Program FRICTION

FRICTION provides an estimate of laminar and turbulent skin friction and form drag suitable for use in aircraft preliminary design. The program 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. It uses standard flat plate skin friction formulas and form factors.

The method uses a build-up approach, where the parasite drag for each component is found and then summed to find the total parasite drag. The output provides the contribution for each component. The basic formula is

$$C_{D_0} = \sum_{j=1}^{N} \frac{FF_j C_{F_j} S_{wet_j}}{S_{ref}}$$

where N is the number of components used to model the configuration. The form factor, FF, depends on whether the component is modeled as a planar surface or a body of revolution. The formulas for the form factor are given below. The skin friction coefficient, C_F, can be for either laminar or turbulent flow and are also described below.

At component junctures, an interference drag can be added, and beyond drag rise the wave drag must be added. See the Gur, Mason, and Schetz, "Full Configuration Drag Estimation," *Journal of Aircraft*, July-Aug. 2010, pp. 1356-1367, for more details.

The compressibility effects on skin friction are 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). As noted above, 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.

Laminar flow

The Blasius formula for skin friction is used, adjusted for compressibility using the Eckert Reference Temperature Method. 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, $\gamma = 1.4$, and edge temperature, $T_e = 390$ (°R). Then, for a given edge Mach number, M_e, and ratio of wall temperature to adiabatic wall temperature T_W/T_{AW}; compute:

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

Remember that

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

and then compute the reference temperature:

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

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

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

where $K = 200$°R for air.

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

$$C_f = \frac{.664\sqrt{C^*}}{\sqrt{\text{Re}_x}}$$

and

$$C_F = 2C_f$$

which comes from

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

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 coefficient, C_D, is twice C_F because the reference area is based on one side only, i.e., $S_{ref} \approx 1/2\ S_{wet}$.

* These values can be changed easily in the source code.

Note that the results are not sensitive to the value of edge temperature for low Mach numbers, and therefore, an exact specification of T_e 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, T_e = 222 (°K). Then, for a given edge Mach number, M_e, and ratio of wall temperature to adiabatic wall temperature T_W/T_{AW} the calculation is started by computing the following constants:

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

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

where

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

$$T_w = F \cdot T_e$$

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

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

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

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

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

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

and

$$F_\theta = \frac{\mu_e}{\mu_w} = \sqrt{\frac{1}{F}}\left(\frac{1+\frac{122}{T_w}\times 10^{-5/T_w}}{1+\frac{122}{T_e}\times 10^{-5/T_e}}\right)$$

which is the Keyes viscosity law.

Finally,

$$F_x = \frac{F_\theta}{F_c}$$

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

$$\overline{\mathrm{Re}}_x = F_x \mathrm{Re}_x$$

solve the Kármán-Schoenherr turbulent skin friction formula

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

for $\bar{C}_F$. Use as an initial guess

$$\bar{C}_F^0 = \frac{.074}{\overline{\mathrm{Re}}_x^{.20}} .$$

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

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

which becomes for this equation:

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

Once this iteration is completed, and $\bar{C}_F$ is known,

$$C_F = \frac{\bar{C}_F}{F_c}$$

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 Schlichting'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

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

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:

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

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,

$$FF = 1.0 + 2.7\left(\frac{t}{c}\right) + 100\left(\frac{t}{c}\right)^4$$

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

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

where d/l is the ratio of diameter to length. This is the reciprocal of the fineness ratio. To model a nacelle remove the inlet area.

* The factor is from Torenbeek, *Synthesis of Subsonic Airplane Design*, Delft University Press, 1982, based on a comparison of FRICTION results with the parasite drag of an NACA 0012 airfoil.

Program Operation:

Running the program, you will be prompted for the name of an input data set. The maximum name 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. The sample data case on the disk is F15frict.inp. Note that the units are assumed to be in the English system.

Notes about units in FRICTION (by Prof Todd Lowe when he was our assistant)

FRICTION exists in two forms (FORTRAN executable and MATLAB script) with two methods for the trial runs (Altitude and Reynolds number per length). Proper units must be used to obtain the correct drag coefficient. The units that may be used differ depending on the trial run method and whether the FORTRAN or MATLAB version is used.

FORTRAN executable:

- If inputting the altitude, all lengths must be in feet, and all areas must be in ft^2. The FORTRAN program assumes that the altitude is entered in thousands of feet.
- If using Reynolds number per length, any consistent set of units may be used. However, the Reynolds number per unit length must be entered as the Reynolds number divided by the characteristic length in the same units. For example, if the configuration dimensions are entered in mm and mm^2, the Reynolds number per unit length must be the Reynolds number divided by the configuration characteristic length entered in mm.

MATLAB:

- For altitude input, all configuration data must be entered in either ft/ft^2 or m/m^2. After choosing the altitude method for trial runs, a prompt will appear asking the user to choose metric (enter 0) or English (enter 1) units. These units must be consistent with the configuration data input If metric units are chosen, the altitude must be entered in km. For English units, the altitude must be entered in thousands of feet.
- For Reynolds number per unit length, the MATLAB script behaves exactly like the FORTRAN executable in this case. Any consistent set of units may be used. The Reynolds number per unit length is the Reynolds number divided by the characteristic length in the units used in the configuration data.

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

Card	Field	Columns	Variable	Description
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 is exposed to the air)
	3	31-40	REFL	Reference Length, i.e. the average chord for a wing.
	4	41-50	TC(I)	*t/c* for planar surf. or *d/l* (1/*F*) for body of revolution
	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 calculation 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.

Sample input for program FRICTION:

```
F - 15  AIRCRAFT
608.      1.         7.        0.0
FUSELAGE             550.00    54.65      .05500    1.0       0.0
CANOPY               75.00     15.0       .12000    1.0       0.0
NACELLE              600.00    35.0       .04000    1.0       0.0
GLV/SPONSON          305.00    35.5       .117      1.0       0.0
OUTB'D WING          698.00    12.7       .05000    0.0       0.0
HORIZ. TAIL          222.00    8.3        .05000    0.0       0.0
TWIN   V. T.         250.00    6.7        .0450     0.0       0.0
     0.200    35.000
     1.200    35.000
     2.000    35.000
     0.000     0.000
```

Sample output from program FRICTION:

```
Enter name of data set:
F15frict.inp

FRICTION - Skin Friction and Form Drag Program
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     Virginia Tech, Blacksburg, VA 24061 email:whmason@vt.edu
     version:   Jan. 28, 2006

     CASE TITLE:     F - 15  AIRCRAFT

     SREF =   608.00000  MODEL SCALE =  1.000  NO. OF COMPONENTS = 7
     input mode =  0  (mode=0: input M,h;  mode=1: input M, Re/L)

    COMPONENT TITLE    SWET (FT2)  REFL(FT)   TC  ICODE FRM FCTR FTRANS
    FUSELAGE            550.0000   54.650   0.055   1   1.0205   0.0000
    CANOPY               75.0000   15.000   0.120   1   1.0744   0.0000
    NACELLE             600.0000   35.000   0.040   1   1.0124   0.0000
    GLV/SPONSON         305.0000   35.500   0.117   1   1.0712   0.0000
    OUTB'D WING         698.0000   12.700   0.050   0   1.1356   0.0000
    HORIZ. TAIL         222.0000    8.300   0.050   0   1.1356   0.0000
    TWIN   V. T.        250.0000    6.700   0.045   0   1.1219   0.0000

      TOTAL SWET =    2700.0000

     REYNOLDS NO./FT =0.480E+06   Altitude =  35000.00   XME =  0.200

      COMPONENT        RN         CF      CF*SWET   CF*SWET*FF   CDCOMP
    FUSELAGE        0.262E+08  0.00251  1.38212     1.41047   0.00232
    CANOPY          0.720E+07  0.00309  0.23164     0.24889   0.00041
    NACELLE         0.168E+08  0.00269  1.61561     1.63573   0.00269
    GLV/SPONSON     0.170E+08  0.00269  0.81944     0.87782   0.00144
    OUTB'D WING     0.609E+07  0.00318  2.21681     2.51746   0.00414
    HORIZ. TAIL     0.398E+07  0.00342  0.75829     0.86114   0.00142
    TWIN   V. T.    0.321E+07  0.00355  0.88656     0.99464   0.00164
                                  SUM = 7.91048     8.54615   0.01406

    FRICTION DRAG: CDF = 0.01301          FORM DRAG: CDFORM = 0.00105

     REYNOLDS NO./FT =0.288E+07   Altitude =  35000.00   XME =  1.200
```

COMPONENT	RN	CF	CF*SWET	CF*SWET*FF	CDCOMP
FUSELAGE	0.157E+09	0.00175	0.96201	0.98175	0.00161
CANOPY	0.432E+08	0.00211	0.15826	0.17004	0.00028
NACELLE	0.101E+09	0.00186	1.11769	1.13160	0.00186
GLV/SPONSON	0.102E+09	0.00186	0.56700	0.60740	0.00100
OUTB'D WING	0.366E+08	0.00216	1.51055	1.71542	0.00282
HORIZ. TAIL	0.239E+08	0.00231	0.51314	0.58274	0.00096
TWIN V. T.	0.193E+08	0.00239	0.59777	0.67064	0.00110
		SUM =	5.42643	5.85959	0.00964

FRICTION DRAG: CDF = 0.00893   FORM DRAG: CDFORM = 0.00071

REYNOLDS NO./FT =0.480E+07   Altitude = 35000.00   XME = 2.000

COMPONENT	RN	CF	CF*SWET	CF*SWET*FF	CDCOMP
FUSELAGE	0.262E+09	0.00140	0.76912	0.78490	0.00129
CANOPY	0.720E+08	0.00169	0.12643	0.13585	0.00022
NACELLE	0.168E+09	0.00149	0.89337	0.90449	0.00149
GLV/SPONSON	0.170E+09	0.00149	0.45321	0.48550	0.00080
OUTB'D WING	0.609E+08	0.00173	1.20667	1.37032	0.00225
HORIZ. TAIL	0.398E+08	0.00185	0.40980	0.46538	0.00077
TWIN V. T.	0.321E+08	0.00191	0.47731	0.53550	0.00088
		SUM =	4.33591	4.68193	0.00770

FRICTION DRAG: CDF = 0.00713   FORM DRAG: CDFORM = 0.00057

SUMMARY

J	XME	Altitude	RE/FT	CDF	CDFORM	CDF+CDFORM
1	0.200	0.350E+05	0.480E+06	0.01301	0.00105	0.01406
2	1.200	0.350E+05	0.288E+07	0.00893	0.00071	0.00964
3	2.000	0.350E+05	0.480E+07	0.00713	0.00057	0.00770

END OF CASE

Press RETURN to quit the program.