AIAA 81-4265

Estimating Stern Plane Effectiveness on a Body of Revolution

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Introduction

IN order to estimate the static stability derivatives of streamlined bodies of revolution with attached stern planes,[1] it is useful to have a way of calculating the lift-curve slope of low-aspect-ratio control surfaces taking into account fin-body interaction factors. Dempsey measured the lift and deduced the lift-curve slopes of a body of revolution with stern planes. These measurements were taken for a family of symmetrical stern planes intersecting the axis of the body of revolution. Dempsey found that the stern plane effectiveness can be correlated on the basis of a partial span factor K in the following manner. Let $C_{L\alpha}$ be the lift-curve slope coefficient of a stern plane without the body present and $C_{Z\alpha}$ be the effective lift-curve slope coefficient of the stern plane mounted on the body. Let A be the total projected area of the stern plane, extended to the body centerline. Let ρ be the density of the fluid, U the freestream velocity, and α the angle of attack of the plane. Then for any force F acting on the plane, the force coefficient slope is defined by $C_\alpha = F/(\frac{1}{2}\rho A U^2 \alpha)$ at $\alpha = 0$. Now suppose that the span of the stern plane is $2b$ and that d is the maximum diameter of the body. Dempsey computed $C_{L\alpha}$ based on integrating an elliptic lift distribution over the entire span of the stern plane and $C_{Z\alpha}$ based on integrating the elliptic lift distribution from the stern plane tips inward to the point a distance of Kb from the centerline of the body. The value of the ratio $C_{Z\alpha}/C_{L\alpha}$ is then only a function of K. Dempsey finds experimentally that the value of $(2b/d)K$ for each stern plane deviates less than 2% from the average value of 0.4 for the entire family of stern planes. This indicates that the body interference effects on the stern planes causes a defect in the stern plane span of about $2Kb \approx 0.4d$.

It would be useful to have a method for computing estimates of the interference factor K in order to avoid relying on experimental data to estimate the value of $C_{Z\alpha}/C_{L\alpha}$. This Note presents a very simple method for relating the value of K to the bare body axisymmetric momentum boundary-layer thickness.

Calculation of Stern Plane Effectiveness

In Dempsey's experiments, the leading edge of a stern plane intersects the body at a distance x_ℓ from the nose of the body and all the stern planes have their trailing edges perpendicular to the axis of the body, located at a distance x_t from the nose of the body and forward of the tail. Let r_ℓ and r_t be the values of the body radius at x_ℓ and x_t, respectively. Also, let θ_ℓ and θ_t be the values of the boundary-layer momentum thickness at points (r_ℓ, x_ℓ) and (r_t, x_t), respectively, on the body surface. We propose that $K \approx K_I$ where

$$K_I = \frac{1}{2}\left[\frac{r_\ell + \theta_\ell}{b} + \frac{r_t + \theta_t}{b}\right] \quad (1)$$

In order to test Eq. (1) we have made a calculation of the values of K_I corresponding to Dempsey's experimental conditions. Dempsey's family of stern planes was divided into four sets of geometrically similar planes. The planes in each set have the same span $2b$ but different values of average chord. All the planes had their trailing edge located at $x_t = 0.956L$ where L is the length of the body.

We computed the thin axisymmetric boundary layer on the body by using Head's momentum integral entrainment method (see Ref. 2 or 3). The potential flow pressure distribution was computed by using the first-order slender body theory of Handelsman and Keller.[4] The value of the length Reynolds number (UL/ν) of Dempsey's experiments is 1.4×10^7. We started the boundary-layer calculations at station $x/L = 0.1$ with the values of $\theta/L = 0.00015$ and $H = 1.35$ (where H is the boundary-layer shape factor defined as the ratio of displacement thickness to momentum thickness). The value of $\theta/L = 0.00015$ is about two-thirds of the value of the flat-plate momentum thickness at the same value of Reynolds number. This value of θ/L was chosen to reflect the strong favorable pressure gradient near the nose of the body. In Dempsey's experiments, sand grain roughness at the location $x/L = 0.05$ was used to stimulate transition. The calculation of the boundary layer requires less than 2 s of CPU time on a DEC-10 computer.

Figure 1 shows the tail section of the body with the largest and smallest stern planes from each of Dempsey's sets. Also, the dashed curve is the momentum thickness θ added to the body and the dashed-dot curve is the displacement thickness added to the body. Dempsey calculated the average value of K for each family set of stern planes. We have calculated values of K_I using Eq. (1) for both the largest and smallest stern planes in each set (these values are designated by $K_{I\max}$ and $K_{I\min}$, respectively). The value of K_I for each set, for the purpose of comparison to Dempsey's value of K, is then assumed to be the average value of $K_{I\max}$ and $K_{I\min}$. Table 1 presents our calculated data for each set of stern planes. The sets are each characterized by the stern plane half-span b/L. We have also computed values of K_I^* which is defined by Eq. (1) with θ replaced by δ, the displacement thickness. Note from Table 1 that the values of K_I agree noticeably better with Dempsey's values of K than the values of K_I^*.

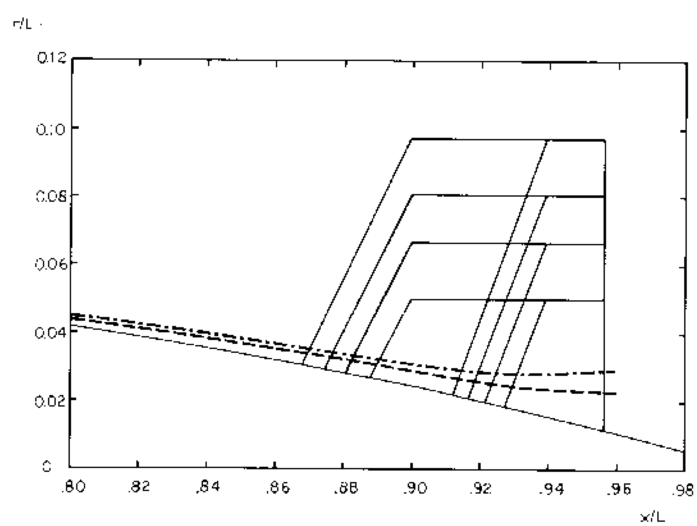

Fig. 1 Stern and largest and smallest stern planes on each set of Dempsey's experiments, and the distribution of momentum thickness (———) and displacement thickness (————).

Received Sept. 12, 1980.

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Table 1 Data for calculating the value of K_I and K_I^* for Dempsey's model

b/L	$(r_\ell+\theta_\ell)_{max}/L$	$(r_\ell+\theta_\ell)_{min}/L$	$(r_\ell+\delta_\ell)_{max}/L$	$(r_\ell+\delta_\ell)_{min}/L$	$(r_t+\theta_t)/L$	$(r_t+\delta_t)/L$	K_{Imax}
0.05	0.0305	0.0245	0.0325	0.0282	0.0229	0.0292	0.534
0.06667	0.032	0.0252	0.0335	0.0285	0.0229	0.0292	0.412
0.08056	0.033	0.0259	0.0343	0.0290	0.0229	0.0292	0.347
0.09722	0.0335	0.0266	0.0352	0.0296	0.0229	0.0292	0.290

K_{Imin}	K_I	K	K^*_{Imax}	K^*_{Imin}	K_I^*	$(K_I-K)/K$	$(K_I^*-K)/K$
0.474	0.504	0.542	0.617	0.574	0.596	−0.07	0.10
0.361	0.387	0.415	0.470	0.433	0.45	−0.07	0.08
0.303	0.325	0.335	0.394	0.361	0.378	−0.03	0.13
0.255	0.273	0.285	0.331	0.302	0.317	−0.04	0.11

Conclusion

We conclude that the loss of lift of a stern plane due to the presence of a body blanketing the center section of the plane can be attributed to the sum of the body plus momentum defect thickness of the boundary layer on the body. Our calculations of this effect agree fairly well with the experimental results of Dempsey,[1] but further experimental confirmation of this effect would be desirable. We note that at very much higher values of Reynolds number than its value in these experiments, the blanketing effect of the body alone would probably be sufficient to determine the value of K since then the boundary layer is much thinner.

References

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