Effects of a Base Cavity on Subsonic Near-Wake Flow

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An experimental investigation has been conducted to study the effects of a base cavity on the near-wake flowfield of a slender, two-dimensional body in the subsonic speed range. Three base configurations were investigated and compared: a blunt base, a shallow rectangular cavity base of depth equal to one-half the base height, and a deep rectangular cavity base of depth equal to one base height. Each configuration was studied at three freestream Mach numbers ranging from the low to high subsonic range. Schlieren photographs revealed that the basic qualitative structure of the vortex street was unmodified by the presence of a base cavity. However, the vortex street was weakened by the base cavity apparently due to the enhanced fluid mixing occurring at the entrance of the cavity. The weaker vortex street yielded higher pressures in the near wake for the cavity bases, increases in the base pressure coefficients on the order of 10–14%, and increases in the shedding frequencies on the order of 4–6% relative to the blunt-based configuration. The majority of the observed changes occurred in going from the blunt base to the shallow cavity base.

Nomenclature

C_p	= coefficient of pressure, $\equiv (P - P_{\text{ref}})/(1/2\rho_{\text{ref}} U_{\text{ref}}^2)$
d	= cavity depth
f	= frequency
h	= base height
M	= Mach number
P	= pressure
Re	= Reynolds number, $\equiv \rho_{\text{ref}} U_{\text{ref}} h / \mu_{\text{ref}}$
St	= Strouhal number, $\equiv fh/U_{\text{ref}}$
U	= freestream velocity
x	= streamwise coordinate measured from the trailing edge plane
μ	= absolute viscosity
ρ	= density

Subscripts

base	= base location
ref	= reference location
∞	= freestream conditions

Introduction

THE near wake of a two-dimensional bluff body at subsonic Mach numbers and sufficiently high Reynolds numbers (greater than 50 based on freestream conditions and body thickness) is dominated by the periodic and alternate shedding of vortices known as the von Karman vortex street. When these vortices form near the leeward side or base of the body, the low pressure of the vortex centers is communicated to the base producing a low-base pressure. This combines with the momentum loss associated with the concentrations of vorticity to yield an especially high-base drag. The von Karman vortex street occurs frequently in engineering applications and has even been observed behind such slender bodies as turbine blades of just 3% thickness ratio.[1] Because the base drag (often the dominant drag component) of both bluff and slender two-dimensional bodies is affected by the strength and proximity of the vortex street, any attempts at base drag reduction must be aimed at weakening the vortex shedding or at displacing the vortex formation position further downstream.

The present investigation focuses on the use of a base cavity as a drag reducing mechanism and on the effect of such a cavity on the near-wake flowfield of a two-dimensional slender body in the subsonic speed range (see Fig. 1). The base cavity has proven effective in reducing drag in several past investigations. However, the precise mechanism of this drag reduction is still unknown. Therefore, the present study is aimed at investigating the interaction between the cavity and the separated flow and the effect of this interaction on the fluid dynamic mechanisms in the near wake. The specific objectives of the investigation are to explain the drag reducing effect of the base cavity, to improve understanding of the phenomena of vortex formation and shedding, and to resolve some of the conflicts that have arisen between the numerical and experimental work on base cavities to date.

Experimental investigations of the base cavity have been conducted by Nash et al.,[2] Pollock,[3] and Clements[4] among others. They have studied cavity depths of from zero to two base heights on slender, two-dimensional bodies. Generally, they have found base drag reductions of 15–20% in the subsonic speed range and no effect into the supersonic speed range. The lack of any effect at supersonic speeds is evidence that the cavity acts on the vortex street since vortex shedding ceases at Mach numbers just beyond 1.0. Clements investigated cavities of various depths and reported base pressure increases for increasing cavity depths up to 1/2 base height, beyond which no further increases in base pressure were observed. Clements also measured a rise in the Strouhal number (i.e., vortex shedding frequency) for increasing cavity depth up to 1/2 base height. Although Nash et al. hypothesized that the walls of the cavity may constrain the upstream part of the vortices and thus improve wake stability, their schlieren photographs did not appear to show any vortex motion extending into the base cavity.

Two important computational efforts on the effects of base cavities have been carried out by Clements[4] and Rudy.[5] Clements employed an inviscid discrete vortex method, whereas Rudy used an explicit, Navier-Stokes, finite-differ-

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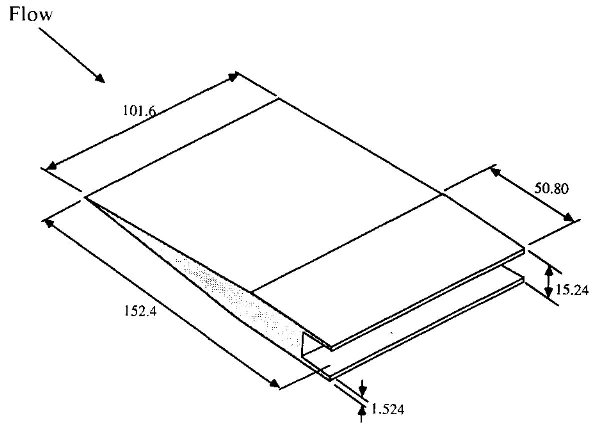


Fig. 1 Schematic of model (dimensions in mm).

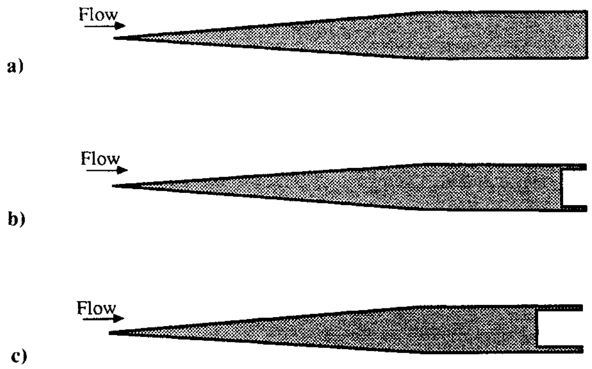


Fig. 2 Model configurations under investigation: a) blunt base; b) shallow cavity base, depth = 1/2 base height; c) deep cavity base, depth = 1 base height.

ence scheme at freestream Mach numbers of 0.4 and 0.6 with laminar Reynolds numbers (based on freestream conditions and the base height) of 700 and 962, respectively. Both investigators studied the effects of a rectangular cavity in the base of a slender, two-dimensional body at subsonic speeds. Clements and Rudy both found that the vortices penetrate partially into the cavity for at least a portion of the shedding cycle. Rudy reported that the pressure rises in the low-velocity region between the first vortex and the back of the cavity yielding a higher base pressure for the cavity base as compared to the blunt base. Because of this result, Rudy hypothesized that the drag reducing effect of the base cavity is similar to that of splitter plates and base bleed,[6-11] i.e., it is due to the increased distance between the base of the body and the vortex formation location. Interestingly, both Clements and Rudy computed a continuous decrease in the Strouhal number with increasing cavity depth in direct contrast to the experimental results of Clements. Rudy attributed the decrease in shedding frequency to the increase in interaction between the vortices in the presence of a cavity.

Experimental Setup

Wind-Tunnel Facilities and Model

A previously fabricated two-dimensional transonic wind tunnel was used in this investigation. This tunnel has a 101.6 mm × 101.6 mm test section and was built based on a NASA design by Little and Cubbage.[12] The sidewalls of the tunnel are solid, whereas the upper and lower walls are slotted to relieve the blockage effect of the model and to allow experimentation through the transonic speed range. A pair of round windows may be mounted in the sidewalls to allow visualization of the flow over the aft end of the model and in the near wake. Solid aluminum inserts may also be used in place of the windows for the wake static pressure traverses and shedding frequency measurements described below. The results of tunnel-empty calibrations at Mach numbers from the low subsonic through transonic speed ranges demonstrated that this tunnel produces remarkably uniform flow.

To accomplish the objectives of this study, the two-dimensional model illustrated in Fig. 1 was constructed. The model has a wedge-shaped forebody, a constant 10% thick afterbody, and three interchangeable base geometries (see Fig. 2): a blunt base, a shallow rectangular cavity base with depth equal to one-half the base height, and a deep rectangular cavity base with depth equal to one base height. This model is similar to that used in the experiments of Nash et al.[2] and is identical to the computational geometry used by Rudy,[5] except that Rudy's cavity heights were 90% of the base height, and those of the current experiments were 80% of the base height to ensure structural rigidity of the extended portions of the base.

The maximum blockage of the model in the wind tunnel of this study was 15% (see Fig. 1), which is a bit high by transonic tunnel standards. This model size was chosen to be as small as possible to minimize blockage effects while remaining large enough to adequately instrument the base with pressure taps and so that the flowfield could be adequately resolved with the available measurement techniques. In addition, larger than normal interference effects were deemed acceptable in light of the objectives of this investigation to study the physical mechanisms of the flowfield and the trends that the data exhibit with either increasing cavity depth or increasing Mach number. These mechanisms and trends should be accurately reflected in the current measurements even if small errors in the absolute values of the data occur due to interference effects. Also, the basic structure of the vortex street, which is of prime importance here, should not be strongly affected by the blockage of the model. As evidence, El-Sherbiny and Modi[13] found that the lateral and longitudinal spacings of the vortices in the wakes behind inclined flat plates were independent of blockage ratios up to 20%.

Measurement Techniques

Black and white schlieren photography was used to visualize the structure of the vortex streets behind the model and to determine to what degree the vortex motions extended into the cavities. The schlieren system used was a standard Toepler arrangement with the sending and receiving optics located off axis in the familiar "z" pattern and with parabolic mirrors directing the parallel light beam through the test section. A straight knife edge in the cut off plane provided exposure and sensitivity control and was set parallel to the flow direction (i.e., horizontally) to allow visualization of the separating shear layers. The light source was a Xenon model 457 flash lamp with a flash duration of 1.4 μs. Processing of large numbers of photographs was accomplished via a 35 mm format camera and Kodak Panatomic-X (ASA 32) roll film.

Surface oil flow visualization was utilized to ascertain flow directions within the cavities and on the model and to examine the streakline patterns formed on the tunnel sidewalls. A mixture of lampblack and a 90 weight viscous oil was used for this purpose. This mixture was either spread evenly on the surface of interest with a paint brush or applied as discrete dots of oil to yield highly defined surface streakline patterns.

Tuft visualization was used to further examine the air motions within the cavities and to complement the results of the surface flow studies. Short strands of a lightweight white thread were fixed with small dots of rubber cement to the trailing edge of the deep cavity, whereas several others were suspended from the upper cavity wall at depths of 1/3, 1/2, and 2/3 base heights from the entrance.

Base pressure measurements were made to determine the effect of cavity depth on base drag. Fifteen static pressure taps were distributed across each base so as to reveal any variations in pressure across the span or height of the base. These taps were connected via nylon tubing to a Pressure Systems Incorporated (PSI) model DPT 6400 electronic pressure scanner. The output from the PSI system was directed to an HP-9000 minicomputer for data analysis and storage.

Vortex shedding frequency measurements were made to determine the effect of the cavities on the shedding frequency and to help resolve the previously mentioned conflict between numerical and experimental results. The shedding frequencies were determined from a Fourier analysis of the signal from fast response pressure transducers. The transducers used were Endevco model 8506B-15 piezo-resistive pressure transducers, which have a 2.31 mm face diam and a resonant frequency of 130 kHz. The data from the transducers were collected with a DEC PDP 11/73 microcomputer using a Data Translation model DT2752 high-speed, 12 bit, 8 channel, A/D converter. For each Mach number-base geometry configuration, 50 sets of 4096 data points were collected at a sampling rate of 20 kHz yielding a bandwidth of approximately 4.88 Hz. The time domain pressure data were analog filtered at 80% of the Nyquist rate (i.e., 8000 Hz) to prevent aliasing and were transformed into the frequency domain via a fast Fourier routine utilizing the Hanning window to suppress side-lobe leakage. The data sets were also averaged in the spectral domain to filter out low-level white noise.

Static pressure surveys of the wake were performed in order to define the position of vortex formation for each of the base configurations. This method has been employed in previous investigations by Nash et al.[2] and Roshko,[6] who state that the location of a low-pressure trough in the wake behind a body coincides with the position of vortex formation. Four different 3.175 mm diam static probes were used with the static holes ranging in distances from 3.175 to 12.5 mm from the tip of the probe. Eight exit holes were drilled in the solid sidewall insert at intervals of 7.62 mm (1/2 base height), and in conjunction with the four probes, these gave up to 32 possible pressure measurement locations from the base of the body to a distance of four base heights downstream. Data gathering and reduction followed the same procedures as described previously for the base pressure measurements.

Further details concerning the experimental apparatus, instrumentation, and measurement and data reduction procedures may be found in Ref. 14.

Experimental Results

Experimental Conditions

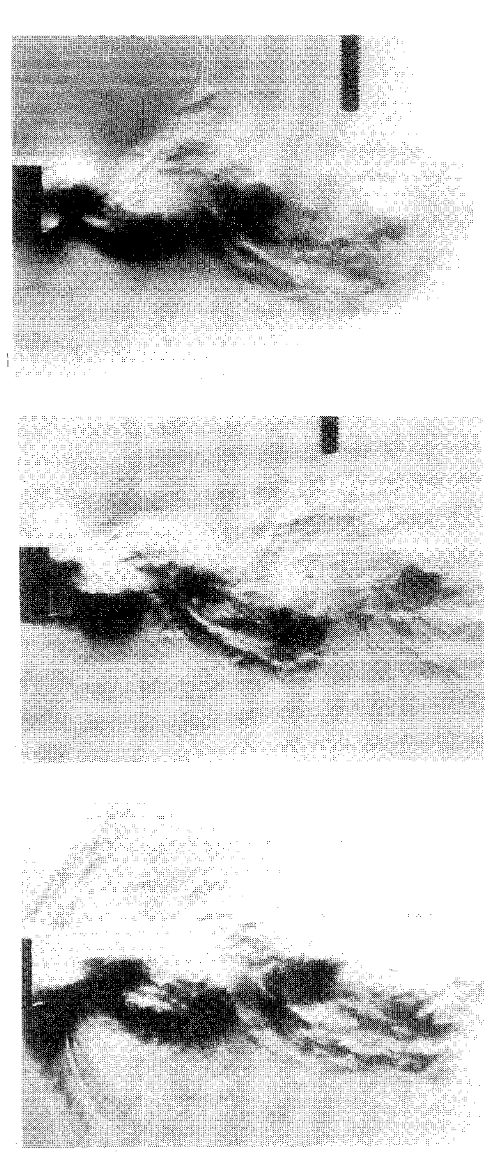
The experimental results for the three base geometries shown in Fig. 2 were obtained at three different Mach numbers ranging from the low to the high subsonic range to give a total of nine different experimental conditions (see Table 1).

Rather than try to apply a freestream Mach number correction to account for the effects of model blockage, a reference Mach number was specified as measured in the tunnel, i.e., without correction factors, that would be most relevant to the flowfield region of greatest interest, namely the vortex street and near wake. Thus, the reference Mach number was chosen to be that outside the boundary layer over the aft end of the model just prior to separation. The three values of the reference Mach number shown in Table 1 were chosen to correspond approximately to freestream flows at Mach 0.4, 0.6, and 0.8. The reference of 0.880 was chosen by matching the schlieren photograph at that condition to the schlieren of Nash et al.[2] of a freestream Mach 0.8 flow over the same model geometry in a much larger tunnel with essentially interference-free conditions. The reference of 0.720 was chosen via Rudy's[5] computations, which indicate that at a freestream Mach number of 0.6 the Mach number over the aft end of the body is 0.720. Finally, the reference of 0.485 was chosen by setting the upstream Mach number in the tunnel to 0.4, as it was known that interference effects would be relatively small at the lower Mach number.

The Reynolds numbers listed in the table are based on conditions at the reference location and the base height. Boundary-layer trips (0.25 mm diam hypodermic tubing) were placed at the 10% chord location to fix the transition points. Thus, the boundary layers at separation from the base were turbulent in all cases. The boundary-layer thickness at separation for each case was estimated to be 1.5 mm from enlarged schlieren photographs.

Table 1 Experimental conditions

Base type	Ref. Mach no.	Ref. Reynolds no., $\times 10^5$
Blunt base	0.485	1.62
	0.720	2.32
	0.880	2.78
Shallow cavity	0.485	1.62
	0.720	2.32
	0.880	2.78
Deep cavity	0.485	1.62
	0.720	2.32
	0.880	2.78



a) b) c)

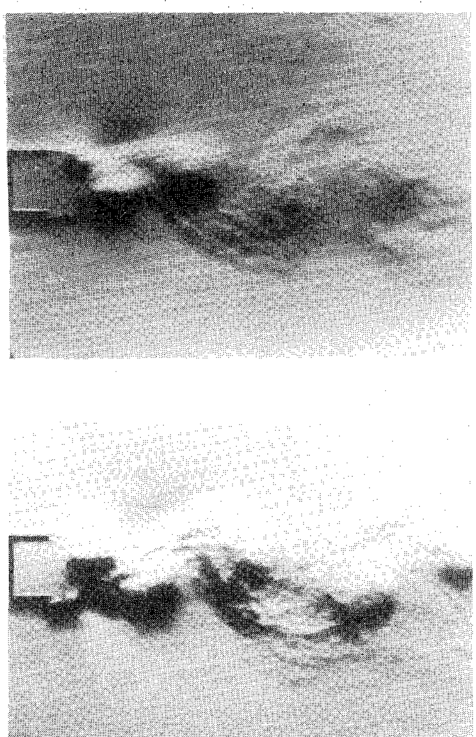
Fig. 3 Schlieren photographs of the near-wake flowfield for the blunt-base configuration: a) $M_{ref} = 0.485$; b) $M_{ref} = 0.720$; c) $M_{ref} = 0.880$.

Schlieren Photographs

Schlieren photography was used to visualize the structure of the vortices behind the models and to reveal any qualitative differences that may exist in the near wakes of the flows for the different base configurations and Mach numbers. Figure 3a depicts the flow over the model fitted with the blunt base at a reference Mach number of 0.485 (the screw visible in the photograph was used for focusing purposes and is outside the tunnel). In this case the vortex shed from the upper surface of the body has apparently reached the fully formed condition, whereas the shear layer separating from the lower surface is just beginning to roll up. It is clear from this figure that the vortices form right at the base of the body and that in the fully formed condition, the vortices extend over the majority of the thickness of the base. Figures 3b and 3c show the flowfield over the blunt-based model at reference Mach numbers of 0.720 and 0.880, respectively. The basic features of the near-wake flowfield for these cases are similar to the Mach 0.485 flowfield, except that the vortex street becomes more obscured by turbulence at the higher Mach numbers and at Mach 0.880 pressure waves generated from the vortex shedding are evident at the base of the model. Comparison of these schlieren photographs with Rudy's[5] computed vorticity contour plots for a freestream Mach 0.6 flow over the same blunt-based configuration indicates excellent qualitative agreement for the near-wake structure, particularly in terms of the proximity of the vortex formation location to the base. Some minor differences, such as more rapid diffusion of the vortices in the experiments, may be attributed to the fact that the boundary layers at separation are turbulent in the experiments and laminar in the computations.

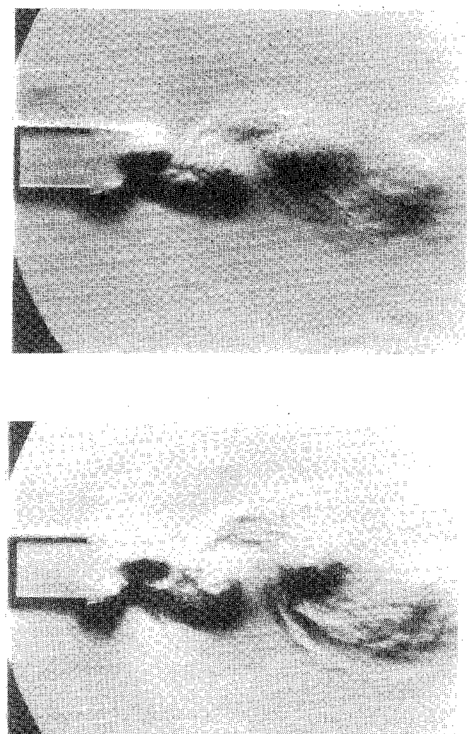
Figures 4a and 4b are schlieren photographs of the flow over the model fitted with the shallow cavity base at reference Mach numbers of 0.485 and 0.720, respectively. The basic structure of the vortex street appears unchanged in comparison to the blunt-based configuration just discussed. By comparing schlieren pictures of the flow for the two geometries at similar points in the shedding cycle, the spacing of the vortices and the spread rate of the vortex street in the early part of the wake appear virtually identical, as though the base cavity does not influence the vortex formation and shedding process at all. However, a closer examination shows that for the cavity base, the vortices may form slightly farther downstream of the trailing-edge plane; whereas this is impossible to confirm from a single still photograph. This point will be discussed further in light of other experimental results to be presented in the sections to follow. The main difference between the various Mach number conditions for the shallow cavity base is again the presence of more turbulence at the higher Mach numbers resulting in greater diffusion of the vortices. Comparison of Rudy's[5] computed vorticity plots with these schlieren photographs for the shallow cavity base shows that the experimental and computational results are not in agreement for this case. The schlieren pictures (including many others not shown here) indicate clearly that the vortices do not extend into the cavity during any portion of the shedding cycle, whereas Rudy's computational results (as well as those of Clements[4]) indicate that the vortices form at least partially within the cavity throughout the shedding cycle. This discrepancy between experiments and computations for base cavity flows was also reported by Clements. Further discussion of this point will follow the presentation of the remainder of the experimental results.

Figures 5a and 5b depict the flow over the model fitted with the deep cavity base at $M_{ref} = 0.485$ and 0.720, respectively. Again the basic structure of the vortex street wake appears unchanged in comparison to the wakes of the two base configurations discussed above. In fact, Figs. 4b and 5b at $M_{ref} = 0.720$ look virtually identical except for the geometry of the base itself. For the deep cavity base, as for the shallow one, it appears that the vortices form slightly further downstream of the trailing-edge plane than they did for the blunt-based configuration. Comparing the schlieren photographs of Fig. 5 with Rudy's[5] constant vorticity lines for the Mach 0.6 computations of the deep cavity configuration indicate the



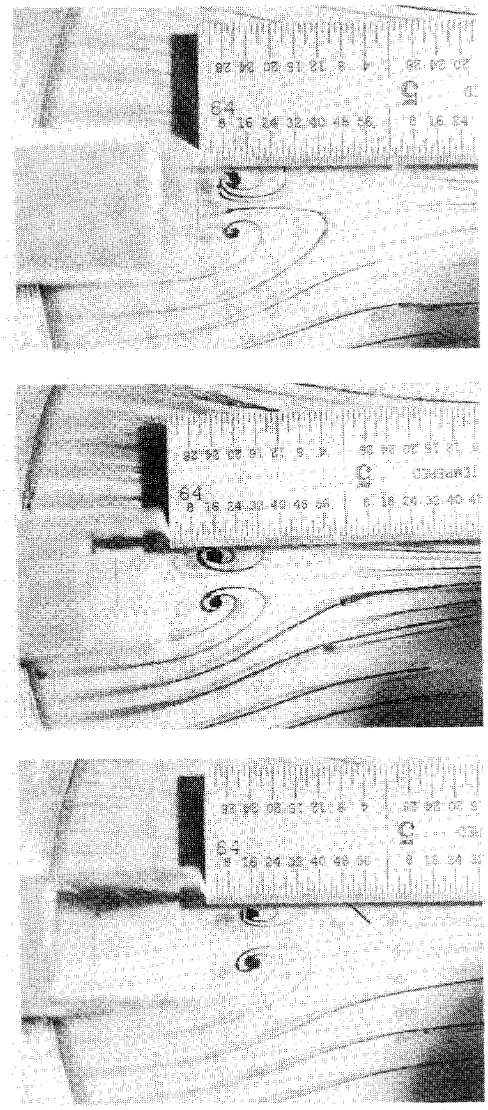
a) b)

Fig. 4 Schlieren photographs of the near-wake flowfield for the shallow cavity base configuration: a) $M_{ref} = 0.485$; b) $M_{ref} = 0.720$.



a) b)

Fig. 5 Schlieren photographs of the near-wake flowfield for the deep cavity base configuration: a) $M_{ref} = 0.485$; b) $M_{ref} = 0.720$.



a)

b)

c)

Fig. 6 Oil streak patterns on sidewall for $M_{ref} = 0.485$; a) blunt-base configuration; b) shallow cavity base configuration; c) deep cavity base configuration.

same discrepancy between the computational and experimental results noted above: the schlierent photographs show no vortex motion extending into the cavity whatsoever, whereas the computations show the vortices extending well into the cavity throughout the shedding cycle. As mentioned, this point will be discussed further below.

Surface Oil-Flow Patterns

The surface oil-flow visualization results presented here are intended to answer several important questions regarding the qualitative nature of the flowfield: first, to ascertain that the flow in the tunnel is satisfactorily two dimensional; second, to determine whether any significant fluid motion occurs within the base cavities; and finally, to help determine if the vortices form farther downstream from the trailing-edge plane for the cavity bases in comparison to the blunt-based model, as was hinted at by the schlieren stills.

The oil-flow patterns across the span of the upper surface of all three models and for all three reference Mach numbers indicated that the flow was appropriately two dimensional, i.e., the streaklines were extremely straight and in the streamwise direction with no recirculatory regions even very near the sidewalls. For the blunt-based model, essentially vertical streak patterns on the base were formed from a series of oil dots placed across the span of the base midway between the upper and lower trailing edges. Apparently, the mean effect of the vortices shed from alternate trailings edges was to push some of the oil to the upper trailing edge and some to the lower trailing edge. The clarity and rapidity with which these streak patterns formed indicates that the vortices do indeed form immediately adjacent to the base for the blunt-based model, as was evident in the schlieren photographs of Fig. 3.

To determine the surface flow patterns on the internal cavity surfaces of the two cavity configurations, oil was spread on all cavity surfaces, and even as discrete dots very near the lip of the cavity. However, no streak patterns were formed on any of these internal cavity surfaces. This indicates that there is no strong vortex motion extending into the cavity and that apparently no significant recirculatory motion occurs in the cavity at all. The specifics of the air motions, if any, in the cavities will be discussed in some of the results to follow.

Figures 6a–6c are reproductions of the near-wake oil streak patterns that were formed on the wind-tunnel sidewalls for each base configuration with a scale placed so as to indicate the distance of the oil "vortices" from the trailing-edge plane. The reference Mach number for these figures is 0.485, although similar patterns were formed for all three reference Mach number conditions. These streak patterns simply represent the time-mean effect of the unsteady vortex street wake phenomenon as determined at the tunnel sidewall. The centers of the vortices of oil that formed on the sidewall are considered to indirectly represent the correct relative position of vortex formation for the three base configurations. In other words, while the absolute position of vortex formation relative to the trailing-edge plane may not be correctly represented due to the time-averaging and sidewall boundary-layer effects, the position of vortex formation for one base geometry relative to the other bases should be approximately correct assuming that these effects influence the oil streaks for all three base configurations approximately equally. These photographs indicate the center of the sidewall oil vortex to be about 3/16 in. (4.76 mm or 0.31 base height) from the trailing edge for the blunt base and about 1/4 in. (6.35 mm or 0.42 base height) for the two cavity bases, a difference of approximately 1/16 in. (1.59 mm). Similar results were found at reference Mach number conditions of 0.720 and 0.880. Therefore, these photographs suggest the qualitative fact that the vortex formation position for the cavity bases is further downstream from the trailing-edge plane relative to that for the blunt-base configuration. Further support for this argument is presented in the section discussing the wake static pressure traverses.

Tuft Visualizations

The fact that the surface oil-flow patterns showed no significant recirculatory flow in the cavity revealed the need for a more sensitive measurement technique to determine if any fluid motion occurs in the cavity. To this end the tuft visualization experiments described earlier were performed with several lightweight tufts attached to the trailing edge of the deep cavity, as well as from the upper cavity wall at several depths from the cavity entrance. The tufts at the trailing-edge plane were extremely active, rotating rapidly back and forth in the streamwise direction in a 75 to 80 deg arc, nearly 45 deg in the downstream direction and roughly 30 to 35 deg back upstream into the cavity. Some spanwise motion was also observed, though to a much lesser extent. This high degree of activity is not unexpected; since the vortices form close to the trailing-edge plane even for the deep cavity; the tufts there are subjected to a rapid periodic pressure variation. For the tufts suspended further back in the cavity, the motion was similar, but the level of activity decreased gradually from the trailing edge to the back of the cavity. These results suggest that the periodic pressure pulses from the shedding vortices set the air in the cavity into a rapid vibratory motion but without any strong net flow direction as would be sensed by the surface oil coatings.

Wake Static Pressure Traverses

The static pressure traverses of the near-wake region, along the centerline of the body and away from the tunnel sidewall boundary layers, were performed to help confirm the apparent observation that the vortices form farther downstream in the presence of a base cavity. Because these measurements were time consuming and because the sidewall surface streaklines indicated similar trends in the vortex formation location for all three reference Mach numbers, these measurements were made at $M_{\text{ref}} = 0.485$ only.

The streamwise variation of the near-wake static pressure coefficient $C_p \equiv (P - P_{\text{ref}})/(1/2\rho_{\text{ref}} U_{\text{ref}}^2)$ for the three base geometries is shown in Fig. 7. The plots display the characteristic features of the vortex street wake as described by Nash et al.[2] and Roshko,[6] namely a low-pressure trough in the near wake at the vortex formation position followed by a gradual rise in pressure to an essentially constant value further downstream. This figure shows clearly that the location of vortex formation has indeed been displaced slightly farther downstream from the trailing-edge plane in the presence of a base cavity. In addition, the plots for the shallow cavity base and the deep cavity base overlap each other quite closely except for some data scatter between two and four base heights downstream of the trailing edge. This result agrees with the sidewall oil-flow visualizations and suggests that increasing the cavity depth beyond 1/2 base height has no further effect in pushing the vortex formation position downstream. Examination of Figs. 6 and 7 also shows that both the sidewall oil streak patterns and the wake static pressure traverses indicate a downstream displacement of the vortex formation position of approximately 1/10 base height for the cavity bases relative to the blunt base.

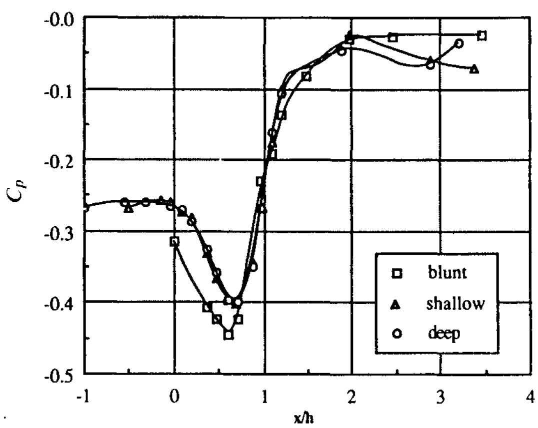


Fig. 7 Near-wake static pressure coefficient at $M_{\text{ref}} = 0.485$.

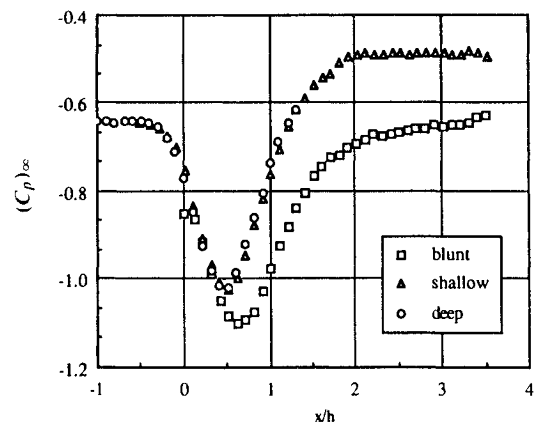


Fig. 8 Near-wake static pressure coefficient at $M_\infty = 0.4$ from Rudy's computations.[5]

The results in Fig. 7 may be compared to those in Fig. 8, which has been adapted from the computational study of Rudy[5] for a freestream Mach number of 0.4. The curves in Fig. 8 have been obtained by averaging the instantaneous pressures at eight different times in the shedding cycle. Also note that Rudy's pressure coefficient is based on freestream conditions, $(C_p)_\infty \equiv (P - P_\infty)/(1/2\rho_\infty U_\infty^2)$, which is the reason for the discrepancy in the magnitudes of the pressure coefficients in Figs. 7 and 8. However, it is the location of vortex formation and the trends with cavity depth that are of primary interest here. The agreement between the experimental (Fig. 7) and computational (Fig. 8) results for the vortex formation location is excellent for the blunt-based configuration but not for the cavity bases where the computations indicate that the vortex formation position moves upstream. These results then follow the same trends seen earlier in comparing the schlieren photographs of the present study to Rudy's vorticity plots.

The experimental results in Fig. 7 also reveal that the static pressure within the cavities remains essentially constant. This is again in contrast with the computations but confirms the experimental observations made earlier that there is no significant recirculatory motion in the cavities. Note in Fig. 8 that the computations indicate a rapid rise in pressure from the trailing-edge plane to about midway back in the cavities as a result of the vortices extending partially into the cavity. A final observation on the measurements in Fig. 7 is that the cavity bases cause an increase not only in the base-pressure coefficient but also in the values of the pressure coefficient in the near wake within roughly 5/8 base heights of the trailing-edge plane. This point will be considered further in the discussion below.

Base Pressure Measurements

As mentioned, 15 static pressure taps were distributed across the base of each model to determine if any significant transverse or spanwise base pressure variations were present. For most of the Mach number-base geometry configurations, the base pressure distributions were quite uniform, though there was a tendency for the pressures near the sidewalls to be slightly higher than at the midpoint (maximum variations were generally less than 2%). The average of the pressures at the 15 taps was therefore taken as the base pressure for the results to be presented here.

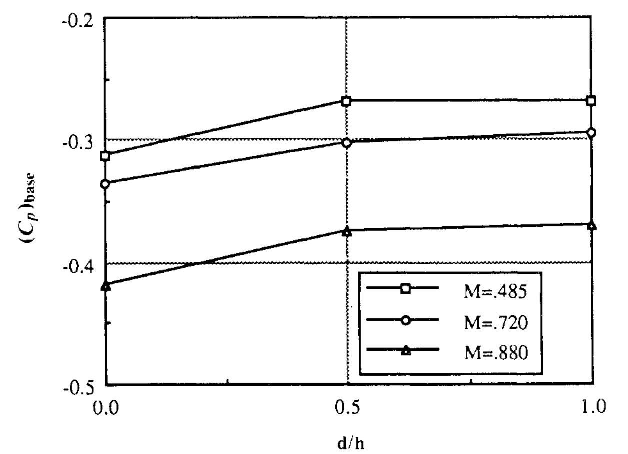


Fig. 9 Base pressure coefficient vs cavity depth and reference Mach number.

Table 2 Base pressure results

Ref. Mach no.	Shallow cavity, %	Deep cavity, %
0.485	+14.1	+14.4
0.720	9.8	11.9
0.880	10.3	11.5

Table 3 Vortex shedding frequency results

Ref. Mach no.	Base type	Shedding frequency, Hz	Strouhal no.
0.485	Blunt	2539.1	0.2375
	Shallow	2705.1	0.2530
	Deep	2690.4	0.2517
0.720	Blunt	3730.5	0.2414
	Shallow	3867.2	0.2502
	Deep	3881.8	0.2511
0.880	Blunt	4379.9	0.2372
	Shallow	4492.2	0.2433
	Deep	4501.9	0.2438

The variation of the base pressure coefficient with cavity depth and reference Mach number is plotted in Fig. 9. The percentage increases in the base pressure coefficient for the cavity bases relative to the blunt base are shown in Table 2. These percentage increases are of the same order as those found by Rudy[5] for his freestream Mach 0.6 case. Figure 9 illustrates quite clearly that the majority of the base pressure increase occurs with a cavity depth equal to 1/2 base height and that increasing the cavity depth to one base height yields only slightly greater drag reducing benefits. This was precisely the conclusion arrived at in the computational results of both Clements[4] and Rudy. Note that although the beneficial effects drop off slightly between reference Mach numbers of 0.485 and 0.720 (see Table 2) there is no significant change between $M_{ref} = 0.720$ and 0.880. It would seem, as reported by Nash et al.,[2] that the base cavity will be effective as long as vortex shedding is present, which means through Mach 1.

Shedding Frequency Measurements

As discussed, the vortex shedding frequencies were determined through a power spectral density analysis of the signal from a fast response piezo-resistive pressure transducer. For all results presented herein, the transducer was located in the tunnel sidewall and downstream of one of the trailing edges. It is realized that the frequency measurements obtained at this location could possibly be distorted by the presence of the sidewall boundary layer. However, comparison of measurements obtained for the blunt-based geometry with the transducer located in the base and in the sidewall showed less than a 4% difference in the value of the shedding frequency. It was felt that this difference was small enough that the more convenient sidewall location could be used. In addition, the fluctuating pressure signal for the cavity bases is stronger at the sidewall location than at the rear cavity wall location.

For all cases, a strong peak in the power spectral density function occurs at the shedding frequency with a second smaller peak apparent at twice the shedding frequency. The relatively broad nature of the peaks in the spectral density plots is at least partly because the vortex street is superimposed on a random turbulent flowfield resulting in the diffusion or feeding of some of the discrete energy (from the vortex shedding) to the continuous (turbulent) portion of the spectra. The shedding frequencies and Strouhal numbers, $St \equiv fh/U_{ref}$, for each of the experimental cases are given in Table 3. Note that these Strouhal numbers are based on the velocity measured at the reference location, i.e., over the aft end of the model just prior to separation.

The Strouhal numbers are plotted vs cavity depth and reference Mach number in Fig. 10. The results of Nash et al.[2] for a similar blunt-based model indicate that for slender, two-dimensional models, the Strouhal number remains constant [at a value based on freestream conditions of $(St)_\infty \equiv fh/U_\infty = 0.25$] from low-subsonic speeds up to a freestream Mach number of about 0.9. The results in Fig. 10 agree reasonably well with this observation except for the drop in Strouhal number that occurs for the two cavity bases at the reference Mach number of 0.880. The reason for this

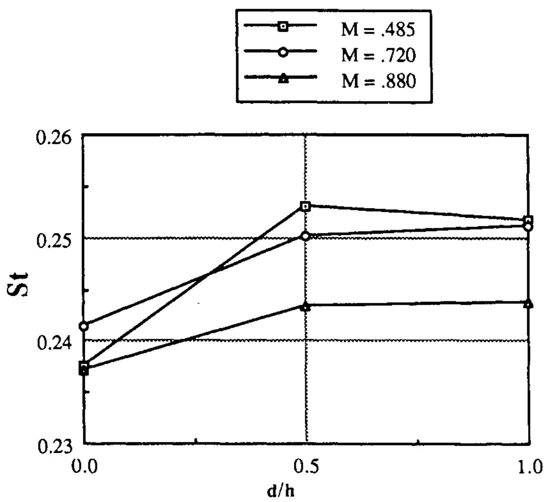


Fig. 10 Strouhal number vs cavity depth and reference Mach number.

drop is unclear. It could be due to the increase in wall interference effects that occurs as the flow approaches Mach 1.0, but that does not explain why a similar decrease did not occur for the blunt-based configuration at the higher Mach number. What is obvious from Fig. 10 is that the effect of the cavity is to increase the shedding frequency, in agreement with the experimental observations of Clements,[4] but again in disagreement with the computational results of both Clements and Rudy.[5] Also, note that the deep cavity again produces virtually no change beyond that which was achieved with the shallower cavity, a trend that has been evident in all of the experimental results presented so far. Further discussion of some of these observations will be given in the following section.

Summary and Discussion

The common thread among all of the experimental results is that increasing the depth of the cavity from 1/2 to 1 base height does not have any significant effect on the parameter being observed; the majority of the changes occur in going from the blunt base to the shallow cavity and may in fact occur for an even shallower cavity, though this was not investigated here. This result was also evident in the computational results of both Rudy[5] and Clements[4] and suggests that, whatever the mechanism is that causes the drag reduction for the cavity bases, it is little affected by depth once the cavity has reached some critical, rather shallow, depth.

It is evident in the schlieren photographs that the basic structure of the vortex street is relatively unmodified by the presence of a base cavity, and that the vortex motions do not extend into the cavity at all. In fact, the vortex formation position is pushed slightly further downstream with a base cavity as compared to a blunt base. This is perhaps somewhat surprising; since the vortices form immediately adjacent to the base for the blunt geometry, one might expect the vortices to move partially into the cavity when the solid boundary of the blunt base is replaced with the compliant fluid boundary of the cavity base. That this does not occur refutes the hypothesis of Nash et al.[2] that the cavity walls improve wake stability and decrease drag by constraining the upstream part of the vortices.

The fact that the present results show that the vortices do not extend into the cavity also accounts for the discrepancy between the experiments and computations regarding the effect of a base cavity on the shedding frequency. In the computations, the cavity was found to increase the interaction between the vortices and thereby decrease the shedding frequency. (Devices such as splitter plates and base bleed that decrease interaction between the vortices have been found to yield an increase in the shedding frequency.[7–11]) In the experiments, the interaction between the vortices is apparently not facilitated by the presence of the base cavity, and so the shedding frequency does not decrease. The observation that the shedding frequency actually increases with a base cavity may be because the vortices form slightly further downstream in this case so that the distance between the separated shear layers is less at the start of vortex formation. (Fage and Johansen[15] have found that the vortex shedding frequency is inversely proportional to the distance between the separated shear layers). This seems plausible: in Bearman's[7,9] splitter plate and base bleed experiments, the vortex formation position was moved downstream approximately one base height, and the Strouhal number increased by roughly 33%. In this investigation the vortex formation position was moved downstream approximately 1/10 base height due to the cavities and the Strouhal number increased by roughly 4–6%.

The fact that the drag reducing mechanism of the base cavity is different than that of either the splitter plate or base bleed is evidenced by the very different degrees of displacement of the vortex formation position for these geometries relative to a plain blunt-based configuration. For the base cavity, there are no structural or fluid elements to interfere with the interaction between the separating shear layers as for splitter plates and base bleed. The effect of the cavity on the vortex street is apparently of a more subtle nature. The results of the present surface flow experiments seem to refute even Compton's[16] theory that the recirculating flow in the cavity forms a steady co-flowing stream on the inner edges of the separated shear layers thereby decreasing mixing and increasing the base pressure. If any significant recirculating flows were present in the cavity, they would most likely have left some directional indication in the oil coatings, and as reported earlier, this was not found to be the case in the experiments reported herein.

A clue as to what is happening in the near wakes of the cavity configurations comes from the results of the wake static pressure traverses. Figure 7 shows that the cavity base increases not only the base pressure coefficient but also the pressure coefficient in the near wake within roughly 5/8 base heights of the trailing edge. Nash et al.[2] have stated that the value of the pressure coefficient in the low-pressure trough in the wake of a bluff body decreases with an increasing degree of bluffness of the body and hence with increasing strength of the vortex street. In Fig. 7 it is apparent that the low-pressure troughs of the cavity bases do not reach as low a minimum as for the blunt base, and this suggests that the vortex streets of the cavity bases are somewhat weaker than the vortex street of the blunt-based configuration. The weaker vortex street results in the higher pressure at the base and in the near-wake, and the higher pressure, in turn, may then move the vortex formation position to a location slightly further downstream of the trailing edge as compared to the blunt-base geometry.

The question then becomes what causes the weakening of the vortex street; there are no interference elements in the wake, there is no constraint of the upstream part of the vortices by the cavity walls, and there is apparently no significant steady recirculating flow causing the formation of a co-flowing stream. The only difference between the blunt base and the cavity bases is that the forming vortices see a solid boundary at the trailing-edge plane in the one case and a compliant fluid boundary in the other. It is quite possible that enhanced fluid mixing at the trailing edge of the base cavity causes a greater loss of vorticity than does the solid wall friction at the trailing edge of the blunt base. The tuft experiments have shown that the air at the cavity entrance is in a state of unsteady pulsating motion as it is forced first one way by the vortex shedding from the upper trailing edge and then the other way by the vortex shedding from the lower trailing edge. These unsteady, oscillating air motions could increase the fluid mixing at the trailing-edge plane to such a degree that the forming vortices are weakened. If this is indeed the case, then the shape or geometry of the cavity would seem to be unimportant; the cavity should be effective as long as it is deep enough to completely replace the fluid-solid wall interaction for the blunt base with a purely fluid interaction for the cavity base and as long as the cavity is of such a height to cover the majority of the base. This was, in fact, evident in the results of Pollock,[3] who found that the drag reducing effect of a special cusp cavity, whose shape was chosen on theoretical grounds was essentially identical to that of the simple rectangular cavity of Nash et al.[2] Furthermore, the results reported herein, as well as the experimental results of Clements,[4] have indeed shown cavity depth to be unimportant once the cavity has reached a somewhat shallow, critical depth.

Having discussed several points of disagreement between the present experimental results and the computational results of Rudy[5] and Clements,[4] it is important to reiterate the differences in the relevant flowfield conditions of these investigations in an attempt to explain why these disagreements may exist. One obvious difference is that the computations model a perfectly two-dimensional flowfield although the experiments can never be completely free from three-dimensional effects. In fact, Nash[17] has stated that over no part of the Reynolds number range is the vortex street strictly two dimensional due to the presence of spanwise periodic structures and/or random turbulent fluctuations. Considering the relatively small scale of the wind tunnel used in this investigation, some effects of three dimensionality are inevitable, despite the two-dimensional indications of the surface oil-flow patterns and the base pressure measurements. Apparently, however, the effects of any three dimensionalities are primarily confined to the interactions of the vortices with the base cavities, as the results for the blunt-based model in these experiments showed excellent agreement with the corresponding results from Rudy's computations. The fact that the tufts suspended in the base cavities did show a degree of spanwise as well as streamwise motion lends support to the argument that three-dimensional effects in the base cavity may affect the interactions with the vortices in the near-wake region.

A second major difference between the conditions of the present experiments and the computational results is the Reynolds numbers. For Rudy's[5] computations, the Reynolds numbers based on freestream conditions and base height were 700 for the $M_\infty = 0.4$ condition and 962 for the $M_\infty = 0.6$ case. Furthermore, the boundary layers at separation were laminar. Clements'[4] computations, on the other hand, were inviscid. In the current experiments, the Reynolds numbers based on the reference conditions and base height were between 1.62×10^5 and 2.78×10^5, and the boundary layers at separation were turbulent. In his study of vortex street wakes behind circular cylinders, Roshko[18] observed that the development and characteristics of the vortex street are strongly dependent on where the transition point is located and that very different trends are displayed depending on whether the separating shear layers are laminar or turbulent. Thus, it is quite possible that the behavior of a vortex street in the presence of a base cavity will likewise depend on the state of the separating boundary layers. Rudy recognized this and suggested that computations be performed at higher Reynolds numbers using appropriate turbulence models in order to better match experimental conditions.

Another point to be considered is that the computations model an unconstrained freestream, whereas the experiments reflect the blockage effects of the wind-tunnel walls. It is recognized that some of the observations reported in the present investigation may have been influenced by wall-interference effects. However, as discussed earlier, it is felt that although wall interference may have somewhat affected the absolute values of the various measured flow parameters, the effects on the basic structure of the vortex street and the trends of the data with increasing Mach number or cavity depth are probably small. Therefore, the blockage effects are probably less likely to be the cause of the observed discrepancies between the computational and experimental results than the three-dimensional and Reynolds number effects discussed above.

A final point to consider is that the cavity geometries for this investigation were not identical in every detail to those used in Rudy's[5] computations; the cavities in the current experiments covered 80% of the base height, whereas Rudy's cavities spanned 90% of the base height. It seems doubtful, however, that this difference could be responsible for the discrepancies reported herein.

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