Drag and Flow regimes Associated with Rectangular Cavities at Yaw at Low Speeds

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Abstract

The paper presents results of an investigation on the drag characteristics of straight and shallow rectangular cavities including the effects of yaw. All the cavity flow regimes, namely, 'open', 'transitional', and 'closed' were investigated. It was found that for a cavity at zero yaw, the drag based on the projected frontal area of the cavity, increased from 'open' to 'closed'. The effect of yaw was such that the cavity in all cases showed a decrease in drag with increase in yaw angle. The maximum reduction in drag was 35 per cent at a yaw angle of 45 degrees and with a closed cavity.

I Introduction

Better understanding of cavity flows is beneficial because such flows are quite common on aircraft structures, for example, landing gear wells, storage of radar and photographic equipment for surveillance and reconnaissance, as well as weapons bays for stores release [1]. Cavity flows are also important in continuous wave (CW) laser applications, ship hulls [2], and sun roofs and windows in automobiles [3]. In most subsonic and supersonic configurations, the presence of cavities has generally undesired effects. The cavities result in drag and give rise to oscillatory flows which generate noise and vibration of structures that can eventually lead to fatigue and buffeting. In this paper, we report an investigation into drag of shallow rectangular cavities including the effects of yaw. Such data on cavities is sparse at present [4], [5]. The drag of cavities can have a significant impact on aircraft performance particularly with respect to fuel consumption and clean aerodynamics.

In the present investigation, we consider 'shallow' cavities, wherein the depth to length ratio (d/l) of the cavity is much less than unity [6]. The cavities are further classified as 'open', 'transitional' or 'closed' depending on their length to depth ratio l/d [1]. An open cavity is one wherein the length to depth ratio is usually less than 10. Such cavities typify bomb bays and landing gear wells of aircraft. With such cavities, the shear layer, which separates from the cavity leading edge, essentially bridges the cavity length. While the mean pressure in the cavity is nearly uniform, the instabilities in the separated shear layer and the upstream traveling pressure waves that are generated as a result of the shear layer impingement onto the cavity rear wall, produce self sustaining pressure oscillations with sharp acoustic tones. These can give rise to vibrations of the structure, which in turn, can lead to buffeting and fatigue. If the cavity length to depth ratio is greater than about 13, the cavity is said to be closed. Such cavities typically represent missile bays. The flow in such cavities first separates at the cavity leading edge, reattaches on the cavity floor at a short distance downstream, before again separating in front of the cavity rear face and then attaching to the trailing edge of the cavity. The (mean) pressure distribution of such a flow yields a low pressure (compared to the pressure upstream of the cavity) in the forward part of the cavity followed by a near plateau where the flow is attached and then a high pressure region at the rear where the flow is again attached at the trailing edge. The closed cavity generally does not produce strong self sustaining pressure oscillations with acoustic tones. The cavities whose length to depth ratio falls between 10 and

13 are in the transitional range. Those that are at the lower end of this range are some times designated as ‘transitional open’ and those at the higher end ‘transitional closed’. This distinction is less obvious at lower speeds where the transition from totally open to totally closed is more gradual [1]. In the present investigation, the drag of cavities in all these regimes are explored.

II Experimental Details and Techniques

The experiments were carried out in a low speed wind tunnel at a freestream speed of 15 m/s and a Reynolds number of 5.5×10^5 at the cavity leading edge. The boundary layer as measured at the cavity leading edge was 20 mm thick and was found to be turbulent. The Reynolds number based on the boundary layer momentum thickness was 1.33×10^4. The turbulence level in the tunnel was less than 0.3%.

To obtain the desired cavity configurations, one of the test section windows was modified to incorporate rectangular box cavity configurations. The basic cavity had a length (l) of 128 mm and width (w) of 285 mm, thus giving an aspect ratio of 2.22. This adequately satisfies the two-dimensionality criterion as suggested by Ahuja and Mendoza [7]. The cavity, which was milled into the circular window of thickness 18 mm, was 8 mm deep (d) and this was maintained constant throughout. Thus the maximum length to depth ratio (l/d) obtainable was 16. To obtain l/d ratios of 6, 8, and 10, inserts of length 80 mm, 64 mm, and 48 mm were used. Cavities with l/d ratios corresponding to open, transitional open, transitional closed, and completely closed configurations were thus possible. The desired cavity yaw angle could be obtained simply by rotating the window with respect to the freestream direction.

The cavity was provided with 34 pressure ports on the floor and 7 on the cavity face. To obtain pressure data on cavity front and rear faces, the cavity was simply rotated through 180°. There were two additional ports, located across the span at a distance of 132.5 mm with respect to the centreline on the cavity floor. These were used to provide a differential pressure measurement in order to set the cavity leading edge normal to the freestream at zero yaw. The pressures were measured using a scanivalve system in conjunction with a Baratron MK 4 pressure transducer. Overall, the pressure measurement system accuracy was of the order of ±1%. The schematic of the model and pressure tap lacations is shown in Fig. 1.

In addition to the mean pressure data obtained with the above system, fluctuating pressures were also measured using two analog KP101-A type transducers. One was used to measure the pressure on the cavity face and the other on the floor 32 mm from the cavity face. The output from the transducer was connected to a differential amplifier and the output from the amplifier was recorded on an oscilloscope. This was then processed on a computer. The transducers were temperature compensated.

A separate model was employed for the oil flow visualisation experiments. These were carried out mainly as confirmatory tests in support of pressure data and are not reported here. Suffice to note that they showed increasing spanwise flow effects with increase in yaw.

III Results and Discussion

Steady Pressure Distributions

The steady pressure data on the cavity floor at zero yaw ($\psi = 0^\circ$) showed that pressure distributions were consistent with the different cavity configurations as postulated by Tracy and Plentovich [1] following their extensive measurements.

The effect of yaw on steady pressure distributions was such as to reduce the pressure levels throughout the cavity, this effect increasing with increase in yaw angle. Figure 2 illustrates the effect of yaw on steady pressure distributions on the cavity floor. The figure shows variation of pressures measured on the cavity floor nearest to the leading edge and the trailing edge. These pressure taps were within 3 mm to 5 mm from the face of the cavity. The pressures are expressed in terms of the pressure coefficient C_p ($=p-p_\infty/1/2\rho U^2$). As can be seen, all the pressures nearest to the front face, denoted by open symbols, are either zero or negative. And those nearest to the rear face, denoted by filled symbols, are all positive as a result of shear layer impingement at the trailing edge.

As can be surmised from this figure, the effect of yaw is two fold. Firstly, while changes in the cavity front pressures are relatively small with increase in yaw angle, those on the rear are quite large. Secondly, with increase in yaw, the effect of impingement of the shear layer on to the trailing edge becomes less stronger as indicated by the decrease in pressures. This effect is accentuated with the increase in cavity length to depth ratio. Thus the yaw induces cross flows in the spanwise direction and this effect intensifies with the increase in the cavity length to depth ratio of the cavity. This has consequences in terms of cavity drag as will be discussed later.

Unsteady Presures and Spectra

As stated in Section II, the two KPA-101A pressure transducers were used to measure fluctuating pressures within the open cavity that had a length to depth ratio l/d of 6.

Tracy and Plentovich [1] have noted sharp resonant peak amplitudes with open cavities while closed and transitional cavities generally displayed a broadband spectra. The sharpness and amplitude of the spectra was also found to be dependent on the Mach number. The spectra obtained here with the straight open cavity ($\psi = 0^\circ$) with l/d = 6, did show peaks in the frequency range 62.5 Hz $\leq$ f $\leq$ 468.75. However, as has been suggested in Ref. [1], at this very low Mach number, the resonant frequencies were not sharp and distinct. This is also supported by the recent low speed shallow cavity data of Daoud et al. [8]. The progressive reduction in sharpness of the peaks at higher frequencies with lower fluctuating pressure levels (FPL) is indicative of the more broadband nature of pressure fluctuations. Thus, although the peaks in the above frequency range are no guarantee that self-sustaining cavity oscillations exist, it was instructive to verify if they were Rossiter modes [9] and compare them with his semi-empirical theory. The Rossiter formula is:

$$\frac{fl}{U} = \frac{m-\gamma}{M+\frac{1}{\kappa}}$$

where f = tonal frequency, l = length of the cavity, U = freestream velocity, m = mode integer, M = freestream Mach number, κ = ratio of convective velocity of vortices to the freestream velocity U, γ = a constant defining the time lag between the arrival of the vortex at the cavity trailing edge and the emission of the main acoustic pulse directed towards the upstream leading edge. Rossiter assumes constant values for both γ and κ with $\gamma = 0.25$ and $\kappa = 0.57$ based on experimental observations. This has been confirmed subsequently by many researchers.

Figure 3 shows this comparison. Here the experimental values for modes m = 1,2,3, and 4 are compared with those calculated using the above Rossiter formula. The straight line through the experimental data has a slope of 0.71 instead of the ideal value of unity. Also shown is the data of Tracy and Plentovich [1] for an open cavity of l/d = 6 at M =0.2, the lowest mach number of their experiments. It has a slope of 1.1. These data suggest that Rossiter type resonance might be occurring in the present case although the Mach number (0.044) here is very much smaller. Also, Howe [6] points out that for cavities with l/d > 2.5 and speed range up to sonic, cavity acoustic modes can be dominated by Rossiter type resonance. Further, Daoud et al. [8] discuss, at some length, the conditions for the existence of Rossiter modes in very low Mach number cavity flows. They point out that for Rossiter modes to exist, the cavity length must exceed a minimum threshold given by $l_{min} \approx 8000\theta Re_\theta^{-1/2}$ based on the earlier work of Sirohia [2] and Gharib and Roshko [10]. Here θ is the momentum thickness of the separating boundary layer at the cavity leading edge and Re_θ is the Reynolds number based on the momentum thickness. Based on this criterion, for the present experimental conditions, l_{min} /d ≈ 1.7 so that Rossiter modes are possible.

The pressure spectra of this cavity at different angles of yaw showed only weak broadband levels with no discernible peaks. The results for transitional and closed cavities were also broadband with no resonant peaks. Tracy and Plentovich [1] data also show that pressure spectra are mainly broadband for transitional and closed cavities for all yaw angles.

The Cavity Drag

The cavity pressure drag based on the average pressures on the front and rear faces of the cavity and based on the projected frontal area is expressed in terms of the ratio C_D/C_f following Squire and Nasser [11]. Here C_D is the cavity pressure drag and C_f is the skin friction on the surface at the cavity position in the absence of the cavity. Then, this ratio corresponds to the cavity pressure drag to the friction drag based on the same projected frontal area. The value of the skin friction drag was calculated using the flat plate turbulent skin friction relation as suggested by White [12].

The cavity pressure drag was determined using the average values of the seven pressure ports on the two cavity faces.

Figure 4 shows the drag variation of straight cavities (ψ=0°) plotted against the inverse of the cavity length to depth ratio. The drag increases monotonically with the cavity length to depth ratio and a nearly linear relationship is seen to exist. It is also interesting to note that the cavity drag is nearly 70 times the skin friction drag for the shortest (open) cavity and increases to nearly 170 times the skin friction drag for the longest (closed) cavity. The results also confirm the justification of the assumption made in the cavity flow analysis that the skin friction drag is negligible compared with the pressure drag.

Figure 5 shows the results for the drag of straight cavities (ψ =0°) in terms of C_D^*, where the drag coefficient is based on the *plan* area of the cavity. This method of expressing the cavity drag is also due to Squire and Nasser [11]. The abscissa is the inverse of the relative boundary layer thickness. The results expressed in this way, are more revealing. Secondly, in the present experiments, the approaching boundary layer was kept constant while the cavity length was varied. We note that the drag initially increases from open cavity case reaching a maximum for the transitional open cavity and then gradually decreases as the cavity becomes fully closed. It is also interesting to note that the values of open and closed cavities are almost the same.

Also shown in Fig. 5 are the theoretical and experimental results of Haugen and Dhanak [13]. These authors performed an analytical and experimental investigation of short and deep cavities in low speed flow with a turbulent approaching boundary layer at the cavity leading edge. The cavity length to depth ratio varied from 0.33 to 1.0 so that the cavities investigated were quite deep.

Haugen and Dhanak also found that the approaching boundary layer had a substantial influence on the cavity drag. Both their theoretical and experimental results showed that for a given cavity length, the drag decreases with the increase in the boundary layer thickness. Their theoretical calculations showed that the drag almost halved when the relative boundary layer thickness (δ/l) increased from 0.1 to 1.0. However, their experiments were only confined to the range $0.1 \le \delta/l \le 0.6$.

In the present experiments all the cavities are shallow and cover all the regimes, open to transitional and closed. The relative boundary layer thickness δ/l varied between 0.16 and 0.41. However, we note that the drag values are increased by more than a factor of three for both open and closed cavities and by nearly a factor of four for transitional cavities. It would appear that when the cavities are short and deep as in the case of Haugen and Dhanak [13], the mean dividing streamline completely bridges the cavity and the vortex/vortices (depending on cavity depth) are trapped. This would imply that the maximum shear stress occurs on the dividing streamline and the momentum transfer from the external flow to the cavity is less. With the shallow cavities, however, where the length to depth ratios are large, the mean dividing streamline is curved even for a marginally open cavity and the cavity vortex is stretched and may be on the verge of being split. With the transitional cavities, the situation is accentuated and the dividing streamline becomes highly concave towards the cavity floor and the single cavity vortex is split creating two separated flow regions in front of the front and rear faces with no clearly attached flow in the cavity and an unstable situation prevails. This would lead to a substantial increase in drag. When the cavity is completely closed, there are two clearly defined separated flow regions at the front and rear faces and a stable attached flow region on the cavity floor. This results in a reduced drag as evidenced by the present experimental data. There is as yet no theory to explain the drag behaviour of long shallow cavities.

The effects of yaw for cavities of different length to depth ratio are shown in Fig. 6. The features to be noted here are, firstly, that the drag decreases with increase in yaw for all the cavities. Secondly, although the drag reductions for different types of cavities show considerable scatter, they generally seem close to the cosine variation of the yaw angle ψ. Also shown on the figure is the theoretical variation of the normal component of the drag force for an *infinite* span cavity in the spirit of Jones [14]. It is seen that the agreement seems marginally better with the simple cosine variation than the theoretical $\cos^2\psi$ variation. This is possibly due to the fact that the cavity aspect ratio is finite in these experiments while the theory assumes infinite span. These results seem to indicate that the effects of cross flows is such as to reduce the impingement effect of the shear layers on to the cavity trailing edge, which would cause a reduction in the magnitude of pressures on the cavity rear face, resulting in reduced drag. The pressure distribution data shown in Fig. 2 confirm this possibility. This was also confirmed by the oil flow visualisation tests.

A comment needs to be made about these results when comparing with the low speed data of Savory et al. [4] and Czech et al. [5]. These authors found that there was an increase in drag with yaw angle up to about 60° and then a steep decrease. However, it needs to be noted that in both their experiments the cavities were deep with d/l=0.5 and w/l=2. The cavity configuration in their case was thus strongly three- dimensional and included the contribution of end wall effects to the total drag. In the present case, the contribution of end wall effects to drag is not included as there was no provision to measure pressures on the end walls. The results, therefore, pertain to drag force normal to the cavity leading edge. Also, in the present experiments, the cavities are shallow with $0.0625 \leq d/l \leq 0.166$ and the aspect ratio varied from 5.93 to 2.2 depending on the cavity length. The cross flow component of the drag, therefore, would not be a significant fraction of the total drag.

IV Conclusions

The steady pressure distributions showed that flow features at zero yaw were consistent with open, transitional, and closed cavity configurations as found in previous studies.

The effect of yaw on steady pressure distributions was such as to reduce the pressure levels in the cavity, this effect increasing with increase in yaw angle.

The unsteady pressure spectra showed that the open cavity at zero yaw generates Rossiter type self sustaining resonant tones although the frequencies were not very sharp and distinct. The agreement between the experimental Strouhal numbers and those calculated using the Rossiter formula was fair at best. This feature of low speed open cavity flow is consistent with previous observations. The frequencies for transitional and closed cavities were all broadband with no well defined resonant tones. The effect of yaw on unsteady pressures was to yield only a broadband spectra.

At zero yaw, the study showed that the cavity pressure drag, based on the projected frontal area, increased as the cavity flow regime changed from open to, transitional, to fully closed.

However, when the drag is expressed in terms of the cavity plan form area, the zero yaw drag initially increased from open cavity flow regime reaching a maximum for the transitional open flow cavity and then showed a gradual decrease towards a fully closed cavity regime. These shallow cavity drag values were found to be 3 to 4 times higher than those of short deep cavities as calculated and measured by Haugen and Dhanak.

With increase in yaw the drag component normal to the cavity leading edge showed a decrease for all cavity configurations. Although the data showed a considerable scatter, they generally followed the cosine variation of the yaw angle. The drag reductions were up to 35% at the highest yaw angle tested.

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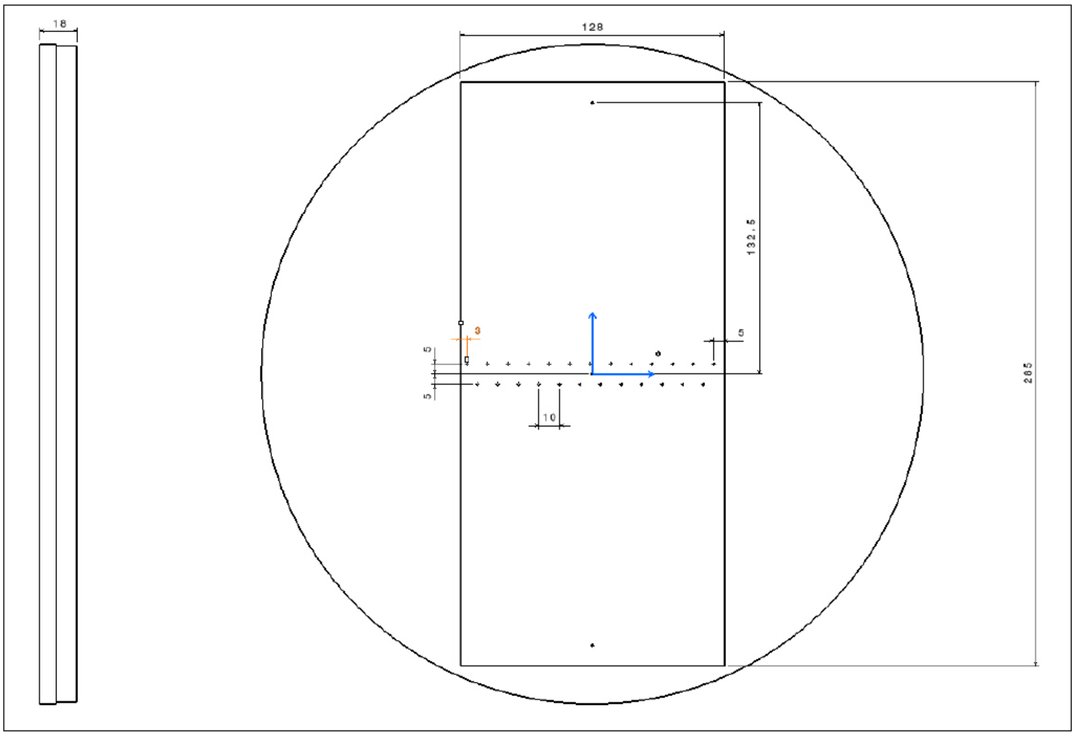

Fig.1. Schematic of model and pressure tap locations. Dimensions in mm

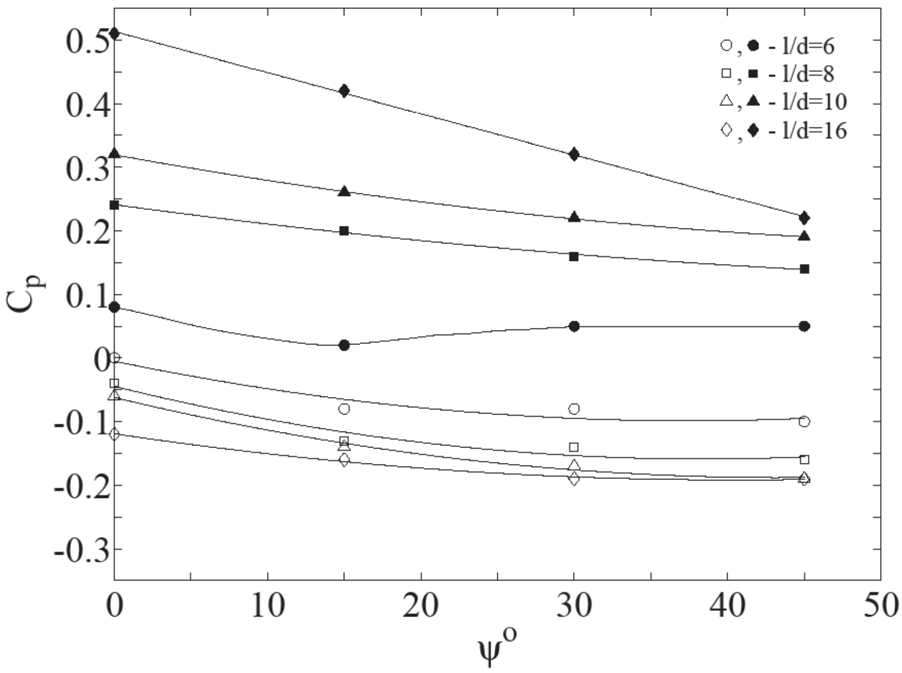

Fig.2. Steady pressure distribution showing effect of yaw

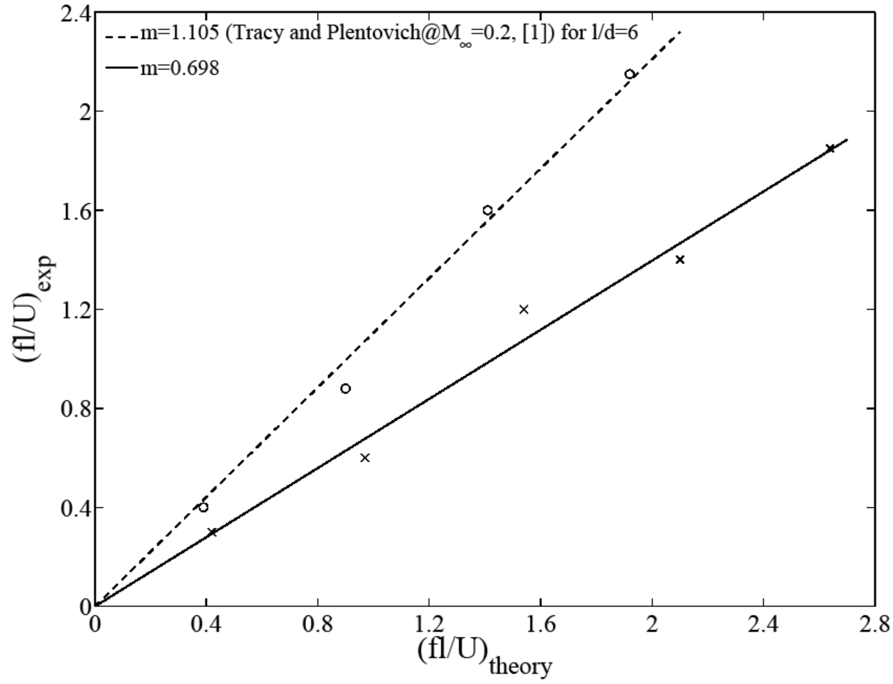

Fig.3. Comparison of experimental and theoretical Rossiter frequencies for l/d=6 at low speeds

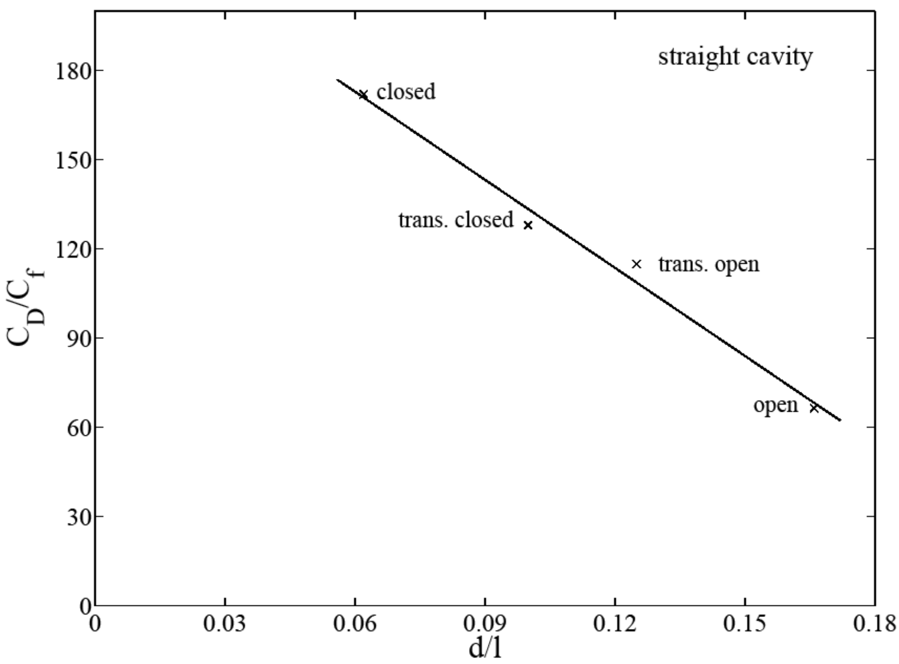

Fig.4. Variation of drag with length to depth ratio for shallow rectangular cavities

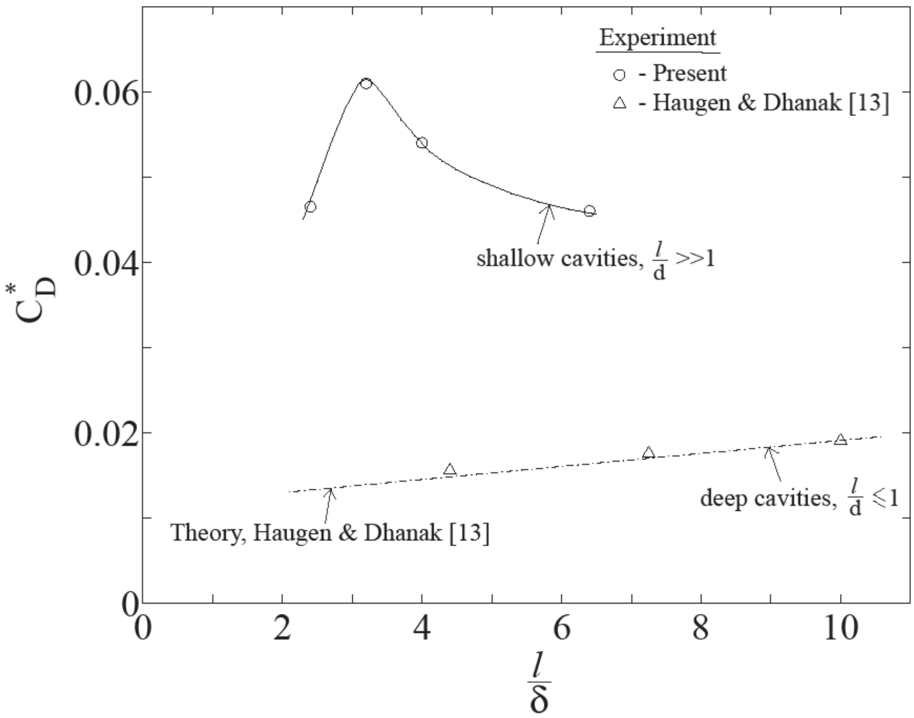

Fig.5. Drag of cavities VS Relative boundary layer thickness

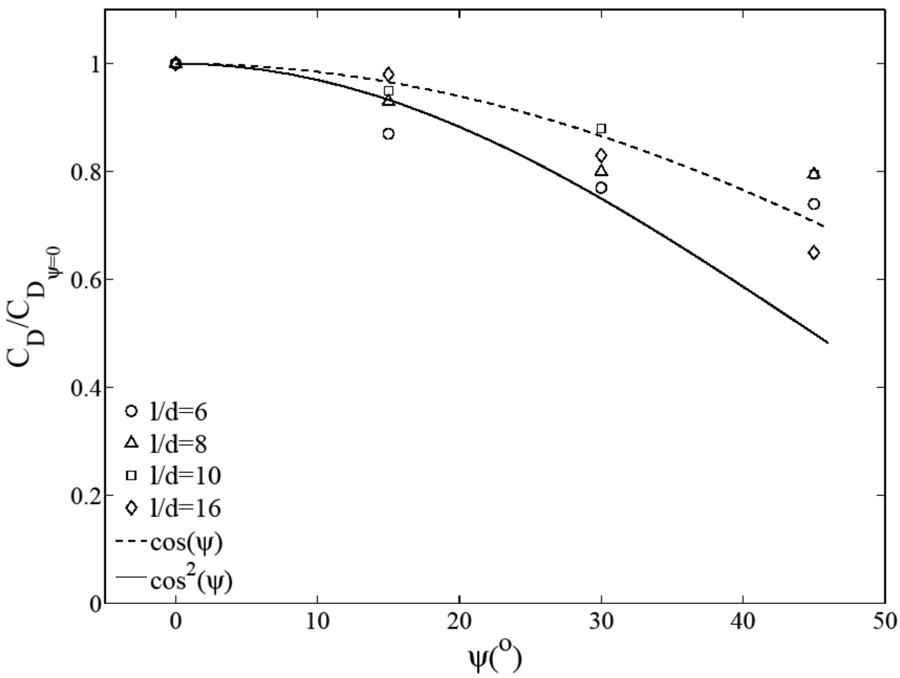

Fig.6. The relative drag coefficient as a function of yaw angle for shallow rectangular cavities

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