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Zero-Lift Drag Characteristics of Afterbodies with a Square Base

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Results of zero-lift drag characteristics of afterbodies with a square base relevant to missile and projectile applications at several transonic Mach numbers and Mach 2 are presented. These afterbodies, at zero incidence, generate vortical flows upstream of the base like that on the lee side of a delta wing at incidence. The measurements made consisted primarily of afterbody drag using a balance and base pressure and extensive surface flow visualization studies were carried out to infer features associated with vortex flows. Results of base pressure, boat-tail profile drag, and total afterbody drag are presented and compared with results from the axisymmetric counterpart involving circular arc and conical boat tailing having the same base area. Some aspects of the flow features on square-base afterbodies are discussed as well.

Nomenclature

A	= forebody cross-sectional area, 490.6 mm^2
A_b	= base area, 201.1 mm^2
C_{DA}	= total afterbody drag coefficient, drag force/$(q_\infty A)$
C_{DB}	= base drag coefficient, base force/$(q_\infty A)$
C_{D0}	= zero-lift drag coefficient of a slender body
$C_{\mathrm{D}\beta}$	= boat-tail profile drag coefficient, $C_{\mathrm{DA}} - C_{\mathrm{DB}}$
C_{pb}	= base pressure coefficient, $(p_b - p_\infty)/q_\infty$
D	= forebody diameter, 25 mm
M_∞	= freestream Mach number
p_b	= base pressure
p_∞	= freestream static pressure
q_∞	= freestream dynamic pressure
β	= boat-tail angle, deg (Fig. 1)

Introduction

THERE has been a great deal of research directed toward the understanding of the aerodynamics of slender bodies with a noncircular cross section[1,2]; the interest triggered by missile applications up to high angles of attack. Nonaxisymmetric nozzles (including two-dimensional) incorporating thrust vectoring concepts are being seriously considered for futuristic fighter aircraft[3–7]; afterbodies of such designs will be necessarily three-dimensional, as will those of twin-engine configurations. Forebodies of fighter aircraft are generally noncircular, but the afterbody tends to be an axisymmetric cross section for single-engine configurations. Minimization of afterbody drag is an important requirement in design. Conical boat tails are very common with missiles and projectiles, whereas afterbodies generally are contoured in fighter aircraft applications. In essence, the axisymmetric boat-tailing concept is very widely used in the design of both missiles/projectiles and aircraft afterbodies with a single engine.

It was demonstrated by Platou[8] that improved aerodynamic performance of projectiles can be achieved by utilizing a variety of nonaxisymmetric boat tails; these resulted in afterbodies of square, triangular, and cruciform wedge bases. The aerodynamic benefits observed for these nonaxisymmetric boat-tailed bodies[8] were similar in certain characteristics but different in others; for example, the pitching moment and normal force characteristics generally were improved compared to those of conical boat tails; the afterbodies with a square base produced nearly the same zero-lift drag reduction ΔC_{D0} as the conical boat tail compared with a cylindrical (unmodified) base. However, in that study,[8] the base areas for the different nonaxisymmetric boat tails were not matched, so that the drag reduction ΔC_{D0} observed in certain cases may have resulted, in fact, from lower base area as well. Agnone and Prakasam[9] made an assessment of the aerodynamic performance of triangular and square-base afterbodies (as in Platou's work[8]) at a hypersonic Mach number. For an effective utilization of these nonaxisymmetric boat-tail concepts in applications, better knowledge of afterbody drag, as affected by Mach number and incidence, is needed. In particular, it would be very informative to know how the different components of afterbody drag are affected compared to well-known axisymmetric boat tails, e.g., conical or circular-arc profiles.

In this paper, the zero-lift drag characteristics of a family of afterbodies with a square base, which have strong potential for future applications, are investigated in some detail. The square base is obtained by cutting a body of revolution by planes inclined at an angle β (Fig. 1), as in Platou's work.[8] The resulting configuration contains flat segments inclined at β to the freestream (assuming zero body incidence). As shown later, this passive (surface) modification results in the formation of vortex flows on the flat segments qualitatively similar to the lee side of a delta wing at incidence. Results of base pressure, boat-tail profile drag, and total afterbody drag are presented at three transonic Mach numbers and at Mach 2.0. These drag characteristics are compared with the axisymmetric counterpart involving conical and circular-arc boat tails. Some aspects of the flow features on square-base afterbodies are discussed as well.

Experiments

Test Facility

Experiments have been performed in a 30 × 38 cm trisonic wind tunnel in the M_∞ range of 0.7 to 1.0. The transonic test section was slotted with 8% open area ratio on top and bottom walls. The freestream Reynolds number [based on model length of 30.5 cm (Fig. 2)] varied between 8×10^6 and 9.5×10^6 in this Mach number range. To assess the typical performance of square-base afterbodies in supersonic flow, experiments were made at $M_\infty = 2.0$, and the corresponding Reynolds number was 10×10^6. The supersonic test section had dimensions of 30 × 30 cm and utilized fixed-block nozzle liners.

Model Support System and Balance

A sketch of the model support system along with the afterbody and drag balance is shown in Fig. 2. The model was supported using a thin wing section between two forks of rectangular cross section, similar to that employed in many earlier investigations involving afterbody studies.[10–12] Sufficient care was exercised in the design of the model support system, keeping in view possible transonic and supersonic interference effects. The support system was designed primarily to withstand the aerodynamic starting loads at Mach 2.0. As a result, the (max) solid blockage of the model including the

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support system at section AA (Fig. 2) was about 1.5% (about 0.5% is desirable). From an examination of the wave system from the body nose, fork tip, and wing leading edge and their (corresponding) reflections from the (solid) tunnel wall, it was confirmed that the base or near-wake flow was free from wave interferences at Mach 2.0. Because all of the tests were made at zero incidence and the major interest in the study involved assessment of the relative merits of afterbodies with square and axisymmetric bases, minor interference effects from the support system or walls should not materially affect the conclusions drawn.

The metric part of the model (Fig. 2) consisted of a fixed cylindrical section 30 mm long and removable afterbody 100 mm long. The balance (designed for an axial load of 2.25 kg) measured the total drag force experienced by the metric part of the model. Total drag measurement naturally included the effects of three-dimensional flows on the square-base afterbodies. All tests were carried out at zero incidence. Base pressure was measured on the model centerline using a static pressure port flush with the surface (Fig. 2). The model boundary layer was tripped in the nose region (using size 40 carborundum particles over a width of 3 mm) at a distance of 25 mm from the apex.

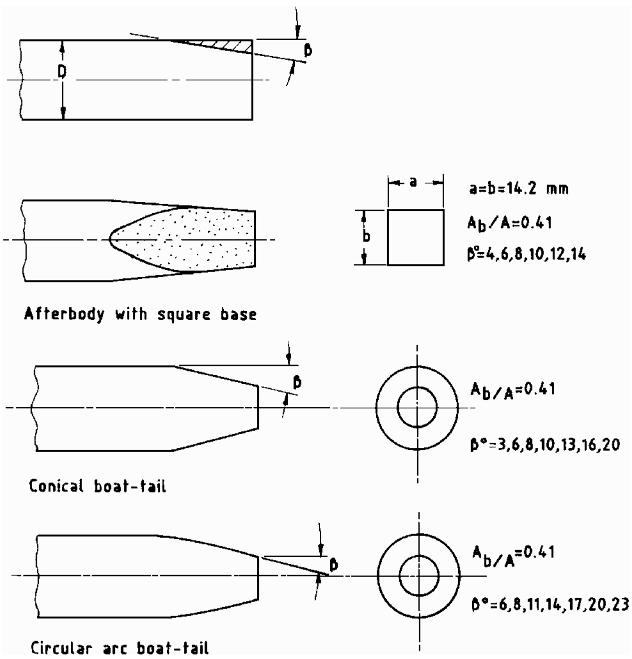

Fig. 1 Geometric details of square and axisymmetric afterbody models.

Afterbody Models

The geometric details of the afterbody models with square base are presented in Fig. 1; it involves four flat segments of equal surface area at any β. To assess the performance of these square-base afterbodies, drag characteristics of axisymmetric afterbodies involving conical and circular-arc boat tailing (Fig. 1) were measured as well in the same tunnel using the same balance system described in the preceding section. Both the axisymmetric and the square-base afterbody models had the same base-to-forebody cross-sectional area $(A_b/A) = 0.41$ so that direct comparison of the drag characteristics of afterbodies with square and axisymmetric bases could be made.

Measurements

The measurements for each blowdown consisted primarily of outputs from the drag balance and different pressure transducers, which were acquired and processed on a personal computer. The tunnel stagnation pressure was measured with a 1035-kPa transducer. Two 17-kPa transducers were employed to measure the differences between the freestream static and the base pressure and between the freestream static and the split pressure; the split pressure was measured in the narrow gap between the metric and nonmetric portions of the model (Fig. 2). Extensive surface flow visualization studies (using titanium dioxide in oil with oleic acid) on the afterbodies were carried out to infer features associated with vortex flows.

Measurement Uncertainties

Uncertainties in the measured data estimated using the methodology of Kline and McClintock[13] and considering data repeatability are

$$\Delta C_{DA} = \pm 0.02 C_{DA} (20 \text{ to } 1) \qquad \Delta C_{pb} = \pm 0.015 C_{pb} (20 \text{ to } 1)$$

Results and Discussion

Square Base at Transonic Speeds

Results of base pressure coefficient C_{pb} for the square base at transonic Mach numbers are presented in Fig. 3. For a direct comparison with results corresponding to axisymmetric cases, results

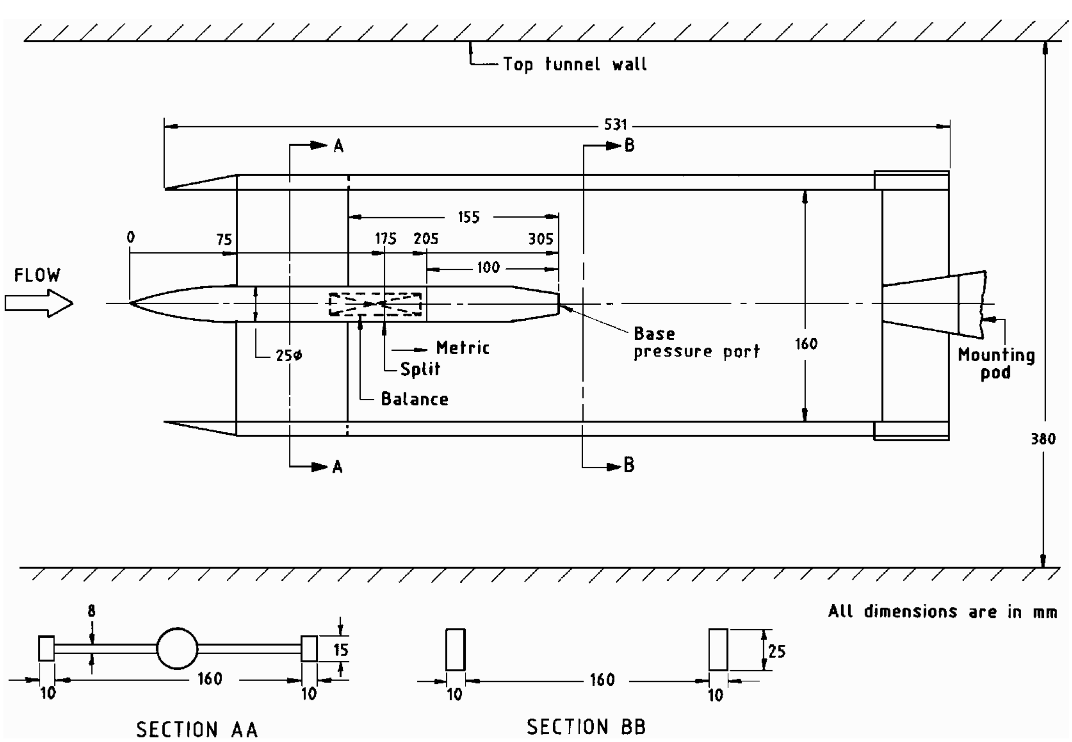

Fig. 2 Sketch of model, balance, and support system.

of C_{pb} measured on conical boat tails at $M_\infty = 0.7$ and 0.9 and on circular arc afterbodies (β here defined as the slope at the base) at $M_\infty = 0.99$ are included in Fig. 3, because these produced the highest base pressure at the different Mach numbers shown. As may be expected, the base pressure increases with β on all three boat-tail shapes. Interestingly, the base pressure on the square base is higher than on the axisymmetric counterpart at any given β (except for $\beta > 10$ deg at $M_\infty = 0.99$), indicating some base drag reduction. A similar increase in base pressure ($\Delta C_{pb} = 0.026$) on a square base (with $\beta = 10$ deg) relative to a circular-arc boat tail (with $\beta = 10$ deg) having the same base area ($A_b/A = 0.40$) has been observed at low speeds[14] as well.

It is informative to examine the gross flow features on the afterbodies with a square base for gaining some insight into the possible flow mechanisms at play; an example of surface flow features at $M_\infty = 0.80$ is displayed in Fig. 4. Similar features were observed at other Mach numbers as well. The surface streamlines reveal vortex-like flows on the flat segments qualitatively similar to those on the lee side of a delta wing[15]; the vortex footprints indicate increasing strength of vortices with an increase in β, which is to be expected. The crossflow features conjectured from the surface flow pattern also are included in Fig. 4.

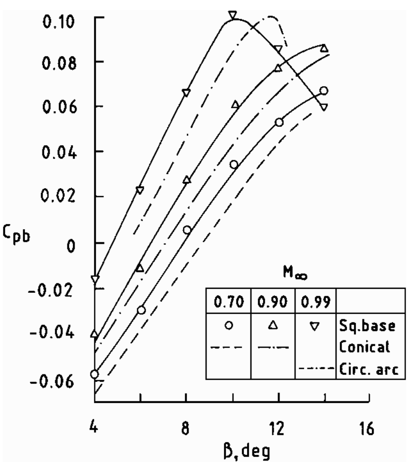

Fig. 3 Base pressure at transonic speeds.

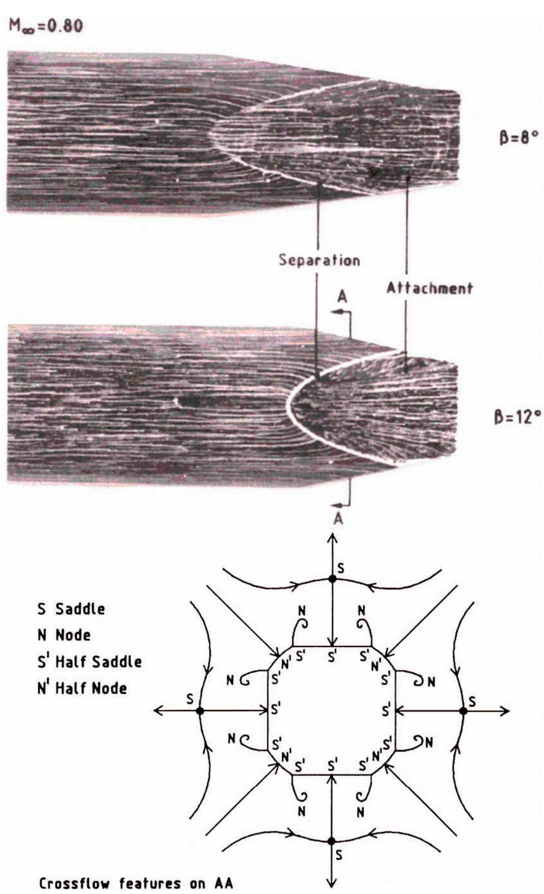

Fig. 4 Surface and crossflow features on square bases.

Although, in general, a decrease in base pressure may be expected with streamwise vortices present, e.g., on slanted bases,[16] on square-base afterbodies the effect appears to be different. The effects of vortical flows generated upstream of the square base, including equal strength of vortices on all four flat segments, lead to an increased base pressure. As discussed by Maull,[17] the possibility of a base bleed-type effect (in the presence of streamwise vortices) leading to an increase in base pressure cannot be ruled out for the square base.

Accurate estimation of base drag reduction associated with the square base is difficult because the base pressure was measured only on the model centerline in the experiments; furthermore, information regarding pressure variations across a square base does not exist in the literature. Considering the symmetry of the flow approaching the square base, we may expect that the base pressure variations may be small, for example, as on axisymmetric bases[18] at subsonic speeds (about 5–10% across the radius with minimum value on the centerline). Such an assumption leads to a base drag reduction of about 5% of C_{DA} in the transonic Mach number range.

Figure 5 shows the results of total drag coefficient C_{DA} for the square base as well as conical and circular-arc boat-tailed afterbodies. The drag characteristics of all three types of boat-tails show dependence both on the Mach number as well as β, and the optimum β for minimum drag is different for the three boat-tail shapes. At $M_\infty = 0.70$ and 0.90, lowest drag is offered by the circular-arc profile (because of the gradually expanding flow on the boat-tail) and the square-base afterbodies have higher drag of about 10–15% (relative to the circular-arc boat tails), depending on β. The conical boat-tails have drag levels even higher than those of the square base for $\beta \gtrsim 6$ deg at $M_\infty = 0.90$ and 0.99.

Results of boat-tail profile drag coefficient ($C_{D\beta}$), which are obtained by subtracting the values of base drag C_{DB} from C_{DA}, for the square-base and circular-arc boat tails at transonic speeds are compared in Fig. 6a. The larger values of $C_{D\beta}$ for the square base (all across the β range) presumably are caused by the lower surface pressure on the flat segments associated with vortices, as discussed earlier; further, the rapidly increasing trend of $C_{D\beta}$ for $\beta \geq 6$ deg possibly indicates increasing strength of vortices on the flat segments consistent with the surface flow features (Fig. 4). As may be expected, the circular-arc profile has the lowest boat-tail profile drag because of gradually expanding flow on the boat tail.

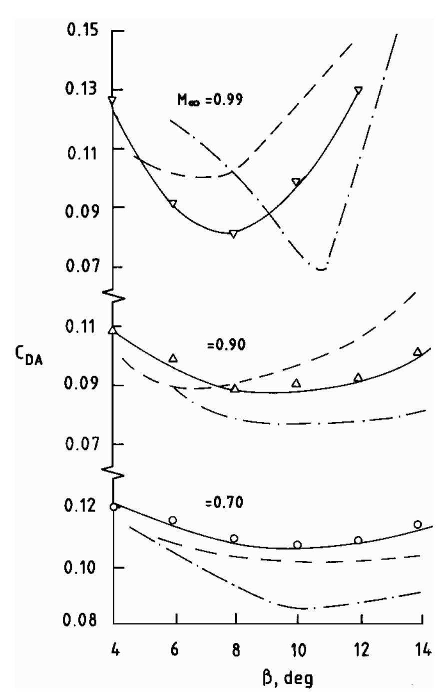

Fig. 5 Afterbody drag characteristics at transonic speeds: ○, △ and ▽, square base; - - -, conical; and —·—, circular arc.

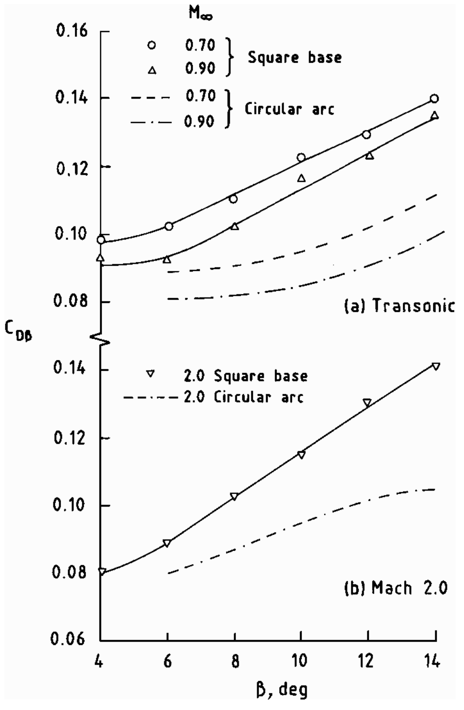

Fig. 6 Boat-tail profile drag characteristics.

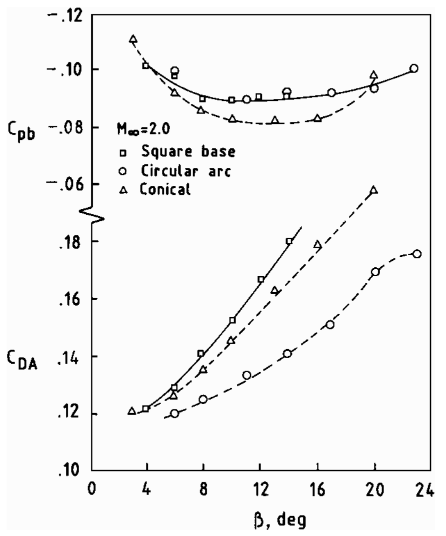

Fig. 7 Base pressure and afterbody drag characteristics at Mach 2.

Square Base at Mach 2

The base pressure and afterbody drag characteristics are illustrated in Fig. 7. The base pressure levels for the square-base and circular-arc afterbodies are essentially the same, whereas conical boat tails produce relatively higher base pressures in the range of β considered. The afterbody drag is lowest for the circular-arc profile because of lower boat-tail profile drag resulting from gradually expanding flow on the boat tail (Fig. 6b). The conical boat tail and square base have common features, such as abrupt expansion at the beginning of the boat tail and therefore have comparable total drag characteristics. Depending on β, the square base has higher afterbody total drag of about 2–5% compared to that of conical boat tails.

Conclusions

Experimental results of zero-lift drag characteristics of afterbodies with a square base at high speeds are presented and compared with axisymmetric bases with circular-arc and conical boat tails having the same base area. The square-base afterbodies generate vortical flows ahead of the base similar to those on the lee side of a delta wing at incidence. At transonic speeds, interestingly, the square-base afterbodies offer base drag reduction of engineering value (relative to the axisymmetric counterpart), although their total drag is higher than the circular-arc boat tails at any given β. The flow on a square-base afterbody is complex, involving vortices, three-dimensionality, and the fluid dynamic mechanisms responsible for the observed increase in base pressure are unclear at present. The total drag of the square base is higher than the axisymmetric counterpart at Mach 2.0 as well. A major factor contributing to the large drag of square bases is the increased boat-tail profile drag due to lower surface pressures on the flat segments as a result of vortical flows.

Nonaxisymmetric afterbodies may be a necessary feature in many future applications, e.g., noncircular missiles, twin-engine fighter aircraft; square-base afterbodies are relevant to projectiles and missiles and the database generated in this study should be very useful in such designs. Study of drag characteristics of square bases with jet flow would have relevance to single-engine fighter aircraft applications.

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