

Cavity oscillations

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CAVITY OSCILLATIONS

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CAVITY OSCILLATIONS

1. NOTATION

		Units
		<i>SI</i>
C_p	pressure coefficient, $(p_f - p_\infty)/q$	
c_0	velocity of sound	m/s
D	depth of cavity	m
f	frequency	Hz
f_m	frequency of cavity oscillations for mode m	Hz
h	altitude	m
K_v	convection speed ratio of shear layer (U_c/U_∞)	
L	length of cavity	m
M_∞	Mach number of free stream	
m	integer representing modes	
$P_{b,max}$	maximum broadband sound	Pa
P_m	one-third octave band level of r.m.s. sound pressure for mode m	Pa
$P_{m,max}$	maximum sound pressure amplitude for modes m (1, 2 and 3)	Pa
p	pressure at altitude h	Pa
p_f	pressure on cavity floor	Pa
p_∞	free stream static pressure	Pa
q	free stream dynamic pressure	Pa
R	gas constant	J kg ⁻¹ K ⁻¹
T	absolute temperature	K
U_c	convection velocity	m/s
U_∞	velocity of free stream	m/s

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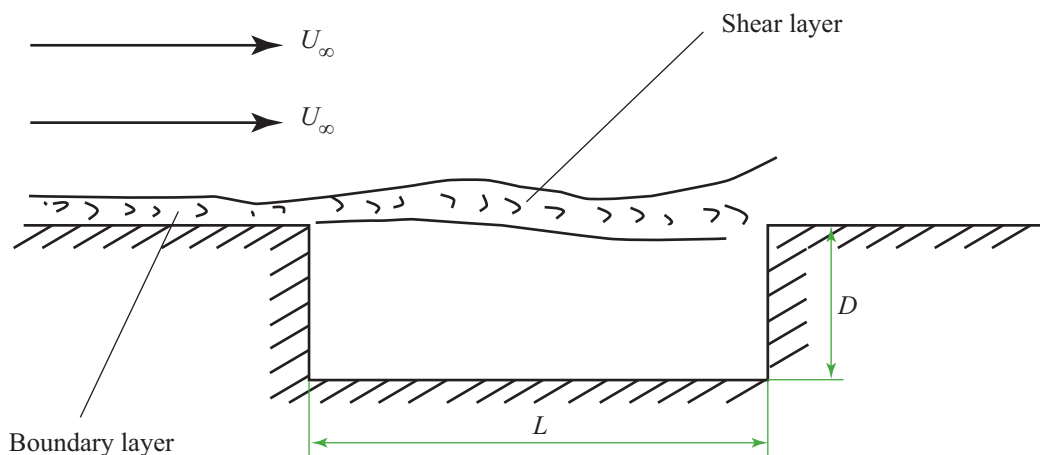
X	distance from upstream cavity edge	m
α	phase lag	
γ	ratio of specific heats (1.404)	
ρ	density of air	kg/m ³

2. INTRODUCTION

Intense sound may be generated by the flow of fluid over a cavity or rectangular cutout and the sound produced can cause structural damage near the cavity or cutout. The weapons bay of an aircraft forms a cavity and, when the bay is open, the aircraft may be flying at high subsonic or supersonic speeds. Cavities can also be associated with aircraft landing gear, but in this case the aircraft speed is low. This Item is mostly concerned with the sound that is generated by flow at high speed over cavities.

In most experimental and theoretical work the cavities have a rectangular cross-section and are considered to be two-dimensional. They are open to the air flow surrounding the cavity. As the problem is assumed to be two-dimensional, the width of the cavity is of secondary importance. The important dimensions are the length L in the flow direction and the depth D .

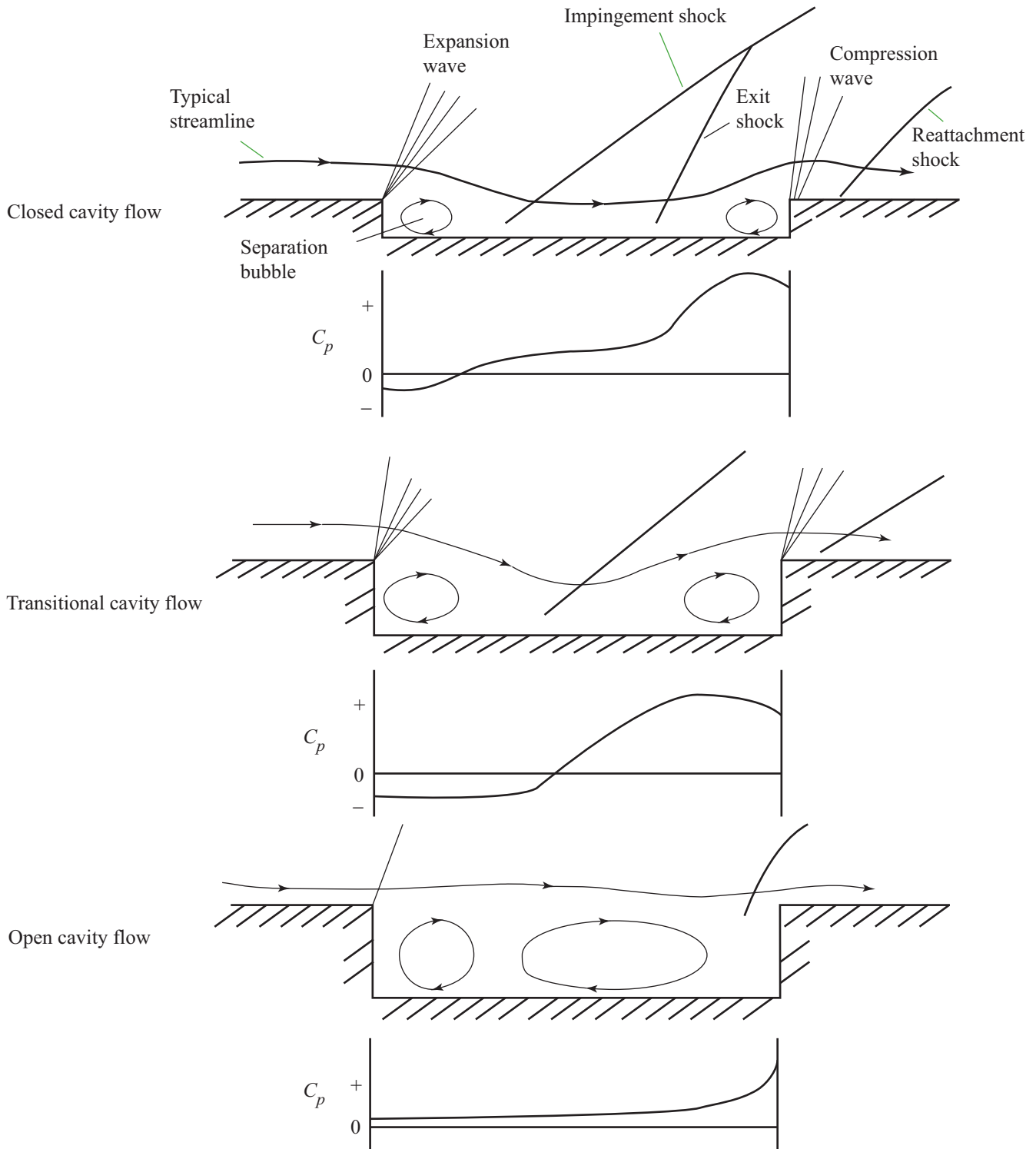
Most explanations of cavity flow are in terms of a free shear layer. When a flow occurs over the cavity, a shear layer is generated at the front (upstream edge) of the cavity. The shear layer is essentially a thin layer of turbulent flow, where the effect of viscosity is important, generated in the boundary layer upstream of the front edge of the cavity. A schematic diagram of a shear layer is shown in Sketch 2.1.



Sketch 2.1 Schematic diagram of shear layer

The boundary layer is a thin layer, where the fluid velocity increases from zero at the wall to that of the free stream flow. At the upstream edge of the cavity the flow separates from the wall and consequently forms the shear layer. Early work on the flow over cavities at low speeds found that for very shallow cavities the shear layer is reattached to the cavity floor (Rothko, 1955). Additionally, Rothko found that the impingement of the shear layer on the downstream wall resulted in an increase in drag. Based on experiments with free stream flows with Mach numbers from 0.25 to 1.5, Krishnamurty observed that there is an optimal length of the cavity at which the shear layer will span the cavity and not impinge on the downstream wall (Krishnamurty, 1955).

Rectangular cavities may be classified in terms of the position of the shear layer in relation to the cavity, as open, transitional and closed. When the shear layer spans the cavity opening, the cavity is described as open. For longer cavities when the shear layer reattaches to the cavity floor, the cavity is described as closed. Cavities in between are referred to as transitional. The flow patterns for the three types of cavity are shown in Sketch 2.2 for supersonic flow (Stallings and Wilcox, 1987). In the case of closed flow, which results in the most intensive sound, the streamlines are deflected downwards into the cavity by an expansion wave, generated at the upstream edge of the cavity. The wave pattern of the closed cavity indicates that an expansion wave at the leading edge is followed by an impingement shock, as the flow impinges on the floor of the cavity. A further shock occurs when the flow is compressed on leaving the cavity. Typical cavity floor pressures are indicated for the closed flow in terms of the pressure coefficient. As the flow expands into the cavity, the pressure is low, increase and reaches a plateau in the region of impingement. Further downstream the pressure increases to a maximum just ahead of the rear face of the cavity. For a cavity which is described as having open flow the pressure on the floor is relatively uniform, apart from an increase at the rear face associated with the shear layer impingement. A transitional cavity flow exists between the closed and the open. For the transitional case the impingement and exit shocks coalesce into a single wave.



Sketch 2.2 Cavity flow models at supersonic speeds (Stallings and Wilcox, 1987)

C_p is the pressure coefficient

Flow patterns are different for subsonic and supersonic regimes. The type of flow depends mostly upon the ratio L/D . For closed cavities Shaw and Shimovetz suggest value of L/D from 9 to 15. For transitional flow L/D should be less than a value between 7 and 14. For open flow L/D should be less than a value between 6 and 8. The large variation occurs because there is a secondary dependence on Mach number (Shaw and Shimovetz, 1994).

Rossiter showed experimentally that shallow cavities ($L/D > 4$) produce mainly broadband acoustic sound (Rossiter, 1964). Deeper cavities ($L/D < 4$) produce discrete tones. The amplitude of the tone can be up to 0.35 of the free stream dynamic pressure. An extensive survey of cavity flow has been provided by ESDU Data Items in the Aerodynamic Series (ESDU, 2002; ESDU, 2004). More details of flow patterns in cavities can be found in these Items.

Empirical methods for predicting the sound levels which result from cavity oscillations have been provided (Smith and Shaw, 1975; Bauer and Dix, 1991; Dix and Bauer, 2000). The method used in this Item is that of Smith and Shaw. It gives an approximate estimation and is suitable for preliminary assessment.

3. FREQUENCY OF CAVITY OSCILLATIONS

Rossiter considered flow-induced resonances in the cavity and found that the cavity oscillations occur at different modes, with a particular frequency f_m associated with each mode m . The frequencies of the resonances, as incorporated into a Strouhal number, are found to lie with certain well-defined bands, when plotted against Mach number. A dimensionless form of frequency, the Strouhal number, is a product of frequency and a dimension divided by a velocity. According to Rossiter, the flow-maintained resonances can be explained in terms of a feedback loop (Rossiter, 1964). In Rossiter's approach the shear layer is modelled as a series of periodically formed vortices, which are convected downstream to the edge of the cavity. A sound pulse is generated when a vortex reaches the downstream edge. The sound wave travels upstream and causes another vortex to be generated at the front of the cavity. The feedback mechanism is said to be similar to the production of edge tones (Nyborg *et al*, 1952; Karamcheti *et al*, 1969). The flow-induced resonances in high speed flow result from the feedback process and are not related to the acoustic cavity modes. For Mach numbers less than 0.2 the normal acoustic modes are applicable (Tam and Block, 1978) and the frequencies of the modes are dependent on the dimensions of the interior cavity (ESDU, 2014). If the shear layer spans the cavity, the feedback mechanism cannot occur and the oscillation is suppressed (Shaw and Shimovetz, 1994).

In the Rossiter model a vortex travels downstream across the cavity in time L/U_c , where U_c is the convection velocity of the vortices. The convection velocity is less than the free stream velocity U_∞ and $U_c \approx 0.4U_\infty$ to $0.6U_\infty$. The sound from the trailing edge radiates back to the front edge of the cavity in time L/c_0 , where c_0 is the velocity of sound. The returning sound will impinge on the front edge at just the right instant to reinforce the periodic shedding by vortices, provided the frequency f_m satisfies Rossiter's equation (Rossiter, 1964; Howe, 1998),

$$\frac{L}{U_c} + \frac{L}{c_0} = \frac{m}{f_m}. \quad (3.1)$$

Equation (3.1) has been modified after comparison with experimental results (Rossiter, 1964; Ahuja and Mendoza, 1995). The mode m is replaced by $m - \alpha$, where α is a constant phase lag which depends upon the cavity depth and is different for each value of m . Additional modifications have been made by Rossiter and his final formula, used for frequency prediction, is

$$f_m = \frac{U_\infty}{L} \frac{m - \alpha}{M_\infty \left(1 + \frac{\gamma - 1}{2} M_\infty^2 \right)^{1/2} + \frac{1}{K_v}}, \quad (3.2)$$

where M_∞ is the Mach number of the free stream and K_v is the convection speed ratio in the shear layer (U_c/U_∞).

Rossiter's formula gives good results, provided the correct values of α and K_v are used. Rossiter found that the best value of K_v is 0.57. The phase lag α varies from 0.25 for $L/D = 4$ and 0.58 for $L/D = 10$.

Rossiter's semi-empirical approach is used in this Item and is applicable to shallow cavities ($L/D > 1$). For subsonic and supersonic flow ($M_\infty > 0.2$) the approach is in good agreement with experimental data, independently of the temperature of the free stream, Reynolds number and the transverse cavity dimension.

4. PREDICTION

The prediction scheme for sound pressures generated by the cavity is based on an empirical method devised at the Wright-Patterson Air Force Base (Smith and Shaw, 1975). The results of their method have been compared with experimental results obtained from wind tunnel tests and from flight tests at different altitudes and Mach numbers. The flight tests were mostly carried out for $L/D = 5$ and $L/D = 7$ at altitudes of 3000, 10,000 and 30,000 ft. The prediction scheme is applicable to empty cavities for the parameter ranges:

$$\begin{aligned} 2 &\leq L/D \leq 7 \\ 0.5 &\leq M_\infty \leq 3 \\ 0 &\leq X/L \leq 1, \end{aligned}$$

where X is the distance from the upstream edge of the cavity. Smith and Shaw reported that the prediction scheme is conservative for almost all flight conditions and cavity configurations, *i.e.*, the predicted levels are higher than the measured. The input requirements are the Mach number, the altitude, the length and depth of the cavity. The prediction scheme should be regarded as a preliminary investigation and is not meant to replace a computational fluid dynamics analysis, which would take into account all details of the cavity. In the preliminary prediction scheme, linear acoustic theory is assumed.

4.1 Modal Frequencies

The prediction for frequency is closely based on Rossiter formula:

$$f_m = \frac{U_\infty}{L} \frac{m - 0.25}{M_\infty \left(1 + \frac{\gamma - 1}{2} M_\infty^2 \right)^{1/2} + 1.75}, \quad (4.1)$$

where $m = 1, 2, 3$. Only the first three modal frequencies are considered. It is assumed that the cavity is empty.

4.2 Normalized Modal Sound Pressure Amplitudes

The maximum sound pressure amplitudes in one-third octave bands are listed for the first three modal frequencies. The maximum sound pressures occur close to the downstream face of the cavity for each modal frequency. The estimation of the maximum sound pressure amplitude for mode 2, $P_{2,max}$, is given with reference to the dynamic pressure of the free stream, q , as a function of Mach number M_∞ and L/D :

$$20 \log(P_{2,max}/q) = 25 \operatorname{sech}[2(M_\infty - 1)] - 3.3L/D - 27. \quad (4.2)$$

Note that $\operatorname{sech}[2(M_\infty - 1)] = 2/(e^{2(M_\infty - 1)} + e^{-2(M_\infty - 1)})$. Equation (4.2) enables the nondimensional sound pressure level for mode 2 to be estimated in terms of Mach number and L/D . The maximum sound pressure amplitudes for modes 1 and 3 are referenced to mode 2.

$$20\log(P_{1,\max}/q) = 20\log(P_{2,\max}/q) + 1.5L/D - 13 \quad (4.3)$$

and

$$20\log(P_{3,\max}/q) = 20\log(P_{2,\max}/q) - 13M_\infty + 9 \quad (4.4)$$

4.3 Longitudinal Distribution of Modal Sound Pressure Amplitudes

The longitudinal sound pressure distribution along the cavity for the first three modes is given by:

$$20\log(P_m/q)_{X/L} = 20\log(P_{m,\max}/q) - 10[1 - |\cos\alpha_m X/L| + (0.33L/D - 0.6)(1 - X/L)], \quad (4.5)$$

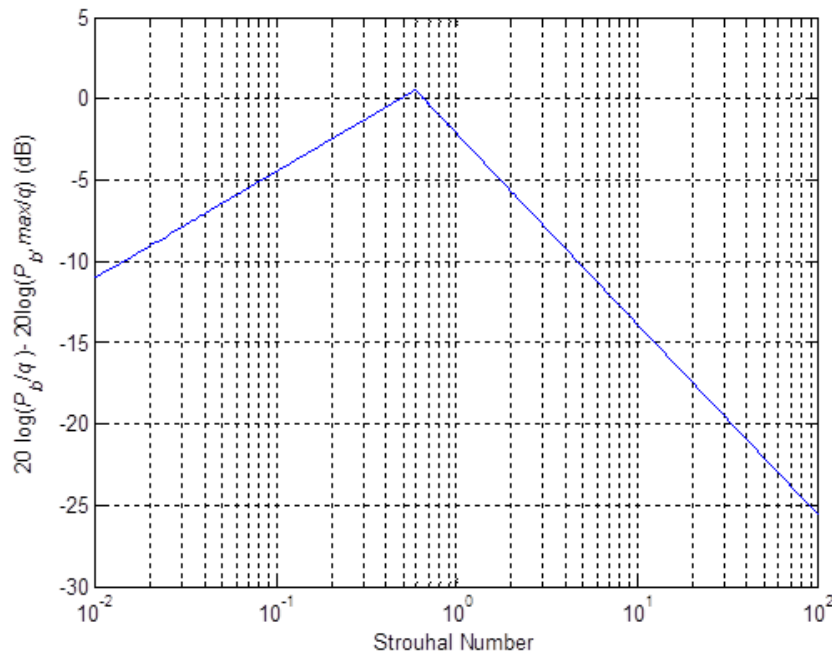
where $\alpha_1 = 3.5$ rad, $\alpha_2 = 6.3$ rad and $\alpha_3 = 10.0$ rad. Note that $20\log(P_m/q)_{X/L}$ are the one-third octave band levels of the r.m.s. sound pressures, normalized with respect to q for the modal frequencies at non-dimensional locations in the cavity. The one-third octave levels of the r.m.s. sound pressure at the rear of the cavity ($X/L = 1$) is typically just less than $20\log(P_{m,\max}/q)$.

4.4 Broadband Sound Levels

The shape of the broad-band spectrum is assumed to be fairly constant, hence it can be represented by a single spectrum shape (Smith and Shaw, 1975). The maximum broadband sound, $P_{b,\max}$, is predicted by means of Equation (4.6).

$$20\log(P_{b,\max}/q) = 20\log(P_{2,\max}/q) + [3.3L/D - 28 + 3(1 - L/D)(1 - X/L)][1.2 - 0.4M_\infty]. \quad (4.6)$$

Equation (4.6) is used in conjunction with Sketch 4.1 (Figure 40 from Smith and Shaw, 1975) in order to determine the broadband sound at a particular centre frequency of a one-third octave. The ordinate in Sketch 4.1 is the logarithm of the non-dimensional, P_b/q , broadband sound at a particular Strouhal number (or frequency) minus the maximum broadband sound given by Equation (4.6), i.e., $20\log(P_b/q) - 20\log(P_{b,\max}/q)$. Note that the Strouhal number is fL/U_∞ .



Sketch 4.1 Broadband sound as a function of Strouhal number (Smith and Shaw, 1975, Figure 40)

4.5 Effect of Stores

For prediction purposes it was recommended that the predictions for the empty cavity should be applied to the cavity with stores. This will tend to be a conservative estimate (Smith and Shaw, 1975).

4.6 Accuracy of Prediction

The predictions that result will be conservative for most flight conditions and cavity configurations. The sound pressure level of the second mode is most accurately predicted. The experimental results at other frequencies are usually written ± 7 dB. Comparison of predicted results with experimental flight measurements are given in Appendix A.

5. DYNAMIC PRESSURE

The prediction formulae are written non-dimensionally in terms of the free stream dynamic pressure q . In order to estimate the predicted sound pressure in Pa (or dB re 2×10^{-5} Pa) the dynamic pressure has to be found in terms of the Mach number and the altitude of the aircraft where the cavity is situated. The free stream dynamic pressure q is given by

$$q = 1/2 \rho U_{\infty}^2, \quad (5.1)$$