# Engineering Notes

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## Drag Reduction by Controlling Flow Separation Using Stepped Afterbodies

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### Introduction

PROFESSOR J. A. C. Kentfield of the University of Calgary has proposed a method of controlling separated base flows as a means of reducing aerodynamic drag.[1,2] A series of steps attached to the base of the body of interest is used to control flow separation by forming a system of captive vortices on the steps. Kentfield's wind tunnel experiments seemed to confirm this concept for axisymmetric bodies at low subsonic Mach numbers and low Reynolds numbers. He reported drag reductions of as much as 56% using stepped afterbodies as compared to identical bodies with flat bases. The best of these stepped afterbodies also reportedly outperformed conical afterbodies of the same length at these low Mach numbers and low Reynolds numbers. This Note presents results obtained from further investigations of this stepped base concept in conjunction with both fin- and spin-stabilized configurations at high subsonic, transonic, and supersonic Mach numbers. These investigations[3,4] were accomplished by obtaining experimental free-flight drag data for a series of flat, stepped, and truncated boattail base configurations.

### Test Procedures

The free-flight tests were conducted in the Air Force Armament Laboratory's Aeroballistic Research Facility.[5] This facility is an enclosed, atmospheric, instrumented concrete structure used to investigate the exterior ballistics of various free-flight configurations. The nominal test conditions were 22.0°C, 50% humidity, and sea-level pressure.

A typical spin-stabilized 20-mm round (see Fig. 1a) with three different afterbodies was tested first.[3] The stepped afterbody configuration was similar to the minimum drag shape as obtained from Kentfield's wind tunnel tests,[2] but with a shorter, wider ring at the base. The second and third configurations tested were a flat base and a 17.5-deg truncated boattail base for comparison purposes. This 17.5-deg boattail angle corresponds to the angle defined by the stepped base configuration, not including the ring at the base.

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The direct measurements obtained in free-flight testing are the distance traveled as a function of time and the instantaneous angle of attack. Two methods were employed to determine the zero angle-of-attack drag coefficient ($C_{D0}$). The first is the classical linear theory technique,[6] which assumes that the basic time and distance measurements can be related by a third-order polynomial function. The second method[7] used for the study involved numerically integrating the linear momentum equation and expanding $C_D$ into $C_{D0} + C_{D2}\alpha^2 + C_{DV}(V - V\text{ref})$. Multiple flights of the same configuration can be analyzed over Mach number ranges that correspond to small changes in the drag curve slope.

A fin-stabilized missile configuration (see Fig. 1b) was tested next with a series of different stepped base geometries as well as with a flat base and a truncated boattail base (see Table 1). The truncated boattail base was constructed with the same length and convergence angle as the lowest drag stepped base. The fin-stabilized models did not contain the surface irregularities inherent in the spin-stabilized projectiles, i.e., rotating bands and crimp grooves; and since these models were launched from a smooth bore gun, the associated spin rates were low.

### Tests and Results

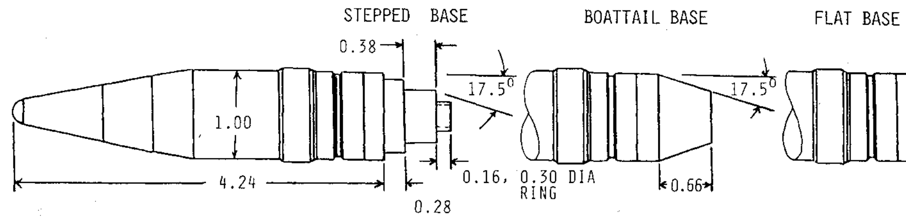
#### Spin-Stabilized 20-mm Rounds

The data presented in Fig. 2 for the spin-stabilized projectiles were obtained using the classical linear theory method. This was necessary because the projectile bodies consisted of inventory rounds and were not precision machined. Hence, there were slight variations between models, especially in the nose region of the projectiles. Also, in-flight photographs revealed that the plastic rotating bands had "burred," and these plastic burrs protruded into the flow. This was particularly severe for the subsonic Mach numbers, whereas at higher velocities these burrs were frequently stripped off early in the flight. These anomalies caused significant variations in the $C_{D0}$ values of the projectiles even when they were launched at the identical Mach numbers. Therefore, although the numerical integration multiple fit results are not shown, they were obtained and were used in confirming that real differences existed from model to model.

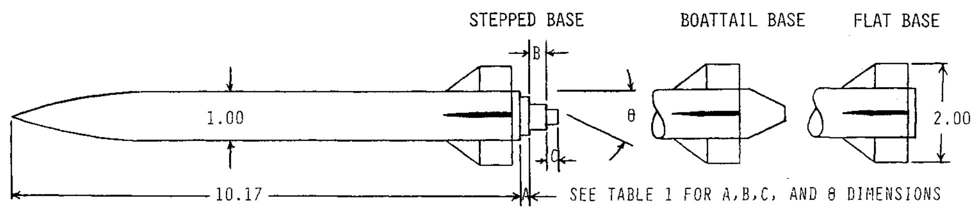
The data clearly show that the stepped configuration has a lower subsonic drag (approximately 19% lower) than the flat base but is higher (by about 21%) than the boattailed models. The data also show that the stepped and flat base drag levels

**Table 1 Step-base configurations for spin-stabilized missile**

| Base | Convergence angle, deg | Step lengths, calibers (caliber = 19.05 mm) First step | Second step | Third step |
|---|---|---|---|---|
| A | 17.94 | 0.151 | 0.300 | — |
| B | 17.64 | 0.080 | 0.147 | 0.280 |
| C | 16.72 | 0.289 | 0.376 | — |
| D | 12.01 | 0.225 | 0.447 | — |
| E | 12.56 | 0.119 | 0.183 | 0.457 |
| F | 11.24 | 0.425 | 0.569 | — |
| G | 7.99 | 0.289 | 0.708 | — |
| H | 7.51 | 0.192 | 0.355 | 0.676 |
| J | 7.13 | 0.688 | 0.912 | — |




a) Spin stabilized projectile configurations (dimensions in calibers, 1 caliber = 19.73 mm)




b) Fin stabilized projectile configurations (dimensions in calibers, 1 caliber = 19.05 mm)

**Fig. 1 Sketches of test configurations.**

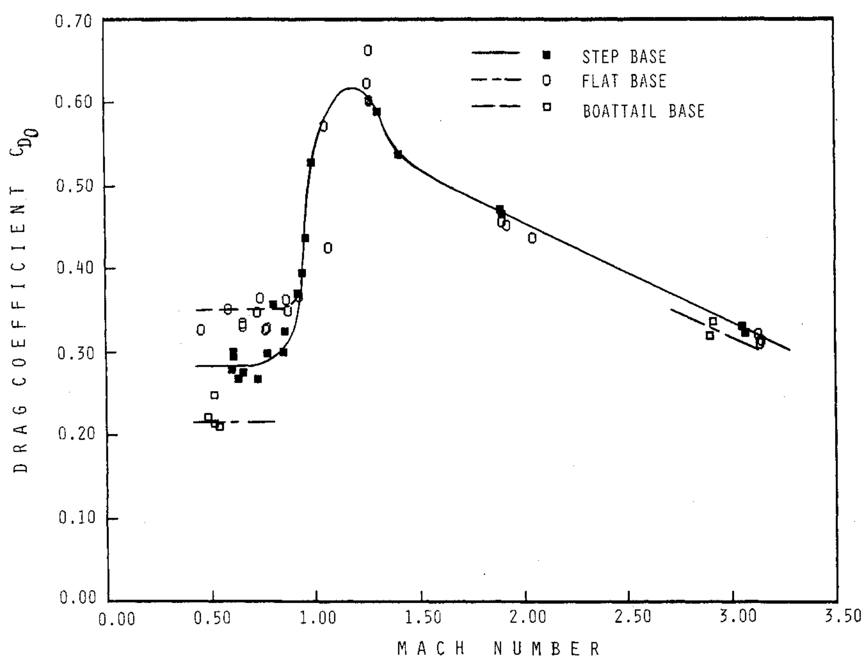



**Fig. 2 Zero-angle drag coefficient results for the spin-stabilized projectiles.**

merge above $M = 1.0$, whereas the boattail configuration apparently maintains a somewhat lower drag throughout the Mach number regime. These results for the spin-stabilized projectiles are only partially consistent with Kentfield's results[1,2] in that the magnitude of the drag reduction is much less. His tests were conducted at very low subsonic Mach numbers ($< M = 0.1$) and low Reynolds numbers. Also, the boattail shape he used was a full boattail (not truncated), and the models were precision made, containing no irregularities. The spin-stabilized models tested here had clearly turbulent flow over the aft portions of the projectiles,[3] but no vortices were observed in the shadowgrams of the models in flight. These models were launched at much higher Mach numbers and Reynolds numbers, and, finally, the models had a high spin rate required for stabilization. Considering all of these differences, it is not surprising that the results are not in complete agreement.

**Fin-Stabilized Missile**

The fin-stabilized projectile zero angle drag is shown in Fig. 3 for each of the stepped configurations tested at $M = 0.6$. The lowest drag base, the E-base from Table 1, was tested through the transonic Mach region along with a truncated boattail base of the same length and convergence angle. All of the drag results for the stepped, flat, and truncated boattail models are presented in Fig. 3. The data illustrate that subsonically the E-base configuration has a lower drag than the flat base but is again outperformed by the boattail afterbody, although these drag differences disappear as the Mach number increases. These results are in close agreement with those obtained from the spin-stabilized rounds. Again, they are only partially consistent with Kentfield's results[1,2] in the magnitude of the drag reduction. As with the spin-stabilized projectile, the differences could be due to the higher Mach and Reynolds numbers of these tests.

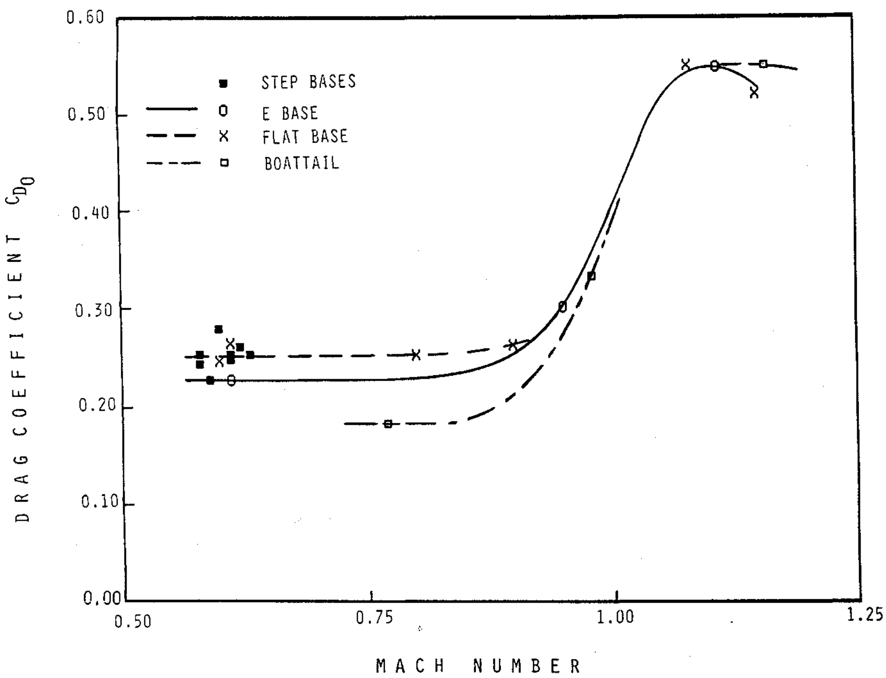



**Fig. 3 Zero-angle drag coefficient results for the fin-stabilized projectiles.**

## Concluding Remarks

Free-flight tests of spin-stabilized projectiles and fin-stabilized missiles with various stepped, flat, and boattailed bases have been conducted at subsonic, transonic, and supersonic Mach numbers. The results indicate that subsonically the addition of a stepped base can significantly reduce the aerodynamic drag over that of a flat base. However, these stepped bases are not as efficient in reducing drag as a standard truncated boattail. Supersonically, these stepped bases have no apparent advantage over that of a flat base. Although the stepped base drag reductions and captive vortices observed in Kentfield's previous low subsonic wind tunnel tests were not realized in the present free-flight tests, significant differences in the test conditions could be the reason. It is suspected that differences in Mach number and Reynolds number were the primary causes. The present tests reaffirm that boattailed bases are the most effective passive drag reduction technique available for typical munitions and missile configurations at their normal flight conditions.

## References

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# Hypervelocity, Minimum-Radii, Coordinated Turns

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## Nomenclature

$A$ = vehicle reference area
$C_D$ = drag coefficient
$C_{D_0}$ = zero-lift drag coefficient
$C_L$ = lift coefficient
$D$ = drag
$g$ = acceleration of gravity
$L$ = lift
$m$ = vehicle mass
$n$ = structural load factor
$R_0$ = planetary radius (6367 km for Earth)
$r_c$ = radius of curvature of fligh path
$r_t$ = radius of turn
$T$ = thrust
$t$ = time
$V$ = flight velocity
$V_s$ = circular satellite speed (7.9 km/s)
$W$ = vehicle weight
$\alpha$ = angle of attack
$\rho$ = freestream air density
$\tau$ = thrust-to-weight ratio
$\phi$ = bank or roll angle

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