ANNALS of the ORADEA UNIVERSITY.

Fascicle of Management and Technological Engineering, Volume VI (XVI), 2007

THE USE OF PRE-CFD COMPUTATIONAL AERODYNAMICS PROGRAMS IN AIRCRAFT PRELIMINARY DESIGN IN ORDER TO ESTIMATE THE LAMINAR AND TURBULENT SKIN FRICTION

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Keywords: VLM, pressure loading functions, drag, FRICTION

ABSTRACT: The VLM in its modern form avoids the use of pressure loading functions and has been developed independently by several investigators including Rubbert [2] (who also considered the induce drag calculation), Dulmovits [3], Hedman [4], and Belotserkovskii [5]. In the application of this method, a division of the surface(s)into small trapezoidal elements (boxes) arranged in strips parallel to the freestream is made so that surface edge, fold lines, and hinge lines lie on box boundaries.

One of this methods had developed into the program named FRICTION. FRICTION provides an estimate of laminar and turbulent skin friction suitable for use in aircraft preliminary design. It is an entirely new program, but has its roots in a program by Ron Hendricksonat Grumman.

The Importance of Drag

Drag is at the heart of aerodynamic design. The subject is fascinatingly complex. All aerodynamicists secretly hope for negative drag. The subject is tricky and continues to be controversial. It’s also terribly important. Even seemingly minor changes in drag can be critical. On the Concorde, a one count drag increase (ΔC_D = .0001) requires two passengers, out of the 90 – 100 passenger capacity, be taken off the North Atlantic run.[6] In design studies a drag decrease is equated to the decrease in aircraft weight required to carry a specified payload the required distance. One advanced fighter study[2] found the drag sensitivity in supersonic cruise was 90 lb/ct and 48 lb/ct for subsonic/transonic cruise. At the transonic maneuver design point the sensitivity was 16 lb/ct (drag is very high here). In comparison, the growth factor was 4.1 lb of takeoff gross weight for every 1 lb of fixed weight added. For one executive business jet the range sensitivity is 17 miles/drag count. Advanced supersonic transports now being studied have range sensitivities of about 100 miles/drag count. When new aircraft are sold, the sales contract stipulates numerous performance guarantees. One of the most important is range. The aircraft company guarantees a specified range before the aircraft is built and tested. The penalty for failure to meet the range guarantee is severe. Conservative drag projections aren't allowed—the competition is so intense that in the design stage the aerodynamicist will be pressured to make optimistic estimates. In one briefing in the early '80s, an aerodynamicist for a major airframer said that his company was willing to invest $750,000 for each count of drag reduction. Under these conditions the importance of designing for low drag, and the ability to estimate drag, can hardly be overstated.

The economic viability and future survival of an aircraft manufacturer depends on minimizing aerodynamic drag (together with the other design key technologies of structures, propulsion, and control) while maintaining good handling qualities to ensure flight safety and ride comfort. New designs that employ advanced computational aerodynamics methods are needed to achieve vehicles with less drag than current aircraft. The most recent generation of designs (Boeing 767, 777, Airbus A340, *etc*.) already take advantage of computational aerodynamics, advanced experimental methods, and years of experience. Future advances in aerodynamic performance present tough challenges requiring both innovative concepts and the very best methodology possible.

Initial drag estimates can dictate the selection of a specific configuration concept in comparison with other concepts early in the design phase. The drag projections have a huge effect on the projected configuration size and cost, and thus on the decision to proceed with the design.

Program FRICTION

FRICTION provides an estimate of laminar and turbulent skin friction suitable for use in aircraft preliminary design. It is an entirely new program, but has its roots in a program by Ron Hendrickson at Grumman. It runs on any computer. The input requires geometric information and either the Mach and altitude combination, or the Mach and Reynolds number at which the results are desired. The skin friction is found using the Eckert Reference Temperature method for laminar flow and the van Driest II formula for turbulent flow. The basic formulas are valid from subsonic to hypersonic speeds, but the implementation makes assumptions that limit the validity to moderate supersonic speeds (about Mach 3). The key assumption is that the vehicle surface is at the adiabatic wall temperature (the user can easily modify this assumption). Form factors are used to estimate the effect of thickness on drag, and a composite formula is used to include the effect of a partial run of laminar flow. Because the methods aren't described in detail in the text, details are provided here.

Laminar flow

The approach used is known as the Eckert Reference Temperature Method, and this particular version is the one given by F.M. White in *Viscous Fluid Flow*, McGraw-Hill, New York, 1974, pp. 589-590. In this method the incompressible skin friction formula is used, with the fluid properties chosen at a specified reference temperature, which includes both Mach number and wall temperature effects.

First, assumptions are made for the fluid properties:* Prandtl number, Pr = 0.72, Recovery factor, r = $Pr^{1/2}$, specific heat ratio, γ= 1.4, and edge temperature, Te = 390 (°R). Then, for a given edge Mach number, Me, and ratio of wall temperature to adiabatic wall temperature TW/TAW; compute:

Remember that:

$$\frac{T_W}{T_e} = \frac{T_W}{T_{AW}}\left(1 + r\frac{\gamma - 1}{2}M_e^2\right). \tag{1}$$

$$T_{AW} = T_e\left(1 + r\frac{\gamma - 1}{2}M_e^2\right) \tag{2}$$

and then compute the reference temperature:

$$\frac{T^*}{T_e} \cong .5 + .039M_e^2 + 0.5\left(\frac{T_w}{T_e}\right) \tag{3}$$

The Chapman-Rubesin constant based on the reference temperature and Sutherland's viscosity law is then computed from:

$$C^* = \left(\frac{T^*}{T_e}\right)^{1/2}\left(\frac{1 + K/T_e}{T^*/T_e + K/T_e}\right) \tag{4}$$

where K = 200°R for air.

Finally, the local friction coefficient (τ_w/q) is found from the standard Blasius formula, with C^* added,

$$C_f = \frac{.664\sqrt{C^*}}{\sqrt{\mathrm{Re}_x}} \tag{5}$$

and

$$C_F = 2C_f \tag{6}$$

which comes from

$$C_F = \frac{F}{qx} = \frac{1}{x}\int_{x'=0}^{x'=x} C_f(x')dx' \tag{7}$$

Recall that C_F accounts for one side of the plate only, so that if both sides are required for a drag estimate, then the skin friction coeficient, C_D, is twice C_F because the reference area is based on one side only, i.e., $S_{ref} = 1/2\ S_{wet}$.

Note that the results are not sensitive to the value of edge temperature for low Mach numbers, and therefore, an exact specification of *Te* is not required. This method is implemented in subroutine **lamcf**.

Turbulent flow

For turbulent flow the so-called van Driest II Method is employed. This method was selected based on the recommendation of E.J. Hopkins and M. Inouye, contained in “An Evaluation of Theories for Predicting Turbulent Skin Friction and Heat Transfer on Flat Plates at Supersonic and Hypersonic Mach Numbers,” *AIAA J.*, Vol. 9, No. 6, June 1971, pp. 993-1003. The particular algorithm is taken from NASA TN D-6945, “Charts for Predicting Turbulent Skin Friction From the Van Driest Method (II),” also by E.J. Hopkins, and dated October 1972.

Again, assumptions are made for the fluid properties: turbulent flow recovery factor, *r* = .88, specific heat ratio, γ = 1.4, and edge temperature, *Te* = 222 (°K). Then, for a given edge Mach number, *Me*, and ratio of wall temperature to adiabatic wall temperature T_W/T_{AW} the calculation is started by computing the following constants:

$$m = \frac{\gamma - 1}{2} M_e^2 \tag{8}$$

$$F = \frac{T_w}{T_e} = \frac{T_w}{T_{AW}} \cdot \frac{T_{AW}}{T_e} \tag{9}$$

where
$$\frac{T_{AW}}{T_e} = 1 + rm$$

$$T_w = F \cdot T_e \tag{10}$$

$$A = \left(\frac{rm}{F}\right)^{1/2} \tag{11}$$

$$B = \frac{1 + rm - F}{F} \tag{12}$$

$$\alpha = \frac{2A^2 - B}{\left(4A^2 + B^2\right)^{1/2}} \tag{13}$$

$$\beta = \frac{B}{\left(4A^2 + B^2\right)^{1/2}} \tag{14}$$

(15)

$$F_c = \frac{rm}{\left(\sin^{-1}\alpha + \sin^{-1}\beta\right)^2} \qquad M_e > 0.1$$

$$= \left(\frac{1 + \sqrt{F}}{2}\right)^2 \qquad M_e \le 0.1 \tag{16}$$

$$\left(1 + \frac{122}{} \times 10^{-5/T_w}\right)$$

(17)

and

(18)

which is the Keyes viscosity law.

Finally,

$$F_x = \frac{F_\theta}{F_c} \quad (20)$$

The analysis proceeds using barred quantities to denote "incompressible" variables, which are intermediate variables not used except to obtain the final results. Given the Reynolds number, Re_x, an iteration is used to obtain the final results. Proceed as follows, finding

$$\overline{\mathrm{Re}}_x = F_x \,\mathrm{Re}_x \quad (21)$$

now solve

$$\frac{.242}{\sqrt{\overline{C}_F}} = \log\left(\overline{\mathrm{Re}}_x \,\overline{C}_F\right) \quad (22)$$

for C_F

Use as an initial guess $\overline{C}_F^0 = \dfrac{.074}{\overline{\mathrm{Re}}_x^{.20}}$.

(23)

Then, Newton's method is applied to the problem:

$$f\left(\overline{C}_F\right) = 0 \Rightarrow \overline{C}_F^{i+1} = \overline{C}_F^i - \frac{f}{f'} \quad (24)$$

which becomes for this equation:

$$\overline{C}_F^{i+1} = \overline{C}_F^i \left[1 + \frac{\left\{ .242 - \sqrt{\overline{C}_F^i} \log\left(\mathrm{Re}_x \,\overline{C}_F^i\right)\right\}}{\left\{ .121 + \sqrt{\overline{C}_F^i} / \ln 10 \right\}} \right] \quad (25)$$

Once this iteration is completed, and C_F is known,

$$C_F = \frac{\overline{C}_F}{F_c} \tag{26}$$

Note that this value applies to one side of a plate only, so it must be doubled if the friction on both sides is desired to account for the proper reference areas. Here again, the results are not sensitive to the value of edge temperature for low Mach numbers, and the default value should be adequate for most cases. This formula is implemented in routine **turbcf**.

Composite formula

When the flow is laminar and then transitions to turbulent, an estimate of the skin friction is available from a composite of the laminar and turbulent skin friction formulas using Schlicting's formula (see T. Cebeci and P. Bradshaw, *Momentum Transfer in Boundary Layers*, McGraw- Hill, New York, 1977, pp. 187). Given the transition position, x_c/L and Re_L, compute

$$\mathrm{Re}_c = \left(\frac{x_c}{L}\right)\mathrm{Re}_L \tag{27}$$

and compute the laminar skin friction based on Re_C and the turbulent skin friction twice, based on both Reynolds numbers and then find the value that includes both laminar and turbulent flow from:

$$C_F = C_{F_{TURB}}(\mathrm{Re}_L) - \left(\frac{x_c}{L}\right)\left[C_{F_{TURB}}(\mathrm{Re}_c) - C_{F_{LAM}}(\mathrm{Re}_c)\right] \tag{28}$$

Several formulas are available, are all roughly equivalent, and have been evaluated extensively for incompressible flow. They are only approximate for compressible flow.

Form factors

To include the effects of thickness, it has been found that the skin friction formulas should be adjusted through the use of form factors. Two different factors are used in this code. For wing-like shapes,

$$FF = 1.0 + 1.8\left(\frac{t}{c}\right) + 50\left(\frac{t}{c}\right)^4 \tag{29}$$

where *t/c* is the thickness ratio of particular component. For bodies,

$$FF = 1.0 + 1.5\left(\frac{d}{l}\right)^{1.5} + 50\left(\frac{d}{l}\right)^{3} \tag{30}$$

where *d/l* is the ratio of diameter to length. This is the reciprocal of the fineness ratio.

Program Operation:

Running the program, you will be prompted for the name of an input data set, the maximum length is 15 characters. The output is sent to the screen, but can be sent to a file by changing the value of IWRIT to something other than 6 in the main program.

INPUT

Card	**Field**	**Columns**	**Variable**	**Description**
1	1	1-60		Title Card
2	1	1-10	SREF	Full Scale reference Area
	2	11-20	SCALE	1./SCALE, i.e. 1/10 scale is input as 10.
	3	21-30	FNCOMP	number of component cards to be read in (15 max).
	4	31-41	FINMD	input mode: = 0.0, input Mach and altitude = 1.0, input Mach and Reynolds No. per unit length
3	1	1-16	COMP(i)	Component Name
	2	21-30	SWET(I)	Wetted Area (*i.e.*, top and bottom sides of the wing,and both left and right sides, the *total* area that isexposed to the air)
	3	31-40	REFL	Reference Length
	4	41-50	TC(I)	*t/c* for planar surf. or *d/l* (1/F) for body of evolution
	5	51-60	FICODE	Component type clue = 0.: Planar surface = 1.: Body of revolution
	6	61-70	FTRANS	Transition location = 0. : means boundary layer is all turbulent = 1. : " " " " " laminar. values between 0 and 1 approximate the value of the friction of the laminar/turbulent boundary layer at the specified length fraction of the component.

Note: card 3 is repeated NCOMP times.

Card	**Field**	**Columns**	**Variable**	**Description**

4	1	1-10	XME	Mach number
	2	11-20	XINPUT	if FINMD =0.0, this is the Altitude (in 1000 feet) if FINMD =1.0, this is the Reynolds no. per unit length in millions

Note: Card 4 is repeated for each value of Mach and altitude desired. The program stops when either the end of the data is reached or a Mach number of zero is read.

OUTPUT:

The input is echoed to allow for easy check of data and to keep all information together. Then the drag calaculation for each *M,h* or *M,Re/L* is made. First, the reference areas, lengths, thicknesses, form factors and the transition position are output. These values are fixed for each combination of Mach and Reynolds number. Next, for each case the Reynolds number of each component and the basic skin friction are found. Then the skin friction times the wetted area and the skin friction times the wetted area and form factor are found. Finally, the latter is divided by the reference area and the contribution to the total drag in terms of a drag coefficient for the particular component, CDCOMP, is then found. These columns are summed, and the bottom value under the CDCOMP column is the total skin friction and form drag coefficient. After all the conditions are computed, a summary of results is presented as a table at the end of the output.

Conclusions:

The use of PRE-CFD Computational Programs in aircraft preliminary design reduces the costs and the time necessary to design an airplane or a glider without needing a big investment in technology. With today's computers, witch are rather cheap, you can use this methods good results, the only condition is the experience and knowledge of the engineers.

References:

1. *W. H. Mason, mason@aoe.vt.edu*
2. *Rubbert, P. E. "Theoretical Characteristics of Arbitrary Wings by a Non-Planar Vortex Latice Method" 1964 The Boeing Co., Seattle, Wash.*
3. *Dulmovist, J., "A Lifting Surface Method for Calculating Load Distribution and the Aerodynamic Influence Coefficient Matrix for Wing in Subsonic Flow" 1964, Grumman Aircraft Engineering Corp., Bethpage , N.Y.*
4. *Hedman, S. G., "Vortex Lattice Method for Calculation of Quasi Steady State Loadings on Thin Elastic Wings," Oct. 1965 Aeronautical Research Institute of Sweden, Sweden*

5. *Belotserkovskii, S. M., "The Theory of Thin Wings in Subsonic Flow: 1967, N.Y.*
6. *Sloof, J.W., ed., "Technical Status Review on Drag Prediction and Analysis from Computational Fluid Dynamics: State of the Art, May 1988.*
7. *Rooney, E.C., "Thrust-Drag Accounting Methodology," in Thrust and Drag: Its Predictionand Verification, Covert, E.E., ed., AIAA, New York, 1985.*
8. *Liepman, H.W., and Roshko, A., Elements of Gasdynamics, John Wiley, New York, 1957,pp. 235-239.*