Aerodynamic Characteristics of Configurations Having Bodies with Square, Rectangular, and Circular Cross Sections

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Wind-tunnel tests, at a Mach number of 0.75, for three families of configurations are described. Three bodies, having identical cross-sectional area and length, were tested alone and with three sets of fins. Their cross sections are a square with rounded corners, a rectangle with rounded corners, and a circle. For configurations having identical fins, the normal-force curve slope was found to be larger for the family with the square body than for that with the circular body and to be largest for configurations with the rectangular body. A component buildup method, which uses experimental data for body alone, lifting-surface analysis for wing alone, and slender-body theory for the influence coefficients, has been developed. The predicted normal-force curve slope is 6–17% larger and the center of pressure is 0.15–0.25 reference lengths more aft than those experimentally determined. Results obtained by the VORLAX, with corrections for body alone code based on test data, are very close to those obtained by the component buildup method. This agreement validates the use of slender-body theory for the evaluation of wing-body mutual influence coefficient for configurations having noncircular bodies.

Nomenclature

Æ	= aspect ratio of exposed fin
b	= span of exposed fin
C_M	= pitching-moment coefficient
C_N, C_{N_α}	= normal-force coefficient and curve slope, respectively
C_R	= root chord
d	= reference length, $d = \sqrt{S_R}$
D	= diameter of circular body
K_{WB}	= wing-body mutual influence coefficient
M	= Mach number
N	= normal force
S_R	= reference area, cross-sectional area of center-body
S_W	= area of exposed fin
X_{cp}	= center-of-pressure location
α	= angle of attack

Subscripts

b	= body alone
c	= configuration
w	= wing alone

Superscripts

e	= experimental
sb	= slender-body theory
v	= VORLAX code

I. Introduction

INTEREST in missiles having bodies of square or rectangular cross sections has expanded in recent years. The main motivation is their superior packaging capability of subloads. Nevertheless, publications concerning the aerodynamic characteristics of such configurations are not commensurate with the growing interest. Only a few reports on experimental parametric studies, such as those of Knoche et al.[1] and Daniel et al.,[2] are available. No specific publications concerning the analysis of the aerodynamic characteristics of these configurations were found.

The Aeronautics Research Center of the Technion initiated an experimental investigation of the aerodynamic characteristics of bodies having square and rectangular cross sections at transonic speeds.[3,4] At the same time, the capability of analyzing slender bodies of general cross section has been developed.[5,6] One possible application of that capability is the evaluation of mutual wing-body interference for noncircular bodies. The present paper describes an extension of these activities by a combined experimental and computational investigation of body-fin configurations.

The first objective of the present work is to start an empirical and comparative data base of the aerodynamic characteristics of configurations featuring bodies having noncircular cross sections. The second is an investigation of the capability of a component buildup method, which uses wing-body influence coefficients evaluated by the above-mentioned capability, and of the VORLAX code, to predict the aerodynamic characteristics of the test configurations.

II. Experimental Investigation

A. Test Configurations

Three bodies having the same cross-sectional area and length were tested alone and with wings. Their cross sections are a square with rounded corners, a rectangle with a width-to-thickness ratio of 1.8 and rounded corners, and a circle. The radius of the corners is 0.1 reference length, which equals the square root of the cross-sectional area. The total fineness ratio is 6.5, and the tangent ogive noses have a fineness ratio of 1.5. The dimensions are presented in Fig. 1.

The wing planform is a delta wing with clipped tips. The aspect ratio is 2.46, the taper ratio 0.1, and the leading edge swept backward 53 deg. Three sets of wings, similar in shape but different in size, were tested. They are defined in Fig. 2. All wings are made of material of the same thickness, and the edges are beveled to a 14-deg total angle.

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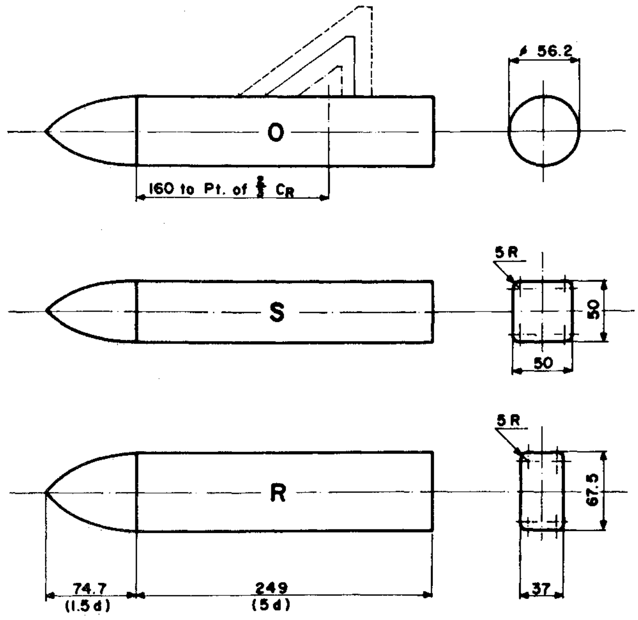

Fig. 1 Geometry of bodies.

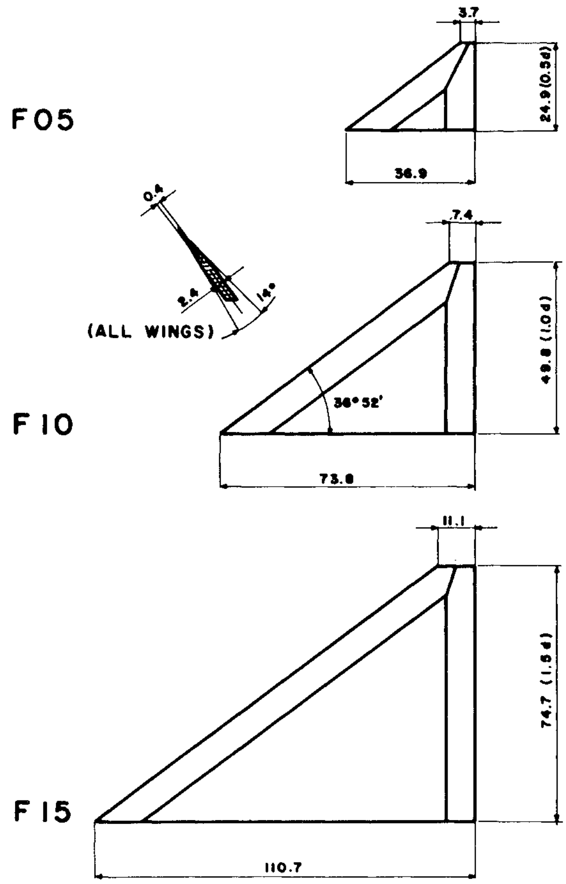

Fig. 2 Geometry of fins.

The wings are mounted on the bodies so that their 2/3 root chord point is 3.2 reference lengths from the nose centerbody interface (see Fig. 1).

The designation of the configurations consists of three parts:

1) A letter for the shape of the body: S, square; R, rectangle; O, circle.

2) A fin code, *F*, indicating the size of the exposed semispan in tenths of the reference length.

3) An $x/+$ symbol referring to the orientation of the wings or $-/|$ symbols referring to that of the rectangular body. Figure 3 shows three test configurations.

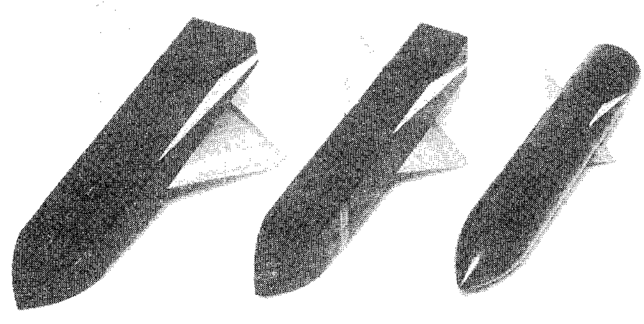

Fig. 3 Photograph of assembled configurations.

B. Tests

The tests were carried out in the transonic wind tunnel of the Aeronautics Research Center of the Technion. The tunnel has a closed cycle and is driven by a circumferential injector. The test section is 60 cm wide × 80 cm high.

The Mach number was 0.75 and the range of angles of attack were −5–15 deg.

A six-component sting balance was used for the measurement of forces and moments. Base pressure was also measured by two probes mounted along the sides of the sting balance.

Reference area and length used in the definition of aerodynamic coefficients are the centerbody cross-sectional area and its square root, respectively. These quantities are independent of the configuration. The center of moment is located 3.5 reference lengths from the tips of the bodies, or 2.0 reference lengths from the nose centerbody interface.

C. Test Results

Because the main objective of the present tests is the study of the aerodynamic characteristics in the pitch plane, only normal-force and pitching-moment coefficients are presented. Figure 4 shows these coefficients for bodies alone. As expected, the normal-force curve slope is largest for the body having the rectangular cross section and smallest for the same body rolled 90 deg. The slope, near the origin, for the body having the square cross section is independent of roll angle. The nonlinearity in normal-force coefficient curve is most pronounced for the body having the square cross section rolled 45 deg. The initial slope of the pitching-moment coefficient curve is only slightly dependent on body cross section and roll angle, indicating about the same center-of-pressure location at small angles of attack. The nonlinearity of the curves, representing a backward shift of the center of pressure, correlates with the nonlinearity of the normal-force coefficient.

Figure 5 is a sample of test results for three configurations featuring F10 wings at x position. The normal-force curve of the square-body configuration is higher than that of the circular-body one, and that of the rectangular-body configuration is highest. The center-of-pressure location, as apparent from the pitching-moment curves, is most forward for the configuration with the rectangular body. The complete data are documented in Ref. 7.

The normal-force curve slope and the center-of-pressure location at small angles of attack were obtained by fitting second-order polynomials to the C_N vs α and C_M vs C_N curves, respectively. These two linear characteristics are presented in the two parts of Fig. 6. The symbols used in the presentation of the data are identical to those used in the designation of the configurations. The normal-force curve slope of the configurations with the circular and square bodies are practically

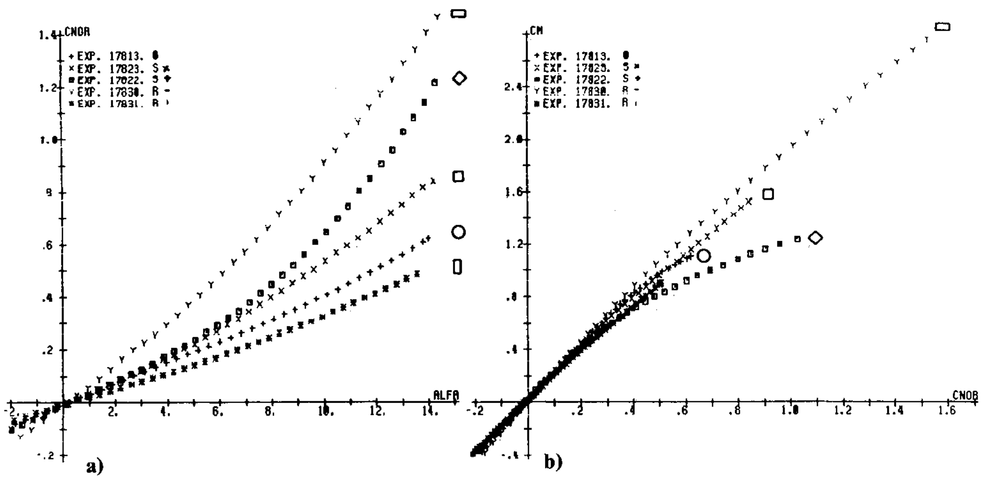

Fig. 4 Test results of bodies alone: a) normal-force coefficient, and b) pitching-moment coefficient.

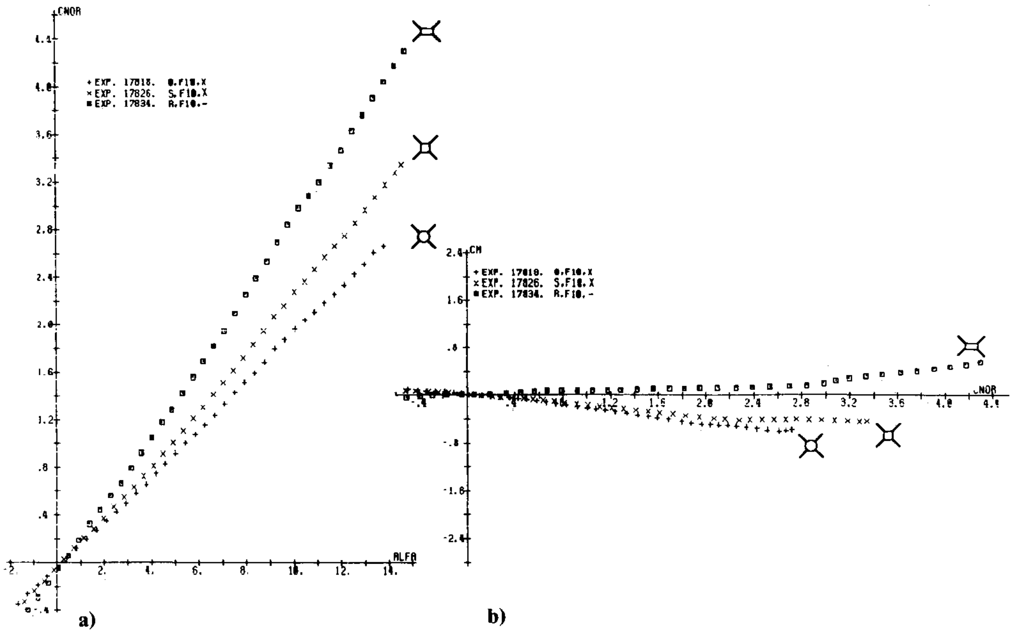

Fig. 5 Test results of configurations having F10 fins: a) normal-force coefficient, and b) pitching-moment coefficient.

independent of roll angle. That derivative is largest for the configurations having the rectangular body in the regular position and smallest for the same configuration rolled 90 deg. Center of pressure moves backward as wing size increases. It is also practically independent of roll angle for the configurations having a circular or a square body. As mentioned before, the center of pressure is farther forward for the configuration with the rectangular body than that for configurations with the other bodies, as expected from the large relative contribution of the rectangular body to normal force.

III. Analysis

A. Component Buildup

Since conceived by Pitts et al.,[8] component buildup (CBU) has become a foundation for many prediction methods and codes in missile aerodynamics. Most of these are restricted to configurations having circular bodies. The recent missile DATCOM[9] code has a capability of handling configurations with elliptical bodies. Here, an attempt is made to extend the CBU method to configurations with bodies having square and rectangular cross sections. The main feature of the method is a code capable of analyzing the aerodynamic characteristics of slender bodies having arbitrary cross sections, approximated by a polygon. The Schwartz-Christoffel transformation is used to map conformally the approximate cross sections into circles. Then, the Sacks[10] formulation of slender body theory is used to evaluate the stability derivatives and the zero angle-of-attack forces and moments. Details are given in Refs. 5 and 6.

The present as well as previous experimental studies of the bodies alone show a considerable gap between the experimentally obtained normal-force curve slope and that predicted by slender-body theory. Hence, experimental values for body-alone stability derivatives are used in the CBU scheme.

The VORLAX[11] code is used to evaluate wing-alone characteristics. As will be discussed in the next section, analytical results are corroborated by comparing them with experimental data.

The normal-force curve slopes of the configurations and of the bodies alone are evaluated using the arbitrary slender-body code. Then, the sum of wing-body and body-wing influence coefficients is extracted by

$$K_{WB} = \frac{C^{sb}_{N_\alpha,c} - C^{sb}_{N_\alpha,b}}{C^{sb}_{N_\alpha,w}}$$

where

$$C^{sb}_{N_\alpha,w} = (S_w/S_R)\,(\pi/2)Æ$$

$$= (\pi/2)\,(b^2/S_R)$$

For the case of the configurations with the circular body, the analytical expression was used:

$$K_{WB} = \left(1 + \frac{D}{D+b}\right)^2$$

Since $D = \sqrt{4/\pi}\,d$, this expression yields

$$K_{WB} = \left(1 + \frac{\sqrt{4/\pi}}{\sqrt{4/\pi} + b/d}\right)^2$$

The dependence of K_{WB} on the normalized exposed span is presented in Fig. 7. The differences between the rolled and unrolled configuration having the square body do not exceed 0.6% and thus do not show graphically. The configuration with the rectangular body in the flat position has the highest influence coefficients. The configurations studied have influence coefficients larger than those of the configurations with the circular body.

The normal-force curve slope and the center of pressure predicted by the CBU method are

$$C_{N_\alpha,c} = C^e_{N_\alpha,b} + K_{WB}C^v_{N_\alpha,w}$$

$$\frac{X_{cp}}{d} = \frac{(X^e_{cp,b}/d)C^e_{N_\alpha,b} + (X^v_{cp,w}/d)K_{WB}C^v_{N_\alpha,w}}{C^e_{N_\alpha,b} + K_{WB}C^v_{N_\alpha,w}}$$

B. VORLAX

The VORLAX code of Miranda et al.[11] is based on a generalized vortex lattice method.

As an interim step, fin-alone linear characteristics were calculated and results compared with test data by Emerson.[12] The pertinent test wings had planform identical to that of the present fins. Emerson's wings had used series 63 airfoils.

Table 1 shows very good agreement between the analytical and the experimental results.

An attempt to model the bodies' noses did not work because of the diminishing cell size near the tip. The bodies were therefore represented as tubes having length and cross section identical to that of the actual ones. Computed body alone normal-force curve slope is very close to that evaluated by slender-body theory. Center of pressure, however, is too close to the tip. Thus, the computed results are corrected, as in Sec. III.A, using body-alone test results:

$$C_{N_\alpha,c} = C^v_{N_\alpha,c} + (C^e_{N_\alpha,b} - C^v_{N_\alpha,b})$$

$$\frac{X_{cp}}{d} = \frac{(X^v_{cp,c}/d)C^v_{N_\alpha,c} + [(X^e_{cp,b}/d)C^e_{N_\alpha,b} - (X^v_{cp,b}/d)C^v_{N_\alpha,b}]}{C^v_{N_\alpha,c} + (C^e_{N_\alpha,b} - C^v_{N_\alpha,b})}$$

C. Comparison

Test results of the configurations having square and circular bodies showed that the linear characteristics are practically independent of roll angle. Likewise, the computed characteristics, which include empirical correction for the contribution of the body alone, showed minute differences owing to roll angle. Average values are therefore used for these two families. Figure

Table 1

Source	C_{L_α}	Comments
VORLAX	3.10	8 × 8 grid
	3.14	5 × 5 grid
Emerson's test[12]	3.18	Thickness ratio 0.02
	3.11	Thickness ratio 0.04

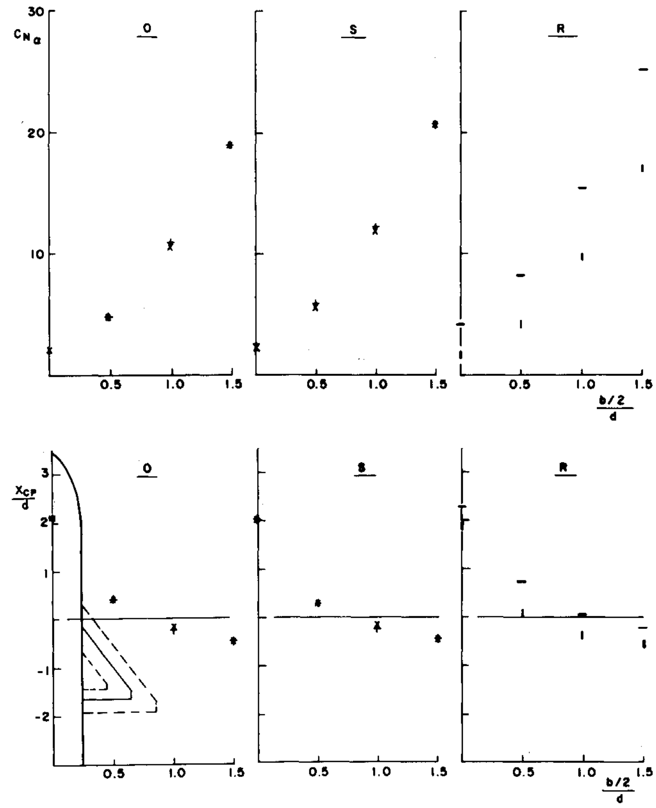

Fig. 6 Measured linear characteristics.

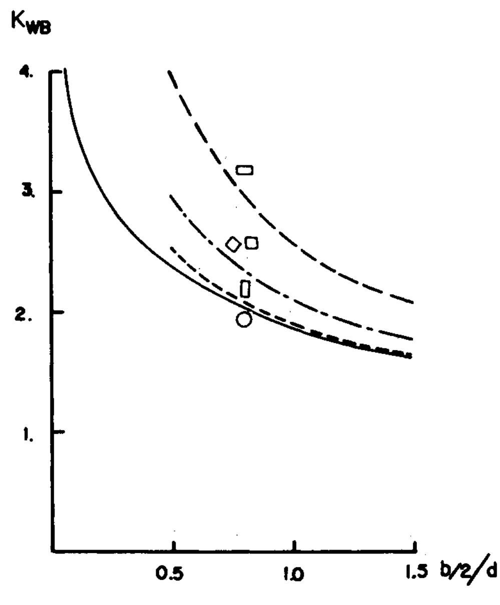

Fig. 7 Influence coefficient.

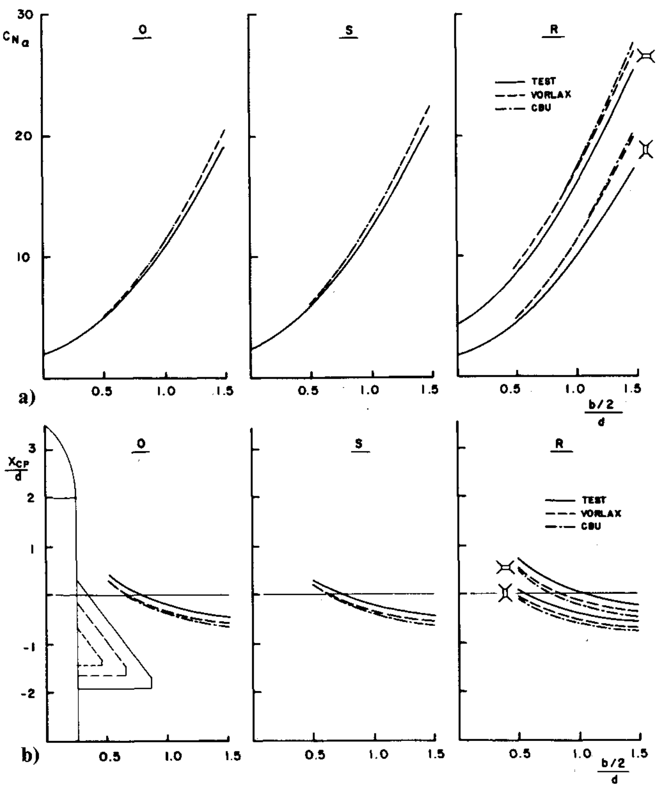

Fig. 8 Comparison between calculated and measured linear characteristics: a) normal-force curve slope, and b) center-of-pressure location.

8 shows a comparison between test results and analysis. The two computational methods give very close values. The maximum deviation in normal-force curve slope is 3.3% for the configurations with the rectangular body. The maximum difference in center-of-pressure location is 0.1 reference length.

The analysis overpredicts the normal-force curve slopes. The differences between results of the CBU method and the experimentally obtained ones are about 6%, 9%, and 11% for configurations having bodies of circular, square, and rectangular cross section, respectively. The differences reach 17% for the configurations having the rectangular body, rolled 90 deg. The computed center-of-pressure location is farther aft than that found experimentally. The differences increase with increase in fin size. The maximum difference between prediction by the CBU method and the experimental values is 0.25 reference length.

IV. Summary and Conclusions

Wind-tunnel tests of three families of configurations having bodies with square, rectangular, and circular cross sections were carried out at a Mach number of 0.75.

The aerodynamic characteristics of the test configurations were calculated using two methods: 1) a CBU scheme that uses experimental data for the body alone, lifting surface analysis for the wing alone, and slender-body theory for the mutual interference; and 2) the VORLAX code with correction for the contribution of the body alone.

The differences between results of the two analytical methods are small. Because VORLAX is a lifting-surface type of method, the very good agreement validates the use of slender-body theory, as well as the code used with the CBU method, for the evaluation of wing-body mutual influence coefficients.

The analysis overpredicts the normal-force curve slope and predicts farther aft center of pressure than that experimentally obtained. Because the computational methods use experimental data for the contribution of the body alone and because the wing-alone results were substantiated, we conclude that the actual mutual wing-body effects are smaller than those predicted by both methods.

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