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In-plane forces and moments on installed inclined propellers at low forward speeds

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IN-PLANE FORCES AND MOMENTS ON INSTALLED INCLINED PROPELLERS AT LOW FORWARD SPEEDS

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IN-PLANE FORCES AND MOMENTS ON INSTALLED INCLINED PROPELLERS AT LOW FORWARD SPEEDS

1. NOTATION AND UNITS

		SI	British
AF	activity factor, see Equation (5.2)		
B	number of propeller blades (for a contra-rotating propeller B is total number of blades for both rotors)		
b	wing span	m	ft
c_b	chord of propeller blade element	m	ft
$\bar{c}_b$	average blade chord, see Equation (4.6)	m	ft
c_{ref}	wing reference chord	m	ft
C_m	pitching moment coefficient, $M / \rho n^2 d^5$		
C_{mref}	pitching moment coefficient based on aircraft reference quantities, $M / q S_{ref} c_{ref}$, see Equation (5.8)		
C_N	normal force coefficient, $N / \rho n^2 d^4$ ($= -Z / \rho n^2 d^4$)		
C_{Nref}	normal force coefficient based on aircraft reference quantities, $N / q S_{ref}$ ($= -Z / q S_{ref}$), see Equation (5.6)		
C_n	yawing moment coefficient, $N / \rho n^2 d^5$		
C_{nref}	yawing moment coefficient based on aircraft reference quantities, $N / q S_{ref} b$, see Equation (5.9)		
C_T	thrust coefficient at zero inclination, $T / \rho n^2 d^4$, see Equation (4.7)		
C_{Tmax}	maximum thrust coefficient, Equation (4.8)		
C_{Tref}	thrust coefficient based on aircraft reference quantities, $T / q S_{ref}$, see Equation (5.10). (Note that C_{Tref} is sometimes denoted as T'_c elsewhere in the literature)		
C_Y	sideforce coefficient, $Y / \rho n^2 d^4$		
C_{Yref}	sideforce coefficient based on aircraft reference quantities, $Y / q S_{ref}$, see Equation (5.7)		
d	propeller disc diameter	m	ft

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J	advance ratio, V/nd		
M	free-stream Mach number		
M	pitching moment, see Sketch 3.1(b)	N m	lbf ft
N	normal force (= - Z), see Sketch 3.1(a)	N	lbf
N	yawing moment, see Sketch 3.1(a)	N m	lbf ft
n	propeller rotational speed	rev/s	rev/s
q	free-stream kinetic pressure, $\frac{1}{2}\rho V^2$	N/m ²	lbf/ft ²
R	propeller disc radius	m	ft
r	radius to blade element	m	ft
S_p	propeller disc area, πR^2	m ²	ft ²
S_{ref}	aircraft reference area	m ²	ft ²
T	propeller thrust	N	lbf
TAF	total activity factor, $B \times AF$		
V	free-stream velocity	m/s	ft/s
V_T	propeller tip speed	m/s	ft/s
Y	sideforce, see Sketch 3.1(b)	N	lbf
Z	force in z-direction	N	lbf
x, y, z	propeller axis system, see Sketch 3.1	m	ft
α	isolated propeller angle of attack, see Sketch 3.1(a)	rad	rad
α_e	effective angle of attack for installed propeller	rad	rad
β_0	blade pitch angle referred to zero-lift line of section at $0.75R$	deg	deg
σ_e	propeller effective solidity, ratio of average blade element area to annulus area at $0.75R$, $(4B/3\pi)(\bar{c}_b/d)$. See also Equation (5.3)		
ρ	free-stream density	kg/m ³	slug/ft ³
ρ_0	value of ρ at sea level in International Standard Atmosphere (ISA)	kg/m ³	slug/ft ³
ψ	isolated propeller yaw angle, see Sketch 3.1(b)	rad	rad
ψ_e	effective yaw angle for installed propeller	rad	rad

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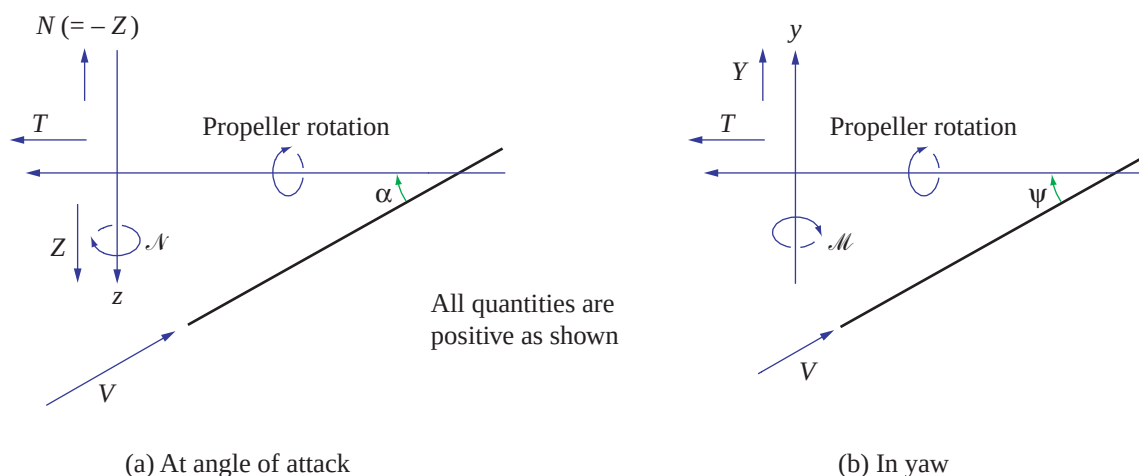
2. INTRODUCTION

This Item provides simple semi-empirical methods for estimating the important in-plane forces and moments at low forward speeds on installed single-rotation and contra-rotating* propellers inclined at moderate angles ($< 20^\circ$, say) to the local flow into the propeller. The data are presented in the form of force and moment coefficient derivatives with respect to the effective local flow angle at the propeller, which requires a separate estimation, see Item No. 90020 (Reference 12). The data are intended primarily for aircraft stability and control calculations at the project stage; more detailed methods will usually be required for load calculations, such as propeller blade stresses and powerplant mounting loads.

Section 3 gives a simple description of the origin of the in-plane forces and moments on an isolated inclined propeller and discusses the effects on the inclination angles of the installation of the propeller on an aircraft. Section 4 lists the equations for the important derivatives and discusses practical means whereby they can be made more amenable to graphical presentation.

Section 5 provides a simple approximate relationship between the propeller effective solidity used as a parameter in the method and the total activity factor, a quantity widely used at the project stage. Further, Section 5 shows how the generalised, dimensionless forms of the equations or graphs can be applied to provide the derivatives in terms of the dimensional parameters for the propeller commonly used in practical applications. Equations are also given for the conversion of the derivatives to ones based on free-stream kinetic pressure and aircraft reference area and length. Section 6 discusses the applicability and accuracy, Section 7 gives the Derivation and References and Section 8 illustrates the practical application of the method by means of a detailed worked example. Appendix A provides details of a computer program for determining the propeller derivatives.

3. IN-PLANE FORCES AND MOMENTS ON INCLINED PROPELLERS



Sketch 3.1 Forces and moments on isolated inclined propellers

* Two rotors revolving in opposite directions on coaxial shafts. "Contra-rotating" propellers are also commonly known as "counter-rotating" or "dual-rotation" propellers.

Each blade of a propeller inclined at an angle of attack to an oncoming flow (Sketch 3.1(a)) generates a load which is dependent on the position of the blade in the rotation cycle. There is an increased loading on the downgoing blades and a decreased loading on the upgoing blades. The loading change is due to changes in angle of attack and kinetic pressure experienced by the blade. For a blade in the vertical position the only change is due to blade sweep (caused by the propeller inclination, α), forward at the bottom position and rearward at the top position. Net, or time-averaged, values of the blade loads result in forces along, and moments about, all three axes x , y and z . Apart from changes to the thrust and torque, which are of course non-zero at zero propeller inclination, the most significant forces and moments due to angle of attack are a normal force, $N (= -Z)$, and a yawing moment, N (see Sketch 3.1(a)). The direction of the yawing moment is dependent on the direction of propeller rotation (positive rotation, as in Sketch 3.1(a), produces a negative yawing moment, and vice-versa). The corresponding situation in yaw, Sketch 3.1(b), produces a sideforce, Y , and a positive pitching moment, M . The moments M and N are relatively small compared with the total values for the aircraft. The moment has the order of magnitude of a moment produced by the in-plane force, N or Y , acting at an arm given by the radius of the propeller disc. Because the signs of the moments are dependent on the direction of propeller rotation, some cancellation will occur for a contra-rotating propeller. In practice, although the two rotors will have different thrust loadings, the self-cancellation of in-plane moments is usually taken as total, giving a zero net moment. The in-plane forces for the two rotors are additive producing an effect of up to a third more than for a single-rotation propeller with the same total number of blades giving the same total thrust under the same operating conditions.

It is found in practice that the in-plane forces and moments are substantially linear for inclination angles up to about 20° (see Derivations 1 and 2, for example). The actual upper limit of linearity depends mainly on the advance ratio J and decreases as J increases.

3.1 Installation Effects on Inclination Angles

It is important to note that for propellers installed on aircraft the effective angles of attack and yaw are relative to the local flow field velocity at the propeller disc. The angle of attack is usually influenced to the greater extent because of the larger velocities induced by the airframe and neighbouring propeller upwash (or downwash) compared to those from the airframe and propeller sidewash that influence yaw angle. For practical application the derivatives in this Item are therefore presented in terms of the effective flow angles, α_e and ψ_e .

4. IN-PLANE FORCE AND MOMENT DERIVATIVES

Early work on the analysis and prediction of the forces and moments on inclined propellers involved the use of propeller performance data for zero inclination as a datum. In the early 1940s Ribner (Reference 10) developed a method based on strip theory which was applicable to small or moderate inclination angles and presented the results (Reference 9) for the sideforce derivative for two propellers with different blade planforms. He also developed a simple means of allowing for compressibility (but see Section 6.1). In the mid-1960s De Young (Derivation 7) simplified the evaluation of many of the functions required in the Ribner method and made use of the data in Reference 9 to produce a set of simple equations that are applicable to any blade planform. He also extended their application to high inclination angles.

This Item makes use of the force and moment derivatives at zero inclination and low forward speeds from Derivation 7, which can be written as follows.

For single-rotation propellers:

$$\frac{dC_N}{d\alpha_e} = \frac{dC_Y}{d\psi_e} = \frac{4.25\sigma_e}{1 + 2\sigma_e} \sin(\beta_0 + 3) \left[\frac{\pi J^2}{8} + \frac{3\left(\frac{\pi J^2}{8}\right)^{1/2} C_T}{8\left(\frac{\pi J^2}{8} + \frac{2}{3}C_T\right)^{1/2}} \right] \quad (4.1)$$

$$-\frac{dC_n}{d\alpha_e} / \frac{dC_N}{d\alpha_e} = \frac{dC_m}{d\psi_e} / \frac{dC_Y}{d\psi_e} = \frac{0.321}{\sigma_e + \tan(\beta_0 + 5)} \left[1 + \frac{\frac{1}{3} \frac{\tan(\beta_0 - 5)}{\sigma_e \cos(\beta_0 - 5)} C_T}{\frac{\pi J^2}{8} + \frac{3}{4} \left[\frac{\tan(\beta_0 - 5)}{\sigma_e \cos(\beta_0 - 5)} \right]^{1/2} C_T} \right] \quad (4.2)$$

For contra-rotating propellers:

$$\frac{dC_N}{d\alpha_e} = \frac{dC_Y}{d\psi_e} = \frac{3.86\sigma_e}{1 + \sigma_e} \sin(\beta_0 + 9) \left[\frac{\pi J^2}{8} + \frac{3\left(\frac{\pi J^2}{8}\right)^{1/2} C_T}{8\left(\frac{\pi J^2}{8} + \frac{2}{3}C_T\right)^{1/2}} \right] \quad (4.3)$$

and

$$\frac{dC_n}{d\alpha_e} = 0, \quad \frac{dC_m}{d\psi_e} = 0. \quad (4.4)$$

It will be noted that Equations (4.1) and (4.3) are invalid for values of C_T that are beyond a certain negative limit. A similar problem exists with Equation (4.2) if $\beta_0 < 5^\circ$. However, see Section 6.1 with regard to the practical use of these equations.

In Equations (4.1) to (4.3), β_0 is the blade pitch angle referred to the zero-lift line of the section at $0.75R$, J is the advance ratio, C_T is the thrust coefficient at zero propeller inclination and σ_e is the propeller effective solidity, given by

$$\sigma_e = \frac{4B}{3\pi} \left(\frac{\bar{c}_b}{d} \right), \quad (4.5)$$

in which $\bar{c}_b$ is the average blade chord from $0.2R$ to the tip, given by

$$\bar{c}_b = \frac{1}{0.8} \int_{0.2}^1 c_b d(r/R). \quad (4.6)$$

In Equations (4.1) to (4.3) β_0 can be deduced from the empirical equation for C_T , given in Derivation 7, i.e.

$$C_T = \frac{4.6\sigma_e \cos(\beta_0 - 5)}{1 + 3\sigma_e + (9\sigma_e/B)} (2.2 \tan \beta_0 - J). \quad (4.7)$$

The derivatives in Equations (4.1) to (4.3) can then be considered as functions of the four variables, σ_e , B , J and C_T . Analysis of these equations shows that for practical ranges of σ_e , J and C_T the derivatives are comparatively insensitive, within a few per cent, to variations in B over the range $2 \leq B \leq 10$, provided that σ_e/B is within the approximate range $0 \leq \sigma_e/B \leq 0.08$. In order to simplify the presentation of data a

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value of $B = 6$ was taken, i.e. $9\sigma_e/B$ in Equation (4.7) was taken as $1.5\sigma_e$. Figures 1 to 3 present carpets for the derivatives as functions of C_T and J over the ranges $0 \leq C_T \leq C_{Tmax}$ and $0 \leq J \leq 3$ for values of $\sigma_e = 0.05, 0.1, 0.2, 0.3, 0.4$ and 0.5 . Figures 1(a) to 1(f) and 2(a) to 2(f) give the force and moment derivatives, respectively, for single-rotation propellers, while Figures 3(a) to 3(f) give the force derivatives for contra-rotating propellers. The hatched boundaries on the Figures represent a rough approximation to maximum thrust coefficient, given in Derivation 7 as

$$C_{Tmax} \approx 2.2\sigma_e. \quad (4.8)$$

5. PRACTICAL CONSIDERATIONS IN THE USE OF THE DATA

5.1 Propeller Effective Solidity

Equations (4.1) to (4.3) and Figures 1 to 3 are presented in terms of σ_e , the propeller effective solidity. However, in the early stages of a project σ_e may not be known. In such cases it is most likely that the designer will have some knowledge of the total activity factor, TAF , for suitable propellers, where

$$TAF = B \times AF \quad (5.1)$$

in which the activity factor per blade is given by

$$AF = 10^5 \int_{0.1}^{0.5} \frac{c_b(r)}{d} \left(\frac{r}{d}\right)^3 d\left(\frac{r}{d}\right) = 3125 \int_{0.2}^1 \frac{c_b(r)}{R} \left(\frac{r}{R}\right)^3 d\left(\frac{r}{R}\right). \quad (5.2)$$

Analysis of a range of blade planforms indicates that there is no simple universally applicable relationship between σ_e and TAF based wholly on parameters likely to be known at an early design stage. However, for a wide range of practical blade planforms (including modern feeder-liner propellers and propellers designed for high subsonic Mach numbers) a reasonable approximation is

$$\sigma_e = 0.0003TAF, \quad (5.3)$$

which is expected to apply to blade planforms with centre of area at about $0.6 R$.

5.2 Propeller Thrust Loading and Tip Speed

The forms of Equations (4.1) to (4.3) with β_0 given by Equation (4.7) are the most generally applicable dimensionless forms. In practice, when applied to specific propellers on project aircraft, dimensional plots in terms of propeller thrust loading, $T/(d^2\rho/\rho_0)$, tip speed, V_T , and σ_e for a given forward speed, V , might be required. For this purpose the following conversions are required:

$$V_T = \pi \frac{V}{J} \quad (5.4)$$

and

$$\frac{T}{d^2\rho/\rho_0} = \frac{\rho_0 V^2}{J^2} C_T. \quad (5.5)$$

5.3 Conversion from Propeller-based to Aircraft-based Coefficients

In order to apply the derivatives to aircraft, the force and moment coefficients need to be based on free-stream kinetic pressure, q , reference area, S_{ref} , and length, c_{ref} or b , used for the airframe force and moment coefficients. The relationships between the corresponding force and moment coefficients are

$$C_{Nref} = \frac{8}{\pi J^2} \frac{S_p}{S_{ref}} C_N, \quad (5.6)$$

$$C_{Yref} = \frac{8}{\pi J^2} \frac{S_p}{S_{ref}} C_Y, \quad (5.7)$$

$$C_{mref} = \frac{8}{\pi J^2} \frac{S_p d}{S_{ref} c_{ref}} C_m, \quad (5.8)$$

and

$$C_{nref} = \frac{8}{\pi J^2} \frac{S_p d}{S_{ref} b} C_n. \quad (5.9)$$

Also

$$C_{Tref} = \frac{8}{\pi J^2} \frac{S_p}{S_{ref}} C_T. \quad (5.10)$$

Note that the force and moment coefficients are referred to the propeller axis system as in Sketch 3.1 and the appropriate conversions will need to be made to transform to the required aircraft axis system.

6. APPLICABILITY AND ACCURACY

6.1 Applicability

The methods of this Item for estimating the in-plane force and moment derivatives for propellers at low forward speeds are expected to apply to any propeller, whether in isolation or installed on an aircraft. However, in order to calculate the forces and moments for an installed propeller using the derivatives, separate calculations of the effective inclination angles of the propeller must be made, with due allowance for airframe interference (see Reference 12). For the purposes of calculating forces and moments it may be assumed that the derivatives apply to effective inclination angles up to about 20°.

The methods have been shown, by comparisons with test data (Derivations 1 to 6, and 8), to apply to conventional single-rotation and contra-rotating propellers with low to moderate thrust loading designed for low subsonic speeds. Although no suitable test data are available for comparison, the methods may also be assumed to apply in principle to the low-speed operation of propellers with high thrust loadings designed for high subsonic speeds. However, until suitable test data are available, the method should be applied with some caution to such cases.

Derivation 7 contains a simple correction factor to apply to the low-speed derivatives to allow for Mach number effects up to the critical Mach number for the propeller. However, comparisons with the only available test data, for a 3-bladed propeller designed for high subsonic speeds (Reference 11), are

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satisfactory at low speeds ($M \approx 0.1$) but are poor at high speeds ($0.6 \leq M \leq 0.9$). Most significantly, while the method of Derivation 7 indicates rapidly increasing values of $dC_N/d\alpha_e$ as M increases to 0.6 and beyond, the test data show a moderate decrease. Until adequate test data are available to make a proper assessment of Mach number effects, the data in this item should be applied only up to $M \approx 0.4$.

The range of parameters covered by the comparisons of the methods with test data for single-rotation propellers at low speeds ($M < 0.15$) are given in the following table. Only one set of data (Derivation 3) for a contra-rotating propeller was available. For that propeller $B = 6$, $\sigma_e = 0.157$, $AF = 86$, $J = 0.3$ to 2.8 and $C_T = -0.2$ to 0.3 .

TABLE 6.1 Parameter ranges in comparisons of the prediction methods with test data for single-rotation propellers at low speeds ($M < 0.15$)

$d(\text{ft})$	B	σ_e	σ_e/B	AF	J	C_T
2 to 12	2 to 6	0.05 to 0.16	0.022 to 0.039	73 to 150	0.1 to 2.8	-0.3 to 0.4

It will be noted that the range of C_T in Table 6.1 extends to negative values. However, bearing in mind the possible problems involving the use of negative values in Equations (4.1) and (4.3), pointed out in Section 4, it is necessary to state that no such problems were encountered in the predictions using these values since they were associated with large values of J . In general, it is suggested that since Equation (4.7) was derived for $C_T > 0$, it is advisable to restrict the use of Equations (4.1) to (4.3) to $C_T > 0$ also. It should also be noted that throughout the test data $\beta_0 > 13^\circ$, so that the restriction $\beta_0 \geq 5^\circ$, imposed by the form of Equation (4.2), is a reasonable one.

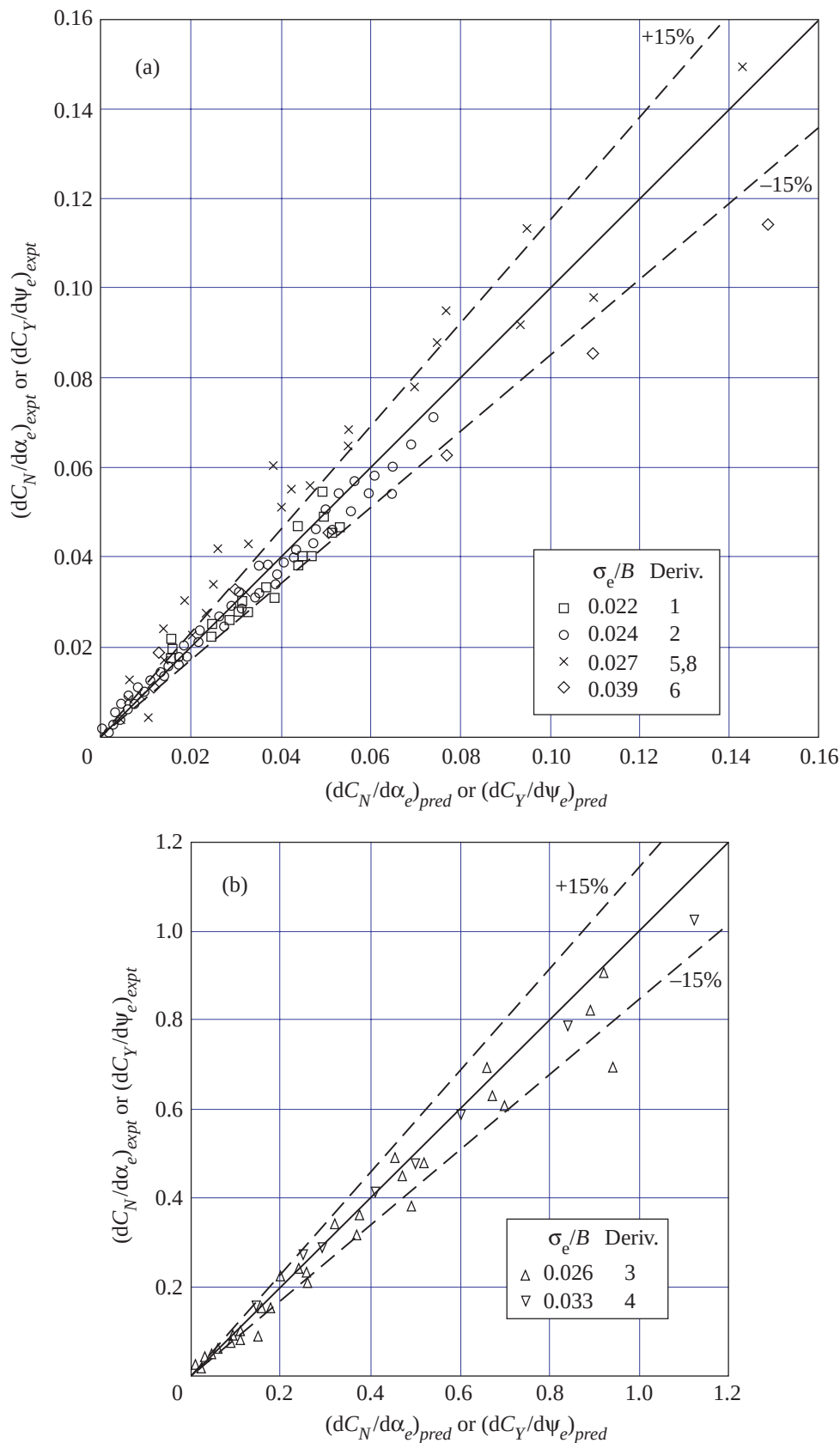
6.2 Accuracy

Sketches 6.1 and 6.2 illustrate the accuracy of the methods of this Item for predicting $dC_N/d\alpha_e$ (or $dC_Y/d\psi_e$) and $|dC_N/d\alpha_e|$ (or $|dC_m/d\psi_e|$), respectively, for single-rotation propellers at low speeds ($M < 0.15$). From these comparisons of calculations using Equations (4.1) to (4.3) and (4.7) with test data (Derivations 1 to 6, and 8) it is suggested that errors in predicting $dC_N/d\alpha_e$ (or $dC_Y/d\psi_e$) can be expected to be within about $\pm 15\%$, while those for the small moment derivatives ($dC_n/d\alpha_e$ or $dC_m/d\psi_e$) can be expected to be within about $\pm 40\%$.

If the data are restricted to those for which the propellers are working at or near the maximum efficiency for a given blade angle, as would be the case for a constant-speed propeller, then most of the extremes of scatter outside the error bands in Sketches 6.1 and 6.2 are eliminated.

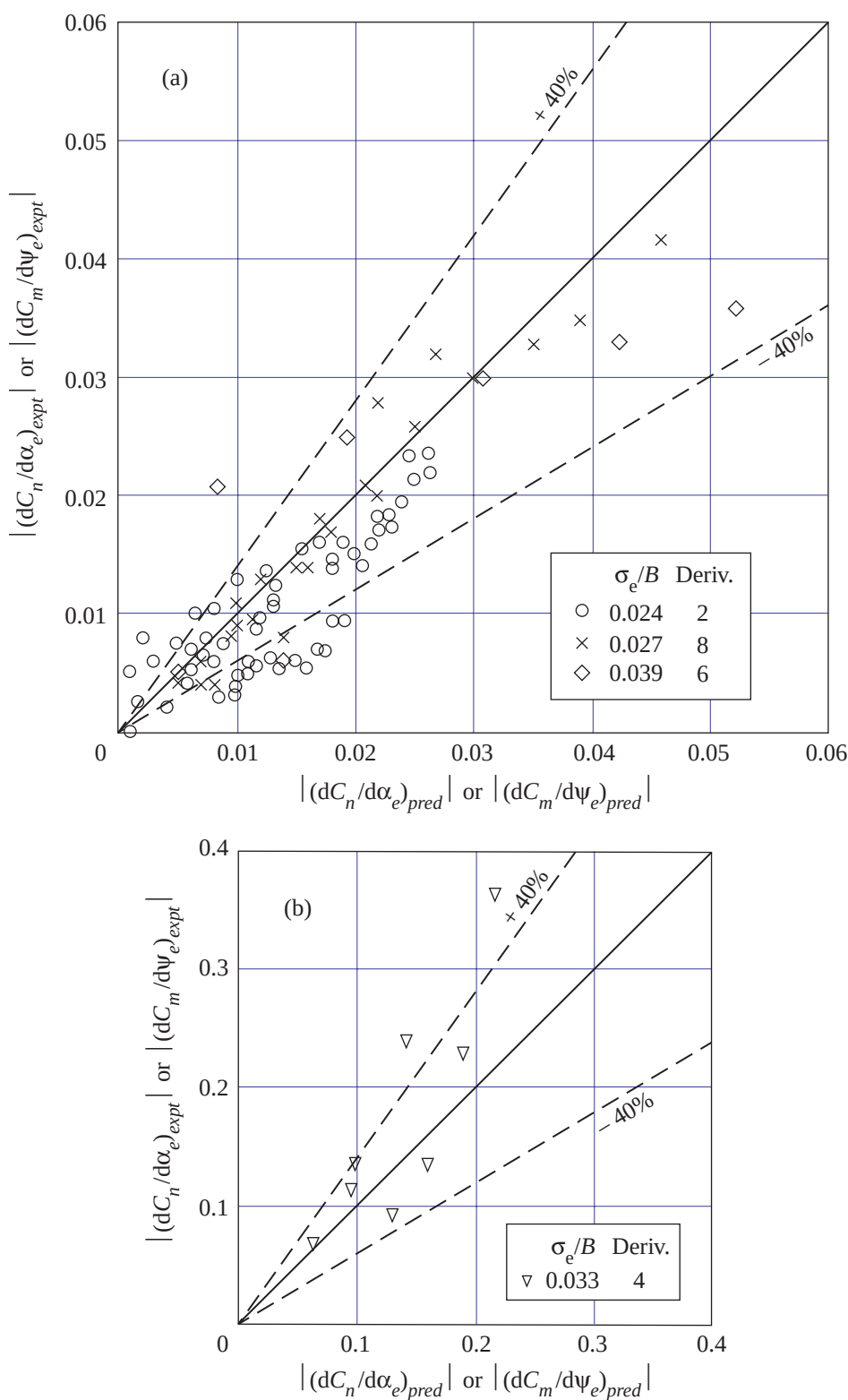
The comparisons of the prediction method for $dC_N/d\alpha_e$ with the only available data for a contra-rotating propeller (Derivation 3) indicate a similar accuracy to that for single-rotation propellers. The corresponding yawing moment data support Equation (4.4) well.

In assessing the accuracy of the methods it is important to bear in mind the many difficulties involved in measuring the small time-averaged forces and moments on inclined propellers. There is also considerable difficulty in ensuring that any nacelle or support structure has a minimal effect, not only on the propeller forces and moments, but also on the flow into the propeller. Because of these problems the suggested errors are probably somewhat pessimistic, particularly that for the moment derivatives.



Sketch 6.1 Comparisons of low-speed test data for $dC_N/d\alpha_e$ (or $dC_Y/d\psi_e$) with predictions using Equation (4.1) for single-rotation propellers

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Sketch 6.2 Comparisons of low-speed test data for $|dC_N/d\alpha_e|$ or $|dC_m/d\psi_e|$ with predictions using Equations (4.1) and (4.2) for single-rotation propellers

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7. DERIVATION AND REFERENCES

7.1 Derivation

The Derivation lists selected sources that have assisted in the preparation of this Item.

- | | | |
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7.2 References

The References list sources of information supplementary to that given in this Item.

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