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Design Forum

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Rapid Estimation of the Zero-Lift Drag Coefficient of Transport Aircraft

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A rapid method for estimating the zero-lift drag coefficient of transport aircraft is presented. The method is based on the principle of equivalent skin friction. The method considers an empirical relation between the equivalent skin-friction coefficient and Reynolds number based on a reference length calculated from the aircraft's geometry. The method can be used throughout the conceptual design phase as a prediction and verification tool.

Nomenclature

b	=	wing span
C_{D0}	=	zero-lift drag coefficient
C_{fe}	=	equivalent skin friction coefficient
ℓ	=	reference length
Re	=	Reynolds number
S	=	wing area
S_{wet}	=	aircraft total wetted area
V	=	speed
ν	=	kinematic viscosity

Introduction

IN the conceptual design phase, simple equations are used to estimate a number of variables of an aircraft like weight and aerodynamic characteristics. One of the important aerodynamic coefficients is the zero-lift drag coefficient. Because of its significant impact on the aircraft's overall size and performance, accurate estimation of this coefficient is important even in the initial stages of a design. A number of conceptual design methods have been developed over the years.[1–3] Some of these methods such as the component drag buildup technique are time consuming and require that detailed information of the aircraft is known.

A simple method for estimating the zero-lift drag coefficient is the equivalent skin-friction coefficient method.[1,4] The zero-lift drag coefficient is related to the total wetted area of an aircraft by using an equivalent skin-friction coefficient. It is based on the fact that the zero-lift drag is mainly skin-friction drag plus a pressure drag part.[1] Usually constant values of the equivalent skin-friction coefficients for different groups of aircraft are used. It appears that size effects, in terms of a Reynolds number, have a significant influence on the value of the equivalent skin-friction coefficient.[4] This is because the skin-friction drag is a function of Reynolds number and because a large part of the zero-lift drag is caused by skin friction.

In this Design Forum paper, a comprehensive equivalent skin-friction method is presented. The method considers an empirical relation between the equivalent skin-friction coefficient and a Reynolds number based on a reference length calculated from the aircraft's geometry. Data of turbo prop, business jet, and transport jet aircraft were used for the method. The method can be used throughout the conceptual design phase as a prediction and verification tool.

Description of the Method

The zero-lift drag coefficient is related to the total wetted area of an aircraft by the following equation[1]:

$$C_{D0} = C_{fe}(S_{wet}/S) \tag{1}$$

The equivalent skin-friction coefficient C_{fe} in Eq. (1) varies typically from 0.0025 to 0.0050 depending on aircraft class, Reynolds number, and aerodynamic cleanness. Aerodynamic cleanness is defined here by the amount excrescence drag on an aircraft. Excrescence drag originates from several sources such as antennas, air data sensors, and surface imperfections.[5–7]

Equivalent skin-friction coefficients (without the possible compressibility drag part) were collected for a large number of aircraft of three different groups (turbo prop, business jets, and transport jets). The data were obtained from Refs. 4 and 8–11 and some unpublished sources. The equivalent skin-friction coefficients were related to the Reynolds number generally defined by

$$Re = V\ell/\nu \tag{2}$$

The Reynolds number was determined using the speed and altitude for which the equivalent skin-friction coefficient was valid. Different kinds of reference lengths ℓ were examined such as wing span, wetted area over wing span ratio, mean wing chord, and fuselage length. A reference length based on the wetted area over wing span ratio gave the best correlation between C_{fe} and Reynolds number and was, therefore, used in the present method. An attempt was made to derive separate C_{fe}–Reynolds number relations for each distinct group of aircraft (turbo prop, business jet, and transport jet). However, the C_{fe}–Reynolds number relations for these aircraft groups did not show a significant difference. The influence on C_{fe} of the expected differences in the aerodynamic cleanness between each aircraft group appeared to be less dominant than the influence of the Reynolds number. Furthermore the aerodynamic cleanness of the different aircraft in each group is not always comparable. Therefore, a single relation between equivalent skin-friction coefficient and Reynolds number was determined for all three aircraft groups

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considered. The following empirical equation was obtained from linear regression of the data:

$$C_{fe} = 0.00258 + 0.00102\ \exp(-6.28 \times 10^{-9} Re) + 0.00295\ \exp(-2.01 \times 10^{-8} Re) \quad (3)$$

with

$$Re = (S_{wet}/b)V/\nu \quad (4)$$

In Fig. 1 the equivalent skin-friction data are compared to Eq. (3). Also shown are some of the aircraft used for the correlation. The standard deviation of Eq. (3) is 8.8%. The range of some variables of the aircraft considered is given in Table 1. When the equivalent skin-friction coefficient is plotted against the total wetted area of an aircraft (Fig. 2), it becomes clear that C_{fe} is strongly influenced by the overall size of the aircraft.

For the aircraft considered, the ratio of the total wetted area and the wing area varied between 4.4 and 6.5. The average value of this ratio was 5.6, which can be used as a first estimation of the total

Table 1 Range of aircraft variables

Parameter	Value
Re (based on S_{wet}/b) $\times 10^6$	35–390
S_{wet}, m^2	120–3400
S_{ref}, m^2	20–580
b, m	10–68

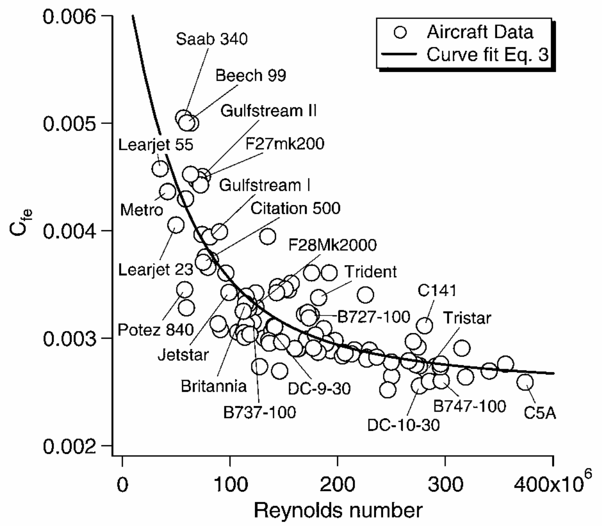

Fig. 1 Equivalent skin-friction coefficient as function of Reynolds number.

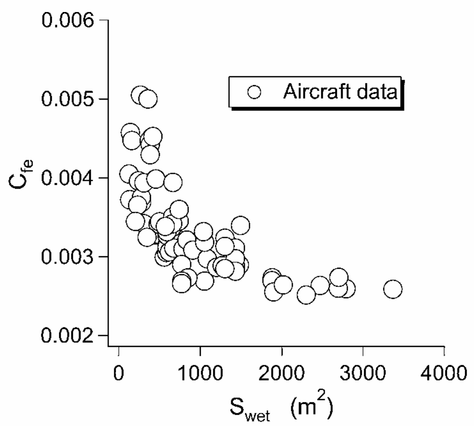

Fig. 2 Influence of wetted area on the equivalent skin-friction coefficient.

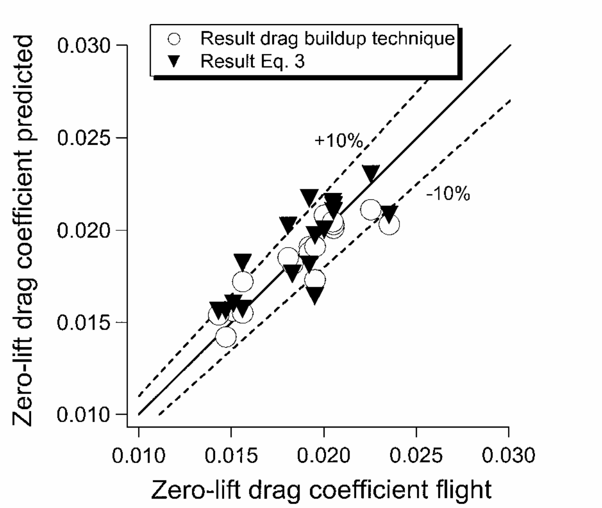

Fig. 3 Comparison between predicted and flight determined zero-lift drag coefficient.

wetted area. A more accurate estimation of the total wetted area of an aircraft can be obtained by calculating the wetted area of each exposed part.

Comparison with Component Drag Buildup Technique

The results of Eq. (3) were compared with a component drag buildup technique presented in Ref. 1. The relations presented in Ref. 1 are comparable to those used by aircraft manufacturers (e.g., Refs. 12 and 13) and other published drag buildup methods (e.g., Refs. 2 and 14). For 17 aircraft, the zero-lift drag was calculated using the drag buildup technique and Eq. (3). The results of both methods are compared with the experimental zero-lift drag data in Fig. 3. For the 17 examined aircraft, the drag buildup technique had a standard deviation of 5.8%, and the equivalent skin-friction method presented here had a standard deviation of 8.3%. The lower standard deviation of the drag buildup technique is normal considering the level of detail of this method.

Examples

Full-scale drag data of the Fokker F27-Mk 200 turboprop aircraft are provided in Ref. 9. The calculated wetted area is 370 m^2 using the method of Ref. 15. The flight tests were conducted at an average Reynolds number of 5.56×10^6/m. The wing reference area is 70 m^2, the wing span is 29 m, and the reference length is $370/29 = 12.8$ m. Hence, the Reynolds number based on the reference length S_{wet}/b is 71×10^6. The zero-lift drag coefficient derived from flight tests is 0.0235, resulting in an equivalent skin-friction coefficient of $0.0235 \times 70/370 = 0.00445$. Equation (3) gives a C_{fe} of 0.0039, resulting in a zero-lift drag coefficient of 0.0206 (−12.3%). When the component drag buildup technique of Ref. 1 is used, the zero-lift drag coefficient is estimated as 0.0203 (−13.6%). Both Eq. (3) and the drag buildup technique underestimate the zero-lift drag coefficient. The underestimation could be due to high excrescence drag levels on the F27-Mk 200. In Fig. 4, the predicted zero-lift drag coefficient is presented as function of Reynolds number. The equivalent skin-friction method shows a somewhat stronger variation of the zero-lift drag coefficient with Reynolds number than the drag buildup technique.

In a second example, the DC9-30 jet transport aircraft is considered. Drag data from flight tests are given in Ref. 11. The calculated wetted area is 610 m^2 using the method of Ref. 15. The Reynolds number based on the reference length S_{wet}/b is 138×10^6. The zero-lift drag coefficient derived from flight tests is 0.0206, resulting in an equivalent skin-friction coefficient of 0.0031. Equation (3) gives a C_{fe} of 0.0032, resulting in a zero-lift drag coefficient of 0.0210 (+1.9%). When the component drag buildup technique of Ref. 1 is used, the zero-lift drag coefficient is estimated as 0.0201 (−2.4%).

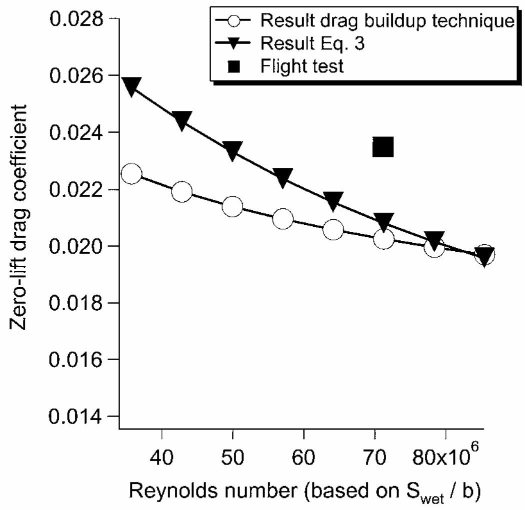

Fig. 4 Zero-lift drag coefficient of the F27-Mk 200 as function of Reynolds number.

Conclusions

A simple method for predicting the zero-lift drag coefficient of turbo prop, business jet, and transport jet aircraft is presented. The method requires only a minimum of input information but does have a dependency on Reynolds number. The method can be used throughout the conceptual design phase as a prediction and verification tool.

References

[1]Raymer, D. P., "Aircraft Design: A Conceptual Approach," AIAA Education Series, AIAA, Washington, DC, 1989, pp. 278–282.

[2]Roskam, J., "Methods for Estimating Drag Polars of Subsonic Airplanes," Univ. of Kansas, Lawrence KS, 1973.

[3]"Estimation of Airframe Drag by Summation of Components: Principles and Examples," Engineering Science Data Unit, ESDU Data Item 97016, London, 1997.

[4]Jobe, C. E., "Prediction and Verification of Aerodynamic Drag Part I: Prediction," *Thrust and Drag: Its Prediction and Verification*, Progress in Astronautics and Aeronautics, Vol. 98, AIAA, New York, 1985, pp. 121–171.

[5]Wieghardt, K., "Erhöhung des Turbulenten Reibungswiderstandes durch Oberflächenstörungen," Jarhbuch der Deutschen Luftfahrtforschung, Göttingen, Germany, 1943, pp. 1–17.

[6]Hoerner, S. F., "The Effect of Roughness Concentration upon Frictional Drag," *Journal of the American Society of Naval Engineers*, Vol. 66, 1954, pp. 497–503.

[7]Callaghan, J. G., "Aerodynamic Prediction Methods for Aircraft at Low Speeds with Mechanical High Lift Devices," AGARD Rept. LS-67, Brussels, Belgium, 1974.

[8]Roskam, J., "Airplane Design Part VI: Preliminary Calculation of Aerodynamic, Thrust and Power Characteristics," Roskam Aviation and Engineering Corp., Lawrence KS, 1987.

[9]Berenschot, G., Torenbeek, E., and Vermeulen, A., "Computer Program for the Drag Prediction of Subsonic, Turbine-Powered Aircraft in the En-Route Configuration," Delft Univ. of Technology, Dept. of Aerospace Engineering, Rept. LR-412, Delft, The Netherlands, 1983.

[10]"Representation of Drag in Aircraft Performance Calculations," Engineering Science Data Unit, ESDU Data Item 81026, London, 1997.

[11]McGeer, T., and Shevell, R. S., "A Method for Estimating the Compressibility Drag of an Airplane," Stanford Univ., Rept. SUDAAR 535, Stanford, CA, 1983.

[12]Morrison, W. D., "Advanced Airfoil Design Empirically Based Transonic Aircraft-Drag Buildup Technique," Lockheed-California Co., Rept. LR-27524, Burbank, CA, 1976; also NASA CR-137928, Jan. 1976.

[13]Feagin, R. C., and Morrison, W. D., "Delta Method, an Empirical Drag Buildup Technique," Lockheed-California Co., Rept. LR-27975-VOL-1, Burbank, CA, 1978; also NASA CR-151971, Dec. 1978.

[14]Jenkinson, L. R., Simpkin, P., and Rhodes, D., "Civil Jet Aircraft Design," Arnold, London, 1999, pp. 170–177.

[15]Torenbeek, E., "The Computation of Characteristics Areas and Volumes of Major Aircraft Components in Project Design," Delft Univ. of Technology, Dept. of Aerospace Engineering, Memorandum M-189, Delft, The Netherlands, 1973.