cylinder independently produces the moment and rotates the cylinder at a greater rate than predicted by the two-dimensional model. Wide sandpaper showed the hysteresis and jump of the $N$ against $V_\infty$, and the $N$ was far less than that predicted by the quasi-two-dimensional model. The three-dimensional effect seems to be great.

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# Reynolds Number Effects on the Aerodynamics of a Body with Square Cross-Section

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## Introduction

RECENTLY, considerable attention has been given to Reynolds number effects on the flow separation about bodies of revolution at angle of attack. This research is perhaps best exemplified by the definitive work of Lamont,[1] which represents comprehensive results over a wide range of Reynolds numbers and angles of attack for a pointed ogive cylinder. Much attention has also been focused recently on the aerodynamic and flow separation characteristics of bodies that are noncircular in cross-section.[2-5] This Note brings together some of both groups of work by presenting experimental results which show the effects of Reynolds number on the normal force and rolling moment of a body that is square in cross-section. Results are presented for body-alone and body-fin configurations. The following paragraphs include a brief description of the wind tunnel facilities, models, and test conditions followed by a discussion of the results and some concluding remarks.

## Facilities, Models, and Test Conditions

The experimental data presented in this Note were acquired in the subsonic and trisonic wind tunnels at the United States Air Force Academy.[6] The subsonic tunnel is a continuous flow, closed circuit facility with a test section of 2 × 3 ft. The trisonic tunnel is a blowdown facility with 1 × 1 ft test section.

Two wind tunnel models, both of the same design and differing only in scale, were used in this study. The primary model was a cylinder of square cross-section with a highly blunted ogival nose. The total body length was 7.5 in. The body cross-section width was 1 in. The cross-section corner radii were 0.2 in. A second model that was twice the size of the primary model was also used to acquire some of the data in the subsonic tunnel.

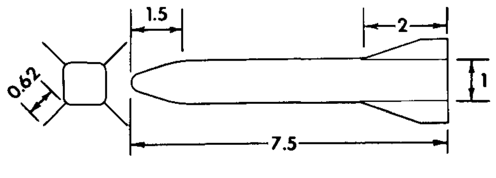
In addition to data for the body-alone configuration, data were also acquired for a body-fin arrangement. For these cases, the fins were arranged in a cruciform manner at the aftmost position on the body. The fins were attached at the body cross-section corners. At zero roll the fins were in an X configuration. The aspect ratio of the fins (based on exposed semi-span) was 0.47. A sketch of the body-fin model is shown in Fig. 1.

Six-component force and moment data were obtained for the angle-of-attack range 0 to 30 deg at roll angles of 0, 22.5, and 45 deg. Reynolds numbers (based on body cross-section width) varied from approximately $1.2 \cdot 10^5$ to $1.2 \cdot 10^6$. In order to obtain this range of Reynolds numbers, it was necessary to vary Mach number. Data required at Reynolds numbers of approximately $2.5 \cdot 10^5$ and below were taken at a Mach number of approximately 0.3, whereas the higher Reynolds number data were taken at a Mach number of 0.8. The effect of this subsonic Mach number variation will be discussed in the following section as required.

## Results

Normal force and rolling moment results for the body-alone and body-fin configurations are shown in Figs. 2, 3, and 4. Figure 2 presents nonrolling, body-fixed, normal force coefficient variation with Reynolds number for both configurations at two roll orientations and at 26 deg angle of attack. Also presented in this figure for comparison are normal force data from Lamont's research on a pointed ogive circular cylinder.[1] Lamont determined that for the angle of attack shown (26°), separation was laminar for Reynolds numbers below approximately 2-$10^5$, transitional for Reynolds numbers between approximately $2 \cdot 10^5$ and $10^6$, and turbulent above $10^6$. As can be seen, the square body-alone results for the zero roll orientation follow the trend of Lamont's data, although the decrease in normal force as the Reynolds number increases is not nearly as pronounced. Likewise the recovery is not nearly as pronounced as the Reynolds number continues to increase. It should also be pointed out that the data points at the higher Reynolds numbers are probably slightly high (~10%) due to increased Mach number. This degree of increase with Mach number for square bodies has been documented by Schneider.[4]

Two data points are also shown on Fig. 2 for the body-alone case at a 45-deg roll orientation. Here the change in normal force is much more pronounced as the Reynolds number increases above $2 \cdot 10^5$. Unfortunately, no data were



(Note: All dimensions in inches.)

Fig. 1 Body-fin wind tunnel model.

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taken for this roll orientation at the higher Reynolds numbers. It is expected, however, that the trend would be approximately as indicated by the dashed line on Fig. 2.

The reason for the change in normal force with increasing Reynolds number for the body of square cross-section is similar to that for the circular cylinder. The circumferential location of the primary leeside separation is changing with the condition of the boundary layer. In the case of the square cross-section at the zero roll orientation, the magnitude of the normal force is dominated by the flat surfaces on the windward and leeward sides with the position of separation changing only slightly around the curved corners. For the 45-deg roll orientation, the circumferential location of separation is affected more readily by changes in Reynolds number due to the sloped leeward sides of the square body. This fact, combined with the greater projected area of the body at this roll orientation, produces the resulting greater change in normal force as separation changes from laminar to transitional.

Also shown in Fig. 2 is the variation of body-fin normal force with Reynolds number. As can be seen from these results, the addition of fins essentially eliminates the Reynolds number effect for the zero roll orientation and slightly reduces the effect for the 45-deg roll case. Again, the data at the higher Reynolds numbers are higher than they would have been had Mach number been held constant.

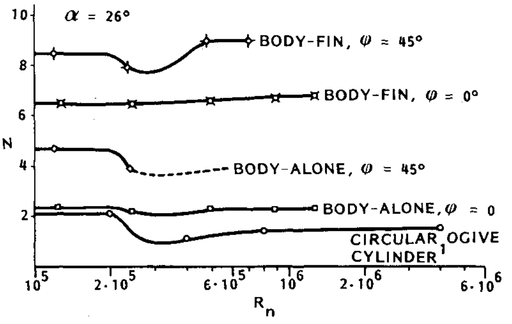

**Fig. 2 Variation of normal force coefficient with Reynolds number.**

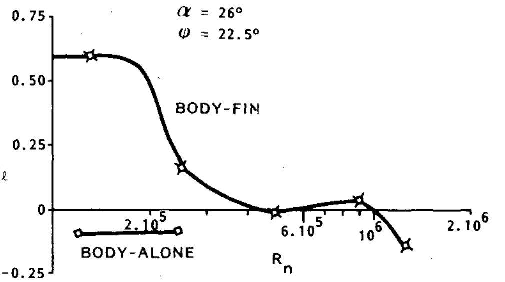

**Fig. 3 Variation of rolling moment coefficient with Reynolds number.**

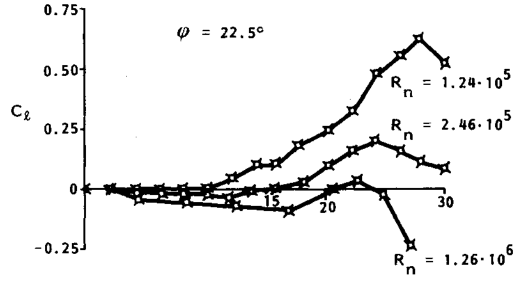

**Fig. 4 Variation of body-fin rolling moment coefficient with angle of attack.**

The final results in this brief Note are shown in Figs. 3 and 4. Figure 3 shows the variation in rolling moment coefficient with Reynolds number for a fixed angle of attack (26 deg). Figure 4 shows the variation in rolling moment coefficient with angle of attack for fixed Reynolds numbers ($1.24 \cdot 10^5$, $2.45 \cdot 10^5$, and $1.26 \cdot 10^6$). The roll orientation was 22.5 deg for all cases.

As can be seen from Fig. 3, there is a significant Reynolds number effect on rolling moment for the body-fin configuration. As was discussed previously, this change is due to changes in the circumferential location of separation as the condition of the boundary layer changes from laminar to transitional to fully turbulent. This change, although small on the body, has a more pronounced effect on the location of the leeside body vortex wake and, consequently, the loadings on the individual fins that are immersed in the wake.

Two data points for the body-alone configuration are also shown on Fig. 3. These data indicate that a slight rolling moment exists for the body-alone configuration at this angle of attack and asymmetric roll orientation. The moment appears to be insensitive to Reynolds number for the limited data acquired.

Figure 4 shows the variation of the body-fin rolling moment coefficient with angle of attack for Reynolds numbers that, based on analogy to Lamont's data, are thought to result in laminar, transitional, and turbulent separation. Although the general shape of each curve is similar, there is a significant change in the magnitude and, in some cases, the sense of the rolling moment. The impact of this on the design, testing, and stability for vehicles of this type could be significant.

## Concluding Remarks

This Technical Note has presented experimental results showing the effects of Reynolds number on the normal force and rolling moment of a body with square cross-section. The normal force results are similar in trend to results for circular cross-section bodies. The observed magnitude and Reynolds number effect was a strong function of roll orientation. The rolling moment for a finned vehicle of square cross-section was shown to vary significantly with Reynolds number.

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