same order of magnitude as the time required for a typical turbulent large-scale shear-layer structure to convect past a given point. The PLS images showed very clearly that these shock events, which are commonly thought to be the source of the acoustic waves, are caused by turbulent large-scale shear-layer structures that exhibited no periodicity (i.e., no quasi-repetitive behavior). Through particle image velocimetry measurements^{5,6} acquired simultaneously with cavity wall pressures, the current authors also

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did not find any evidence of a large-scale flapping or deflection of the shear layer that could be correlated with the pressure oscillations within the cavity. Similarly, instantaneous PLS images^{4,6} of the turbulent shear layer did not exhibit any evidence for coherent vortical structures induced by the cavity acoustics, which are typical of flows at lower Mach numbers.⁷ Furthermore, Murray and Elliott⁸ studied the characteristics of the shear layer over a cavity at Mach numbers ranging from 1.8 to 3.5 and found a decrease in organization (i.e., coherence) of the shear-layer structures with increasing Mach number. This trend is similar to the reduced organization and increased three-dimensionality that has previously been observed in mixing layers at increasing levels of compressibility.^{9–12} In mixing layers, stability theory and direct numerical simulations have shown that the two-dimensional Kelvin–Helmholtz instability, which is dominant at low compressibility, is greatly suppressed at high Mach numbers and three-dimensional instability modes become more dominant.¹³ It is this suppression of the two-dimensional instability that is responsible for the reduced growth rates of mixing layers at high compressibility.¹⁴

In summary, the evidence suggests that the cavity flow at high freestream Mach numbers (e.g., Mach 5) is significantly different from that at low Mach numbers. These differences likely include a shear layer that exhibits increased stability to two-dimensional perturbations and a higher degree of three-dimensionality in the large-scale turbulence. Furthermore, the increased stability of the shear layer is undoubtedly related to the apparent reduction in the interaction between the cavity acoustics and the shear-layer dynamics in Mach 5 cavity flow.⁶

The aim of the current study is to explore, in a direct way, this apparent decoupling between the shear-layer dynamics and the cavity acoustics, in Mach 2 and 5, high-Reynolds-number, turbulent cavity flow. This was accomplished by using a plate that covered a large portion of the cavity to essentially isolate the cavity from the shear layer above it. Fluctuating surface-pressure measurements were made for this covered-cavity case as well as for the baseline (i.e., uncovered) case. The specific goal of these measurements was to determine how the resonance frequencies are affected when the widely accepted feedback loop between the shear layer and the cavity is broken by the presence of the cover plate. The measured resonance frequencies from both the covered and baseline cavities are compared with the predictions of Rossiter's model and a pure acoustics model. These models are discussed in the next section.

Flow Models

In 1964, Rossiter¹⁵ developed a model for predicting the frequencies of the cavity oscillation modes based on experiments carried out in subsonic and transonic flows. This semi-empirical model assumes a feedback loop between the vortex shedding and the acoustic radiation: acoustic radiation initiates the vortex shedding at the upstream lip of the cavity and the passage of the vortices over the rear lip of the cavity is responsible for the acoustic radiation. Based on these assumptions, the fluid mechanic frequency is equal to the acoustic frequency:

$$f = k_c U_\infty / \lambda_v = a_c / \lambda_a \quad (1)$$

where k_c is the ratio of vortex convection speed, U_c , to freestream velocity U_∞ ; a_c is the speed of sound inside the cavity; and λ_v and λ_a are the vortex and acoustic wavelengths, respectively. Rossiter relates the two mechanisms (i.e., vortex shedding and acoustic radiation) by taking into account a phase difference α by which a vortex is downstream of the rear wall when the acoustic wave leaves the rear wall in the upstream direction. This approach results in a semi-empirical equation in which the resonance frequencies can be predicted using known flow parameters as well as some empirical quantities. This semi-empirical equation has been modified by Heller and Bliss¹⁶ such that the sound speed in the cavity is based on the recovery temperature of the flow. Rossiter's modified formula¹⁶

then takes the form of

$$\frac{f_n L}{U_\infty} = \frac{n - \alpha}{\left[M_\infty / \sqrt{1 + (r/2)(\gamma - 1)M_\infty^2} \right] + (1/k_c)} \quad n = 1, 2, 3, \dots \quad (2)$$

where f_n is the frequency at a given mode number n , r is the recovery factor, and M_∞ is the freestream Mach number. It should be noted that appropriate values of the empirical parameters α and k_c and their dependence on flow conditions and L/H is still an unresolved issue, which is discussed in earlier work.^{3,17} For example, measurements spanning the Mach number range 0.4–2.5 have suggested values of k_c ranged from 0.50 up to 0.75.^{15,18,19} Murray and Elliott⁸ directly addressed this issue by measuring the convection velocity of structures in the shear layer over a supersonic cavity. They used double-pulse planar Rayleigh scattering imaging from a condensed fog and found that the structure convection velocity is not constant, but rather the convection velocity varies across the shear layer. This observation is in agreement with previous measurements of structure convection velocities in supersonic mixing layers.^{11,20} Murray and Elliott found that the experimentally obtained convection velocities of turbulent structures for the Mach numbers 1.8, 2, and 2.7 agree well with a k_c value of about 0.57, but for their highest Mach number, 3.5, the experimental value of k_c was found to be 0.8. A similar visualization technique was used by the current authors to measure shear-layer structure convection velocities in a Mach 5 cavity flow.⁶ These measurements indicated that k_c could be as high as 0.9. It should be noted that condensation-fog techniques have the limitation that the fog crystals/droplets tend to evaporate when they encounter the low-velocity (hence, relatively warm) fluid within the cavity. Because of this evaporation, low-velocity structures are not marked by the technique and this leads to a bias in the measured convection velocity; that is, the measurement sample is biased toward higher velocities because particles are present only in the high-speed cold fluid. It is possible that the large values of k_c measured in Refs. 6 and 8 for the high-Mach-number cases may be influenced by evaporation; however, this same bias would also be present in the low-Mach-number cases in Ref. 8, but those values of k_c were much lower. Furthermore, the PLS images captured in Mach 5 cavity flow in Ref. 6 showed the propagation of large-scale turbulent structures with speeds of $0.9U_\infty$ that interacted with the rear-wall, and these structures were undeniably dynamically significant because they were often associated with the creation of a visible shock wave at the impingement point and an impulse in the rear-wall pressure signal. Perhaps a better explanation for the large value of k_c in Ref. 6 is that the cavity flow was formed with a relatively thick initial boundary layer ($\delta_0/H = 0.76$, $\delta_0/L \geq 0.13$). Bauer and Dix¹⁷ point out that the value of 0.57 for k_c is, strictly speaking, only valid when the upstream boundary layer is “thin” because in this case the cavity is long enough for a shear-layer instability to develop. In Ref. 6, the shear layer may have been effectively a detached boundary layer, rather than a fully developed mixing layer, and its turbulent structures may have been more representative of those in the upstream turbulent boundary layer than of a mixing layer. Interestingly, the convection velocity of large-scale structures measured using surface-pressure measurement data in the same Mach 5 boundary layer is consistent with a k_c of 0.9 (Ref. 21).

The purpose of this discussion is to emphasize that k_c does not have a universally accepted value and should depend on a range of variables such as M_∞ , Reynolds number, δ/H , δ/L , and other aspects of the cavity geometry. Even more problematic for modeling purposes is that using a single value of k_c may be overly simplistic because its value varies across the shear layer. Accordingly, for given flow conditions and cavity geometry, it is not always clear what values of k_c and α should be used to calculate the mode frequencies. The practical answer is to use those values that give the best agreement with the data, but this is not satisfying because the adjustment of parameters can mask the fact that the physics have been incorrectly modeled. This issue will be discussed further later.

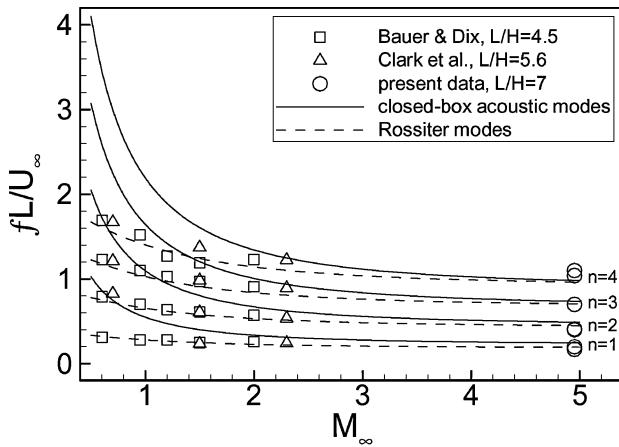


Fig. 1 Variation of Strouhal numbers (based on cavity resonance frequencies) with Mach number and comparison with closed-box longitudinal acoustic and Rossiter modes (from Ref. 6).

The experimental values of the mode frequencies measured at Mach 5 by the current authors⁶ together with the subsonic and supersonic data of Clark et al.,²² and Bauer and Dix¹⁷ are shown plotted together in Fig. 1 (taken from Ref. 6). For comparison, the mode frequencies computed from Rossiter's modified formula [Eq. (2) with the most commonly used values of $\alpha = 0.25$, $k_c = 0.57$, and $r = 0.89$], and the corresponding closed-box longitudinal acoustic mode frequencies are also shown. The closed-box longitudinal acoustic modes are based on a purely acoustic model²³ and correspond to longitudinal standing waves in a box of length L filled with approximately stagnant air with speed of sound, a_c . The closed-box longitudinal resonance frequencies are then given by

$$f_{A_n} = (a_c/2L)n, \quad n = 1, 2, 3, \dots \quad (3)$$

and the closed-box acoustics Strouhal number is

$$\frac{f_{A_n} L}{U_\infty} = \frac{\sqrt{1 + (r/2)(\gamma - 1)M_\infty^2}}{2M_\infty} n, \quad n = 1, 2, 3, \dots \quad (4)$$

Figure 1 shows that at low Mach numbers ($M_\infty < 1.5$) closed-box acoustic theory does not predict the measured resonance frequencies correctly, whereas agreement with Rossiter's modified formula is good. In contrast, as the Mach number increases, the measured resonance frequencies approach the closed-box longitudinal acoustic modes. Overall, Rossiter's formula does a good job at all Mach numbers but, at the higher Mach numbers, the simple closed-box acoustics model does just as well. This result is supported by Heller et al.,²⁴ who suggest that the closed-box frequencies are approached as a result of the increased acoustic impedance of the shear layer at higher Mach numbers. The acoustic impedance is the product of the density and the sound speed, ρa , and it is readily shown that the freestream-to-cavity acoustic impedance ratio is given by $(\rho a)_\infty/(\rho a)_c = [1 + (r/2)(\gamma - 1)M_\infty^2]^{1/2}$. This equation shows that the mismatch in acoustic impedance does indeed increase with Mach number and, therefore, pressure waves that originate in the cavity will be less efficiently transmitted through the shear layer. This reduced transmission efficiency may reduce the coupling between the shear layer and the cavity pressure fluctuations.

It is important to note that in a purely acoustic model (i.e., closed box) no information is introduced from the shear layer into the cavity. Because the Mach 5 cavity flow seems to exhibit closed-box longitudinal acoustic modes, it can be inferred that the clear coupling between the shear layer and the cavity pressure oscillations in low-Mach-number flows may be less significant in high-Mach-number flows. Investigating the validity of this inference was the motivation behind the following set of experiments in which two different cavity configurations (with and without cover plate) were tested at two different Mach numbers (2 and 5). The configuration with the cover plate was used to simulate a closed-box system with minimal coupling between the shear layer and cavity.

Experimental Program

Wind Tunnel and Flow Conditions

Experiments were conducted in the blowdown wind tunnel at the University of Texas at Austin. Two different nozzles were used to provide nominal Mach numbers of 2 and 5. The test sections for both flows were 6 in. (15.2 cm) wide and 30 in. (76.2 cm) long. The heights were 7 in. (17.8 cm) for Mach 5, and 6.3 in. (16 cm) for Mach 2. The stagnation chamber pressure and temperature for the Mach 5 experiments were 333 psia (2.29 MPa) $\pm 1\%$ and 635°R (353 K) $\pm 1\%$, which, for a test-section Mach number of 4.95, result in a freestream Reynolds number of $15.24 \times 10^6/\text{ft}$ ($50 \times 10^6/\text{m}$). The freestream velocity was 2509 ft/s (765 m/s). For the Mach 2 flow the stagnation chamber pressure and temperature were 38 psia (0.26 MPa) $\pm 2\%$ and 525°R (292 K) $\pm 1\%$, respectively. The test-section Mach number was 2.1, and the freestream velocity was approximately 1675 ft/s (510 m/s).

In both cases, the incoming turbulent boundary layer underwent natural transition well upstream of the cavity and developed under approximately adiabatic wall temperature conditions. The incoming boundary-layer thickness and the momentum thickness were 0.76 in. (1.93 cm) and 0.03 in. (0.076 cm), respectively, for the Mach 5 flow. The properties of the incoming undisturbed turbulent boundary layer at approximately the location of the cavity model in the test section have been reported in previous work,⁶ as have the details of the test facility, instrumentation, and data acquisition. Particle image velocimetry measurements²⁵ have shown that the incoming boundary-layer thickness for the Mach 2 flow is 0.51 in. (1.3 cm), and the momentum thickness is 0.035 in. (0.09 cm).

Cavity Model/Experimental Setup

A rectangular cavity model with $L/H = 6$ and $W/H = 3$ was used in the current experiments. With $L/H = 6$, the cavity flow is an open type; that is, the separated shear layer bridges the cavity and reattaches onto the downstream face of the cavity. Figure 2a shows a schematic diagram of this arrangement. The tunnel floor has a 3-in. (7.6-cm)-wide by 6-in. (15.24-cm)-long cutout that forms the front, rear, and side walls of the cavity. The nominal depth of the cavity is 1 in. (2.54 cm). A bottom plate is then used to form the cavity floor.

A fast-response pressure transducer (Kulite Semiconductor Products, Inc., Model XCQ-062-15A or XCQ-062-50A) was flush-mounted on the vertical surface of a 1-in. (2.54-cm) rectangular block that served as the front wall of the cavity. The transducer was positioned on the spanwise centerline at a depth of 0.125 in. (0.3175 cm) from the surface of the test-section floor (Fig. 2). This

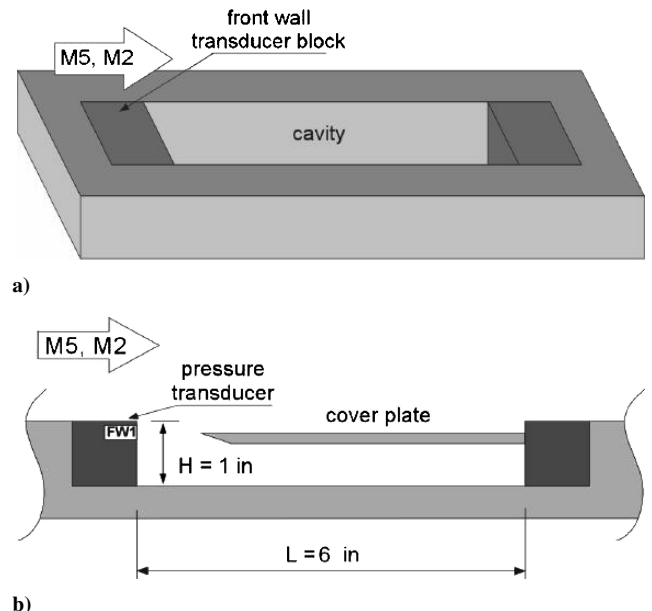


Fig. 2 Cavity geometry and transducer blocks: a) baseline and b) cover-plate configuration.

transducer was used to record the fluctuating pressure signal from which the sound pressure levels (SPLs; $20 \log_{10} \{ \sqrt{[\Delta f \Phi(f)] / P_{\text{ref}}} \}$) were calculated. The signal was usually sampled at 50 kHz and analog-filtered at 20 kHz.

For some of the cases, a 5-in. (12.7-cm)-long by 3-in. (7.6-cm)-wide by 1/8-in. (0.32-cm)-thick cover plate was used to partially shield the cavity (Fig. 2b). The plate had a semiwedge leading edge facing the cavity floor. The leading edge of the plate was 1 in. (2.54 cm) downstream of the front wall and its upper surface was 0.2 in. (0.51 cm) below the test-section floor so that the shear layer flows over the plate without impinging on the leading edge. The plate was attached to the rear wall using two set screws. To eliminate vibration problems, the cover-plate edges were glued to the cavity side walls, and thin 90-deg angle brackets were glued to the cover plate and the side walls for additional support. This configuration provided very rigid support of the plate, and inspection after the runs showed that the glued joints were not broken during the runs. Furthermore, the behavior of the plate was observed during the run and shutdown of the tunnel through a window placed on the side wall of the test section. There were no noticeable vibrations. With this configuration, it was possible to isolate the cavity from the effects of the shear-layer impingement at the rear wall and, hence, break the feedback loop that is central to Rossiter's model.

Results

The pressure power spectra in the form of SPLs obtained from the front-wall transducer with and without the cover plate in place are shown in Fig. 3 as a function of Strouhal number, fL/U_∞ , for the Mach 5 flow. The most important result that can be deduced from Fig. 3 is that although the SPL levels differ markedly with and without the cover plate, the resonance frequencies exhibit strong similarities. For example, the agreement is excellent for the first two modes ($n = 1$ and $n = 2$ on Fig. 3), whereas the third mode ($n = 3$) is close. Furthermore, the resonance frequencies for both covered and uncovered cases are, within the experimental uncertainty, the same as the closed-box longitudinal resonance frequencies computed by using Eq. (4). The SPLs in the baseline case (i.e., no cover plate) are higher due to the shear-layer turbulence, which introduces broadband, high-amplitude fluctuations into the cavity. With a covered cavity, the SPLs for different modes have approximately the same magnitude, which is contrary to the baseline cavity spectra where the modes usually have different magnitudes. The fact that there is almost no difference between the SPLs of the modes (110–112 dB) suggests that there is also no dominant mode and this may also be seen as further evidence that a simpler mechanism is in effect rather than a more complex, combined effect of the shear layer and the cavity acoustics. It can be argued that, in the case of the covered cavity, the effect of the turbulent shear layer is substantially reduced, if not entirely eliminated, and thus the measured resonance frequencies must be a result of a primarily acoustic phenomenon.

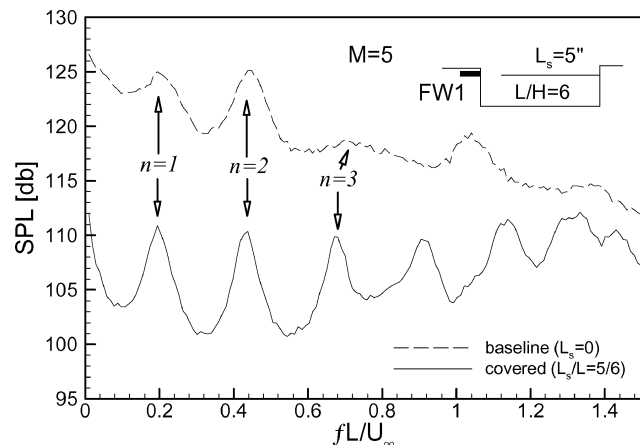


Fig. 3 Front-wall SPLs with and without cover plate for the Mach 5 flow.

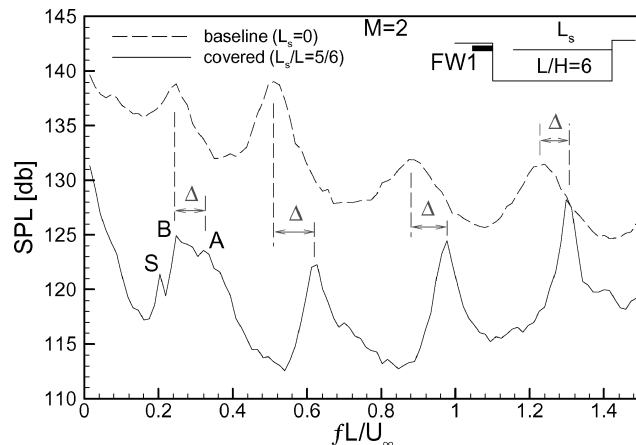


Fig. 4 Front-wall SPLs with and without cover plate for the Mach 2 flow.

The measurements were always performed on the centerline of the cavity, and only the longitudinal modes were considered here. It should be noted that because the cavity has a finite width, three-dimensional effects should be expected to some extent. In a recent report, Dix and Bauer²⁶ show that when data from either laterally or vertically separated transducers (located on the vertical phase of the upstream wall, like in the current study) are compared, the longitudinal modes (defined by $f_L = a_c/2L$) dominate for the frequencies lower than the natural width ($f_W = a_c/2W$) or depth ($f_H = a_c/4H$) frequencies. If we apply this finding of Dix and Bauer to our data, it can be shown that the first two modes are not likely to be affected by the lateral and vertical waves (the frequencies of the first two longitudinal modes are below those of the first lateral and vertical modes), whereas the third mode might be affected by the lateral waves only, and the fourth mode might carry all the three-dimensional effects including the vertical waves. It is possible that the small shift for the third mode in Fig. 3, and the large shift for the fourth mode, could be due to these three-dimensional effects.

The pressure power spectra for the same two configurations in the Mach 2 flow are shown in Fig. 4. The overall SPLs have increased by about 10 to 15 dB, which is expected because more high-momentum fluid enters the cavity than at Mach 5, because of the higher growth rate of the shear layer, and, consequently, the noise levels are higher. Most important, closer inspection shows that the resonance frequencies, with and without the cover plate, do not match as they did at Mach 5. Specifically, the resonance frequencies are higher for the covered-cavity case. As in the case of the Mach 5 flow, the resonance frequencies for the covered case are again approximately the same as the theoretical closed-box longitudinal resonance frequencies that would be obtained by using Eq. (4). It appears that when the cavity is covered, regardless of the freestream Mach number ($M_\infty = 5$ in Fig. 3 or $M_\infty = 2$ in Fig. 4), the measured peak frequencies are the same as the purely acoustic resonance frequencies and thus can be correctly predicted by using Eq. (4). Furthermore, the shift between the mode peaks for the covered and uncovered cavities at Mach 2 demonstrates the different physics between these two flows. In fact, it will be shown later (Fig. 5) that, contrary to the covered-cavity case which is predicted well by the closed-box model, the baseline cavity physics for the Mach 2 flow can be captured by Rossiter's model quite well, confirming the model assumption of the coupling that exists between the shear layer and the cavity acoustics.

It should be noted that the behavior of the first mode in the case with the covered cavity in Fig. 4 is somewhat different compared to the other modes: not only is the peak region broader but there also appear to be two local peaks (aside from an initial, secondary peak *S* at the lower Strouhal number). One of the peaks (*B*) has the same Strouhal number as the baseline case, whereas the other local peak, *A*, is shifted from that of the baseline case by about the same amount as observed for the other modes. It appears that whatever causes the shift in the higher modes exists also for the first mode and seems to be responsible for local peak *A*. Nevertheless, peak *B*

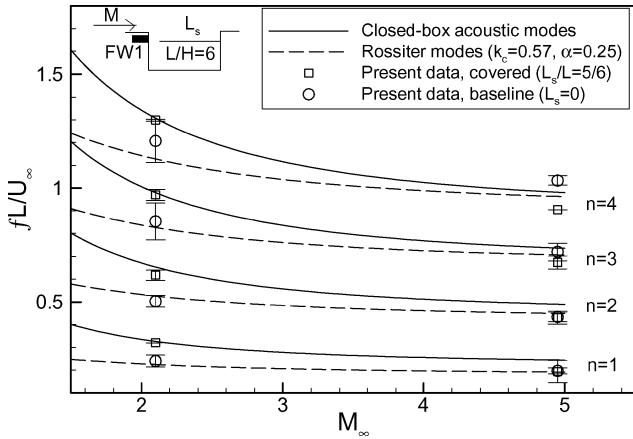


Fig. 5 Variation of Strouhal number (based on cavity resonance frequencies) with Mach number and comparison with closed-box longitudinal acoustic and Rossiter modes (with $k_c = 0.57$ and $\alpha = 0.25$).

suggests that some other physical phenomena are also taking place at this frequency.

To determine whether this broader region with different local maxima was due to vibration of the cover plate, additional tests were conducted. In these tests a different set of electronic equipment (transducer, analog filter, and amplifier) was used. Also, during the steady-state run and shutdown process of the tunnel the cavity model was visualized through a window placed on the side wall of the test section. No vibration of the plate was detected and the spectra, including the multiple peak near the first mode, were repeatable in all the tests. It is likely that the reason for the multiple peak is that the plate covers only $\frac{5}{6}$ of the cavity, and the higher growth rate of the shear layer at Mach 2 (as opposed to Mach 5) may lead to a small interaction of the shear layer with the cavity acoustics. In other words, at Mach 2, the covered-cavity may not be completely isolated from the surrounding flow. Even with this possible small amount of shear-layer interaction, the Mach 2 covered cavity exhibits mode peaks that vary significantly less in SPL than the uncovered cavity. This observation is similar to the Mach 5 case and suggests the oscillation mechanism is essentially the same for both covered cavities.

When the data of Figs. 3 and 4 are plotted in a fashion similar to Fig. 1, the observations made earlier become more evident (Fig. 5). At Mach 2, all the modes have a similar tendency: the Strouhal numbers for the covered cavity are in good agreement with the closed-box longitudinal acoustic modes, whereas the Strouhal numbers without the cover plate match the Rossiter modes well. At Mach 5, the Strouhal numbers with and without the cover plate are essentially the same as are the theoretical closed-box longitudinal acoustic modes and the Rossiter modes.

These experimental results demonstrate that when the feedback loop between the shear layer and the cavity is broken (i.e., by means of a cover plate), the measured resonance frequencies and the predicted closed-box frequencies agree well, even at lower Mach numbers. This result also validates the use of the cover plate to simulate the closed-box model. In the case of the higher Mach number, the fact that closed-box acoustics agrees well with the covered cavity case as well as with the baseline case (without cover plate) implies a decoupling between the shear layer and the cavity acoustics.

Discussion

Rossiter or Closed Box?

Examination of Figs. 1 and 5 shows that both Rossiter's modified formula and closed-box acoustics successfully predict oscillation modes for higher Mach numbers. A pertinent question to ask is why is this so, considering that the physical mechanisms are apparently so different? If we let $M_\infty \rightarrow \infty$ in Eq. (2), then for the first Rossiter mode ($n = 1$) the Strouhal number reduces to

$$\frac{f_1 L}{U_\infty} = \frac{1 - \alpha}{\sqrt{2/[r(\gamma - 1)]} + 1/k_c} \quad (5)$$

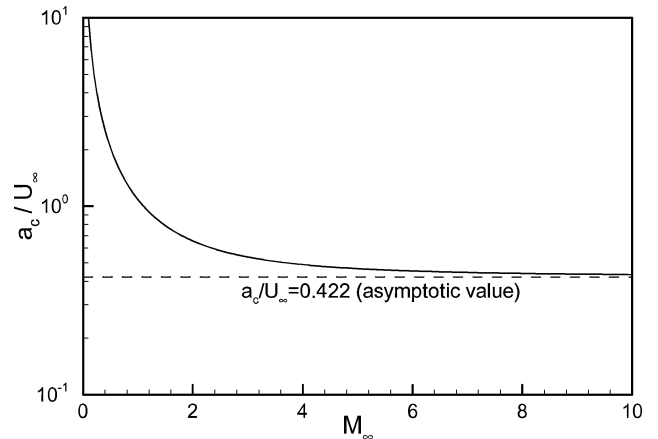


Fig. 6 Variation of the ratio of cavity sound speed and freestream velocity as a function of freestream Mach number.

as $M_\infty \rightarrow \infty$. If we let $M_\infty \rightarrow \infty$ in Eq. (4) then for the first closed-box longitudinal mode we have

$$f_{A_n} L / U_\infty = \sqrt{r(\gamma - 1)/8} \quad (6)$$

as $M_\infty \rightarrow \infty$. Assuming $k_c = 0.57$, $\alpha = 0.25$, $r = 0.89$, $\gamma = 1.4$, and $n = 1$, Eqs. (5) and (6) give $f_1 L / U_\infty = 0.18$ and $f_{A_1} L / U_\infty = 0.21$, which differ by only 14%. The fact that the high-Mach-number limit is nearly the same is not because the two models represent the same physical mechanisms. This is clear to see because Eq. (5) retains its dependence on the fluid-mechanic quantities k_c and α , whereas Eq. (6) depends only on fluid properties.

To investigate these two models in more detail it is useful to consider the implications of the underlying physical mechanisms. First of all, it is useful to consider how the ratio of the cavity sound speed to freestream velocity varies with freestream Mach number. This ratio is given by the Eq. (7) and is plotted as a function of M_∞ in Fig. 6:

$$a_c / U_\infty = \sqrt{r(\gamma - 1)/2 + 1/M_\infty^2} \quad (7)$$

It can be seen from Fig. 6 that, as the Mach number tends to infinity, this ratio approaches an asymptotic value of 0.422 for $r = 0.89$ and $\gamma = 1.4$. The significance of this asymptotic value will be clear in the following examples.

Consider two different Mach number regimes, low ($M_\infty = 0.2$) and high ($M_\infty = 5$). In the lower Mach number case (Fig. 7a), according to Rossiter's model for the $n = 1$ mode, the vortex shedding wavelength (or spacing) is equal to the cavity length L . In other words, the shedding vortices created at the front lip at time t_0 convect past the rear wall at time t_1 , at which time an upstream propagating acoustic wave is created. Equation (7) gives $a_c / U_\infty \approx 5$ in a Mach 0.2 flow. Assuming a convection velocity of one-half the freestream velocity ($k_c \approx 0.5$) for the shedding vortices, the sound speed inside the cavity is then approximately 10 times the convection velocity of the vortices [Eq. (1)]; thus, it can be assumed that, as the vortex convects past the rear wall, the acoustic wave is felt almost instantaneously at the front wall. Therefore, as soon as a vortex impinges on the rear wall a new vortex is immediately generated at the front wall. This leads to $\lambda_v = L$, which is consistent with Rossiter's formula when the phase term α is neglected. It is interesting to note that from Eq. (1) we can write $\lambda_a / \lambda_v = a_c / U_c$, which implies that the acoustic wavelength is 10 times larger than the vortex wavelength; that is, $\lambda_a = 10L$. This large acoustic wavelength, which is significantly larger than the size of the cavity, emphasizes just how different the Rossiter mode is from the closed-box longitudinal acoustic mode that would have a wavelength of $2L$. Neglecting any phase shift between the vortex train and the acoustic wave, the vortex frequency for the first Rossiter mode is given by

$$f_1 = U_c / \lambda_v \approx (U_\infty / 2) / L \quad (8)$$

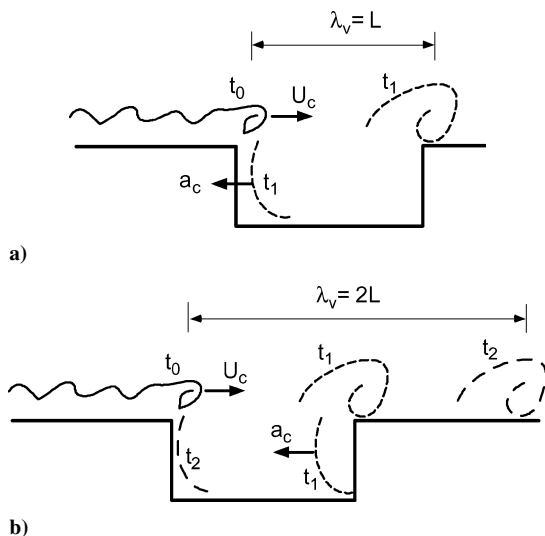


Fig. 7 Cavity feedback cycle according to Rossiter's model: a) low-speed case and b) high-speed case; t_0 is the time at which the vortex is created, t_1 is the time at which the vortex impacts the rear wall (which is equal to the time at which the acoustic wave arrives at the front wall for the low-speed case), and t_2 is the time at which the vortex convects downstream by the cavity length (which is equal to the time at which the acoustic wave arrives at the front wall for the high-speed case).

This frequency is five times smaller than the closed-box longitudinal frequency obtained from Eq. (3).

Consider now the higher Mach number case for which case Eq. (7) gives $a_c \approx U_\infty/2$, as discussed earlier. If we also assume $k_c \approx 0.5$ then $U_c \approx a_c$, which under the Rossiter model [Eq. (1)] implies that $\lambda_a \approx \lambda_v = 2L$. This is illustrated in Fig. 7b. As the vortex interacts with the rear wall, the acoustic wave is created, but, in the time it takes for the acoustic wave to arrive at the front wall, the vortex convects downstream approximately the same distance (i.e., the distance L); therefore, the vortex train associated with the acoustic disturbance has a wavelength of $\lambda_v = 2L$.

This agreement between Rossiter and closed-box longitudinal frequencies at the high-Mach-number limit is intriguing, because we start with two different physical mechanisms but end up with approximately the same result. The question remains: which one of these two approaches makes more sense from a physical standpoint? Figure 5 seems to show that Rossiter's model gives slightly better agreement with the Mach 5 experimental data than does the closed-box acoustics model. However, it is very clear from Fig. 3 that the resonance frequencies obtained with the covered and uncovered cavity are nearly identical (at least for the first three modes). The covered cavity must be driven by a pure acoustic mechanism (because there is no interaction with the shear layer) and, thus, this is strong evidence that the uncovered cavity is driven by the same mechanism. The fact that Rossiter's model seems to do slightly better at Mach 5 is really just a reflection of the values of a and k_c that were used.

For example, the phase parameter a is, by definition, based purely on the coupling of fluid mechanics and cavity acoustics and is known to be flow dependent.¹⁵ Furthermore, as was pointed out earlier, the structure convection velocity and, hence, k_c , is a rather ill-defined quantity. Measurements suggest that it will be dependent on the particular flow conditions and is not even constant for a given flow because it varies across the shear layer. Furthermore, measurements of structure convection velocities in the current Mach 5 cavity flow suggest that $k_c \approx 0.9$ is more appropriate.⁶ Rossiter's model predicts the correct resonance frequencies at Mach 5 only because we used $k_c = 0.57$, but, as shown in Fig. 8, if a more physical value had been used for k_c (such as the experimentally observed value of 0.9), then Rossiter's formula would not have agreed with the data or with closed-box acoustics. Because there is good reason to believe that k_c may not in fact equal 0.57 in the current Mach 5 cavity flow, then it can reasonably be inferred that the good agreement obtained

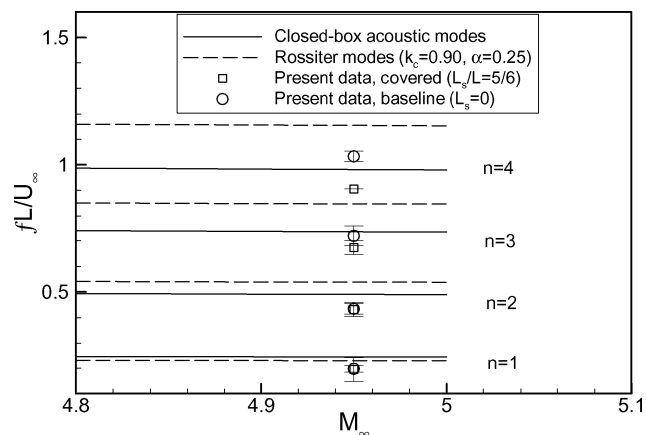


Fig. 8 Variation of Strouhal number with Mach number and comparison with closed-box longitudinal acoustic and Rossiter modes (with $k_c = 0.9$ and $\alpha = 0.25$).

with Rossiter's formula (as shown in Fig. 5) is largely fortuitous or coincidental and does not indicate that the physics has been properly modeled.

Additional Evidence

Leu and Dolling²⁷ investigated the effects on the pressure oscillations of a store inside the cavity as well as the impingement of a shock wave on the shear layer for a cavity with $L/H = 3$, also at Mach 5. Their results showed that the impingement of a shock wave on the shear layer or the placement of a store inside it did not have significant effects on the cavity flowfield, which was essentially the same as that of the empty cavity. They found that, although shock impingement would increase the mean pressure, rms levels, and sound pressure levels, it only enhanced or depressed some modes and shifted the mode frequencies very little. Even when the store was fully immersed in the shear layer, the resonance frequencies were still the same as when the store was inside the cavity. Considering that Rossiter's model involves impingement of vortices on the rear wall thereby causing acoustic radiation, it might be anticipated that a store in the shear layer would have an effect on this feedback process. No evidence of such was observed. These results can also be seen as an additional support for the different physics of the high-Mach-number cavity flows as suggested by the current work.

Conclusions

Experiments were conducted at Mach 2 and 5 in a high-Reynolds-number, turbulent, open-cavity flow. The cavity length-to-depth ratio was 6. To isolate the interaction between the cavity and the shear layer, a plate was used to cover $\frac{2}{3}$ of the cavity. Fluctuating surface-pressure measurements were made on the front wall of the cavity with and without the cover plate. The results demonstrate that when the interaction between the shear layer and the cavity acoustics is inhibited, then the measured resonance frequencies are predicted well by a pure acoustic "closed-box" model. This is true at both Mach 2 and 5. Furthermore, the uncovered Mach 2 resonance frequencies agree well with Rossiter's model but do not agree with closed-box acoustics. Interestingly, the Mach 5 resonance frequencies are virtually identical whether the cavity is covered or uncovered. Furthermore, the modes agree equally well with both Rossiter's model and closed-box acoustics.

The fact that the Mach 5 cavity is so similar in its characteristics to a covered cavity strongly suggests that the coupling between the shear layer and the cavity acoustics is greatly reduced, and the physical mechanisms that cause the pressure oscillations in the cavity are primarily acoustic in nature. It can be argued that the success of Rossiter's model at high Mach numbers is probably in large part coincidental, because there appears to be little physical basis for the vortex-to-freestream velocity ratio that gives good agreement with the measured data.

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