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Circulation Control Propellers for General Aviation, Including a BASIC Computer Program

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Circulation Control Propellers for General Aviation, Including a BASIC Computer Program

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SUMMARY

A study has been made to determine the feasibility of replacing variable-pitch propeller mechanisms with circulation-control propellers on general aviation airplanes. The study used a specially-developed computer program written in BASIC and placed emphasis on comparing the aerodynamic performance of circulation-control propellers with conventional propellers.

The aerodynamic performance of circulation-control propellers is compared with the aerodynamic performance of both variable-pitch and fixed-pitch propellers against the requirements of a 1600 Kg (3600 lbs) single-engine aircraft. The application of a circulation-control propeller with a supercritical airfoil was found feasible under representative design conditions. All propellers had approximately the

same performance at high speed cruise (design condition). At low speed, the performance of the circulation-control propeller was higher than that for a fixed pitch propeller but lower than that for a variable pitch propeller.

It appears feasible to replace variable-pitch propellers with circulation-control propellers on single engine aircraft or on multi-engine aircraft which have their propellers on a common axis (Tractor-Pusher). The economics of these replacements require a study for each specific aircraft application.

1.0 INTRODUCTION

The feasibility of using circulation-control (C/C) airfoils (blunt-based airfoils utilizing the Coanda effect) for general aviation airplane propellers is being appraised. Fuel consumption and/or total life cost advantages might occur through replacement of variable-pitch propellers with fixed-pitch C/C propellers. The required changes in propeller aerodynamic characteristics throughout the speed range of the airplane could be obtained through changes in the mass-flow rate of the blown jet. A simplified analytical approach with hand calculations provided a first-order estimate of propeller aerodynamic performance with elliptical and supercritical (S/C) circulation-control (C/C) airfoils (ref. 1). These results indicated that a S/C-C/C airfoil for which data became available appeared aerodynamically suitable for use in a propeller. This study was undertaken to more accurately define the characteristics of C/C propellers by a more refined analytical approach which used a specially-developed computer program written in BASIC.

This program is presented in the Appendix. A brief assessment was made of the required air compressor and the installation considerations.

As part of the assessment of a S/C - C/C propeller, performance comparisons were made for a selected airplane with S/C variable-pitch and S/C fixed-pitch propellers. Although none of the propellers were optimized for maximum performance, the basic relative characteristics should be valid. The propellers were designed for a high-speed steady-state flight condition of a typical single-engine airplane. Further comparisons were made at a low-speed flight condition for steady-state performance and for rate-of-climb or acceleration performance.

This study was initiated by Mr. H. Douglas Garner of the Langley Research Center, who proposed the concept as a result of his work with fluidic devices. The study received support from Mr. Emanuel Boxer, Distinguished Research Associate LaRC and the analytic software was adapted from a procedure developed by Mr. William H. Phillips, Distinguished Research Associate LaRC, Mr. Wayne H. Bryant of The LaRC programmed the technique in BASIC, primarily for this study, however the program can support other general design evaluations. The program prepared by Mr. Bryant appears as the Appendix.

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2.0 SYMBOLS AND COEFFICIENTS

a	Induced axial velocity ratio
B	Number of propeller blades
c	Propeller chord, m (ft)
c_d	Airfoil wake drag coefficient
c_ℓ	Airfoil lift coefficient
c_μ	Blowing Momentum coefficient, $\dfrac{\dot{m}\,V_j}{1/2\,\rho_\infty V_j^{\,2} c}$
D	Propeller diameter, m (ft)
HP_{aero}	Propeller aerodynamic horsepower, 746 watts $\left[\dfrac{550\text{ ft-lbs}}{\text{sec}}\right]$
HP_c	Compressor horsepower, 746 watts $\left[\dfrac{550\text{ ft-lbs}}{\text{sec}}\right]$
HP_{pc}	Propeller-compression horsepower, 746 watts $\left[\dfrac{550\text{ ft-lbs}}{\text{sec}}\right]$
HP_u	Useful horsepower, $\dfrac{T\,V_\infty}{550}$, 746 watts $\left[\dfrac{550\text{ ft-lbs}}{\text{sec}}\right]$
HP_{total}	Required horsepower, 746 watts $\left[\dfrac{550\text{ ft-lbs}}{\text{sec}}\right]$
HP_{avail}	Available horsepower, 746 watts $\left[\dfrac{550\text{ ft-lbs}}{\text{sec}}\right]$
h	Altitude, km (ft)
L/D	Ratio of Lift Force to Drag Force for an airfoil
$\dot{m}$	Blowing mass flow per unit span, kg/sec/m (slugs/sec/ft)
n	Propeller rotational speed, rev/sec
P	Static pressure N/m^2 (lb/ft^2)
P_t	Total pressure, N/m^2 (lb/ft^2)
P_∞	Ambient pressure, N/m^2 (lb/ft^2)

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Q	Propeller torque, N-m (ft-lb)
R	Universal gas constant, m^2/sec^2 °K (ft^2/sec^2 °R). Also: Propeller radius at the tip of the blade, m (ft)
(RN)	Reynolds number based on chord, $\frac{c_i V_i \rho_\infty}{\mu_\infty}$
r	Propeller radius at a radial station, m (ft)
T	Static temperature, °K (°R) Also: Thrust, N (lb)
V	Velocity, m/sec (ft/sec)
V	Freestream velocity, m/sec (ft/sec)
W	Airplane gross weight, kg (lb)
α	Angle of attack, deg (See Diagram below)
β	Propeller blade angle, deg (See Diagram below)
η	Propeller Efficiency
λ	Advance Ratio, $\frac{V_\infty}{2\pi Rn}$ (See Diagram below)
μ_∞	Ambient viscosity, N sec/m^2 (lb sec/ft^2)
ρ	Density, kg/m^3 ($slugs/ft^3$)
ρ_∞	Ambient density, kg/m^3 ($slugs/ft^3$)
ϕ	Angle of advance, $\tan^{-1}\left[\frac{V_\infty}{2\pi n r}\right]$, deg (See Diagram below)

Subcripts

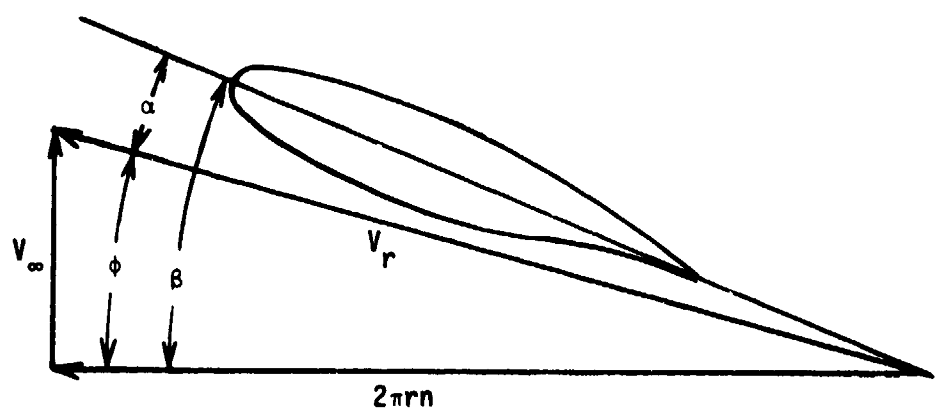
h Blade hub station

i Blade element radial station, (0 to 20)

(NOTE: Units for T and Q with subscript i are per unit span)

j Jet

Propeller Blade Definition of Terms



3.0 RESULTS AND DISCUSSION

3.1 Choices of Analysis Conditions

3.1.1 Choice of Airplane

The design and comparisons of propeller performance were based upon applications to a specific model general aviation airplane. A survey of general aviation airplanes (ref 2) showed the following ranges for maximum speeds.

(a) Single Engine, Fixed Pitch 59.2-77.1 m/sec (194-253 ft/sec)

(b) Single Engine, Variable Pitch 66.8-97.6 m/sec (219-320 ft/sec)

(c) Twin Engine, Variable Pitch 87.5-123.5 m/sec (287-405 ft/sec)

One of the well established models of single-engine general aviation airplanes showed a maximum speed of 82.3 m/sec (270 ft/sec) which is about the maximum for which a fixed pitch propeller might be used. This airplane was selected because its performance overlapped the range for both fixed and variable pitch propellers. The aircraft selected had a maximum weight of 1600 kg (3600 lbs) and used a 3 bladed variable pitch propeller driven by an unsupercharged engine. Alternate models of the airplane are available with supercharged engines. Reference 1 presents some of the specific characteristics of this airplane.

3.1.2 Choice of Propeller Airfoil

A result from the previous study (ref 1) indicated superior performance for a propeller which utilized C/C-supercritical airfoils as compared with the previously analyzed C/C -elliptical airfoils. Available data for S/C - C/C airfoils (ref 3) were therefore used for this study. In the previous analyses, preliminary data were provided by the David Taylor Naval Ship Research and Development Center with the drag characteristics obtained on a 17 percent chord thick S/C airfoil reduced to values equivalent to a 15 percent chord thick S/C airf... direct comparison with the previously tested 15 percent chord t... elliptical airfoils. For this study, no thickness correction was ... The probable use of thinner airfoils in an actual propeller application is expected to have an insignificant effect on the propeller.

3.1.3 Choice of Flight Conditions

A high-speed cruise flight condition of 82.3 m/sec (270 ft/sec) at 3.05 km (10,000 ft) altitude was selected as the design point for the propellers. Although the performance of the airplane should be computed at many flight conditions, a selected low-speed flight condition of 38.1 m/sec (125 ft/sec) at sea level should provide a meaningful indication of off-design propeller performance. Relative propeller efficiency in steady-state low-speed cruise and relative thrust margin available for climb or acceleration with the given engine provides a useful comparison of the propellers. A practical design must evaluate the entire range of flight conditions including take-off performance, obstacle clearance, maximum speed etc. This limited comparison investigated only two flight conditions.

3.1.4 System Description

The system analyzed, Figure 1, represents the simplest concept that could be applied to the circulation-control propeller. Air inducted from an inlet at P_∞ is fed to an engine-driven compressor. This air is furnished to the propeller hub via ducting, valves, and rotary seals. The propeller provides additional compression by centrifugal pumping so that a variable pressure head exists from the hub to the outboard

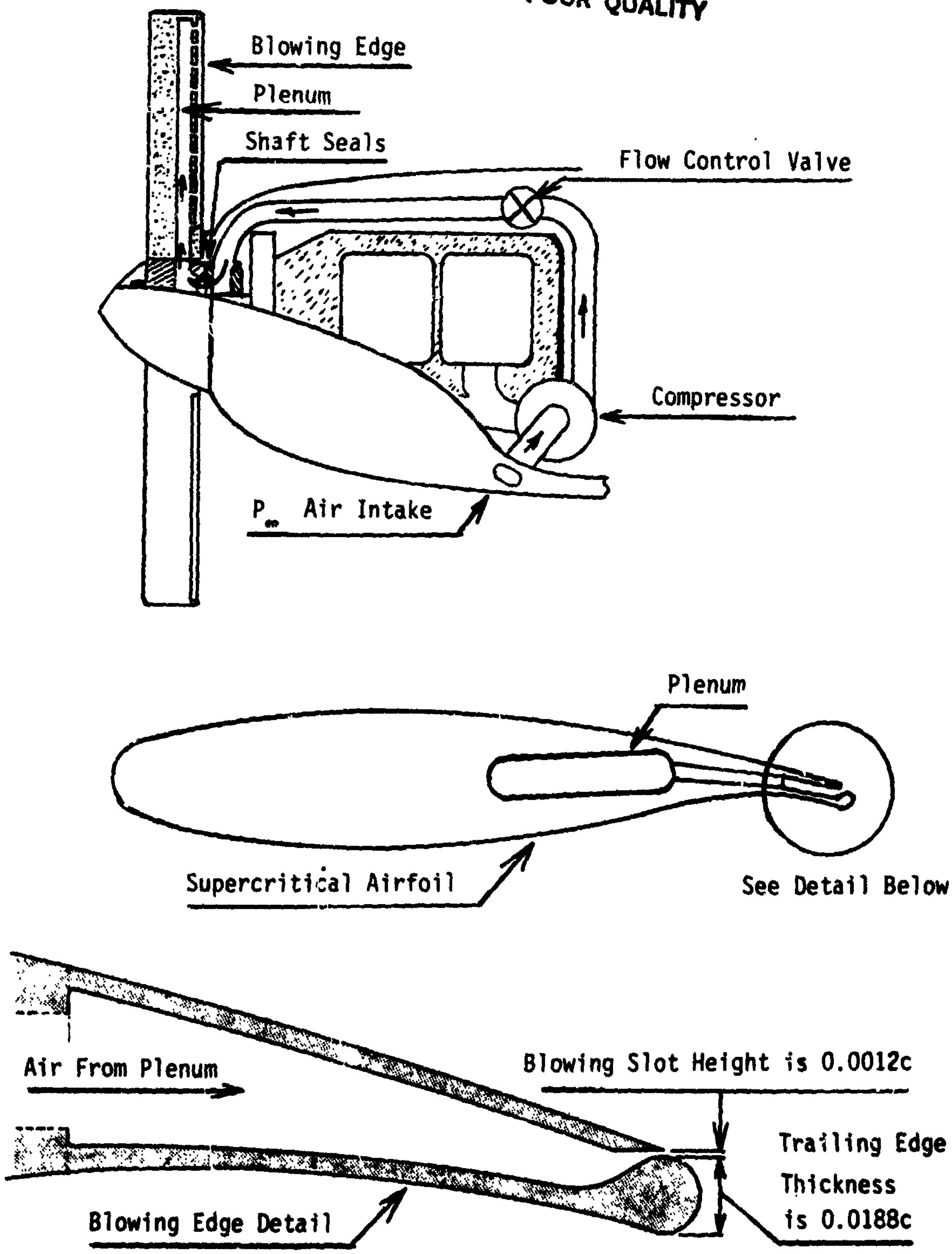


Figure 1, Circulation Control Propeller System end of a single blowing-slot plenum chamber. The exit slot is assumed to be the major flow restriction in the system so that the pressure gradient in the propeller plenum is calculated from the hydrostatic equations for pressure equilibrium. The radial cross-flows which may exist in the exit slot and exhaust have been ignored in this study.

3.2 Derivations

3.2.1 Aerodynamic Relationships

The propeller section aerodynamic characteristics are described by the standard c_ℓ and c_d values as functions of angle of attack α for the non-blown propellers. Circulation control propellers require the additional parameter of momentum coefficient . These relationships are shown graphically in Figure 2 for the supercritical 17 percent thick airfoil, and the same airfoil modified for trailing- edge blowing. The polars shown were linearized over small angle- of- attack ranges (usually 3 degrees) with the numeric results, extrapolated, shown in Tables 1, 2, and 3. The software described in the Appendix linearly interpolates between these tabulated values to obtain specific values of the aerodynamic characteristics.

The momentum coefficient at any section is related to the plenum total pressure as follows:

$$V_{j_i} = V_i \, (26.4) \, (c_{\mu_i})^{1/2} \qquad (1)$$

This relationship is derived from Figure 3 (reproduced from ref 1). Sample points computed from the above equation have been added to the original figure.

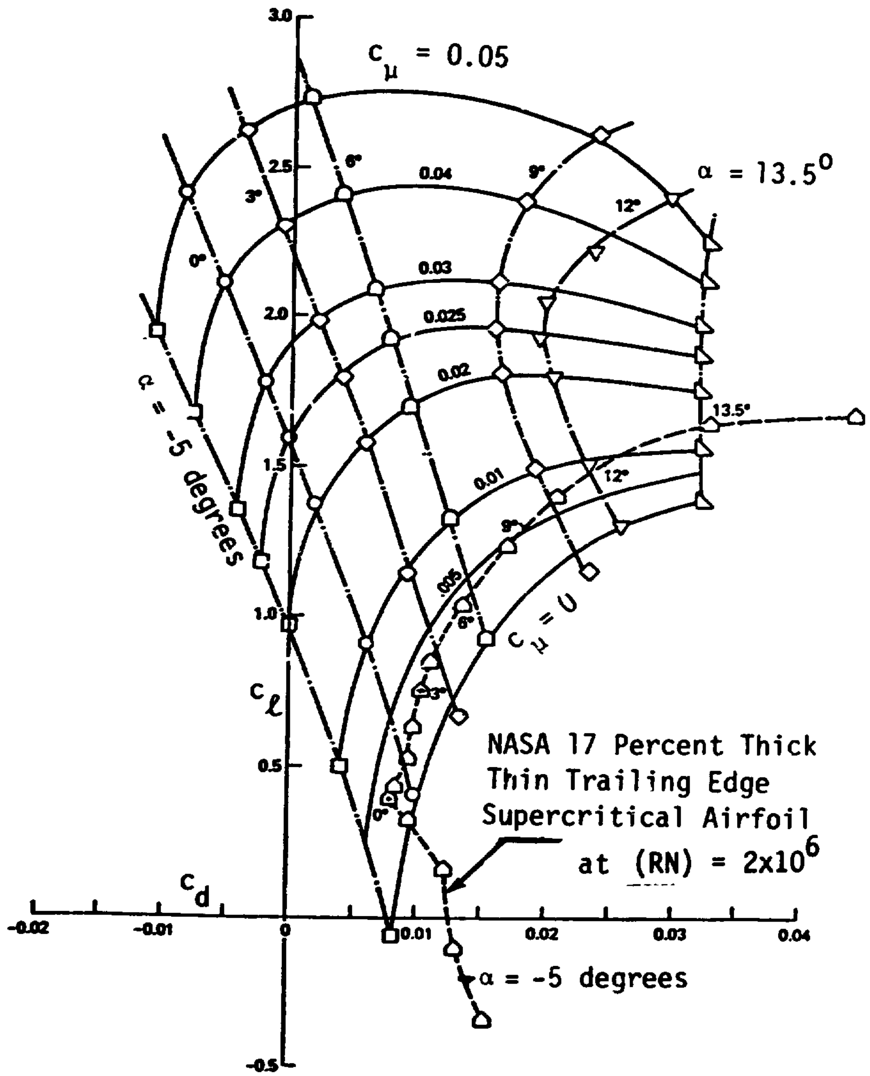


Figure 2, Drag Polars for NASA Supercritical Airfoils (configuration 5 of ref 3)

Table 1, Characteristics of a Supercritical Circulation Control Airfoil (ref 3)

α	$c_\mu = 0$		$c_\mu = 0.01$		$c_\mu = 0.02$	
	c_ℓ	c_d	c_ℓ	c_d	c_ℓ	c_d
-12	-0.68	0.009	-0.06	0.004	0.39	0.000
- 9	-0.42	0.008	+0.18	0.004	0.63	0.000
- 6	-0.15	0.008	0.42	0.004	0.88	0.000
- 3	+0.13	0.0089	0.66	0.0046	1.12	0.004
0	0.38	0.0100	0.90	0.0062	1.36	0.0[illegible]
+ 3	0.66	0.0131	1.14	0.0093	1.57	0.0058
6	0.92	0.0155	1.32	0.0128	1.72	0.0097
9	1.16	0.0224	1.48	0.0193	1.80	0.0166
12	1.33	0.0259	1.55	0.0232	1.78	0.0205
14	1.40	0.0336	1.53	0.0336	1.74	0.0336
>14	0.	Sin α	0.	Sin α	0.	Sin α

Table 2, Interpolation Coefficients for the Characteristics of a Supercritical Circulation Control Airfoil (ref 3)

$$c_\ell \text{ and } c_d = A + Bc_u + (C + Dc_u)\left[\frac{\alpha - \alpha_1}{\alpha_u - \alpha_1}\right]$$

Coefficients to determine c_ℓ

α_1 lower	α_u upper	A	B	C	D
-12	-9	-0.68	53.5	0.26	-1.0
- 9	-6	-0.42	52.5	0.27	-1.0
- 6	-3	-0.15	51.5	0.28	-2.0
- 3	0	+0.13	49.5	0.25	-0.50
0	+3	0.38	49.0	0.28	-3.50
+3	6	0.66	45.5	0.26	-5.50
6	9	0.92	40.0	0.24	-8.00
9	12	1.16	32.0	0.17	-9.50
12	14	1.33	22.5	0.07	-5.50
14	>14	0	0	0	0

Coefficients to determine c_d

α_1 lower	α_u upper	A	B	C	D
-12	-9	0.009	-0.40	-0.001	0.000
-9	-6	0.008	-0.40	0.0000	0.000
-6	-3	0.008	-0.40	0.0009	-0.025
-3	0	0.0089	-0.425	0.0011	+0.020
0	+3	0.0100	-0.405	0.0031	0.040
+3	6	0.0131	-0.365	0.0024	0.075
6	9	0.0155	-0.290	0.0069	0.000
9	12	0.0224	-0.290	0.0035	0.020
12	14	0.0259	-0.270	0.0077	0.270
14	>14	sin α	sin α	sin α	sin α

Table 3 Characteristics of a Supercritical 17 Percent Thick, Thin-Trailing-Edge Airfoil (ref 3)

α	c_ℓ	c_d	c_ℓ/c_d
-3	0.001	0.0123	0.08
0	0.37	0.0081	45.7
+3	0.73	0.010	73.0
6	1.01	0.0127	79.5
9	1.30	0.0181	71.8
12	1.52	0.0242	62.8
14	1.66	0.0365	45.5
17	1.66	Sin α	5.7
>17	0.001	Sin α	-

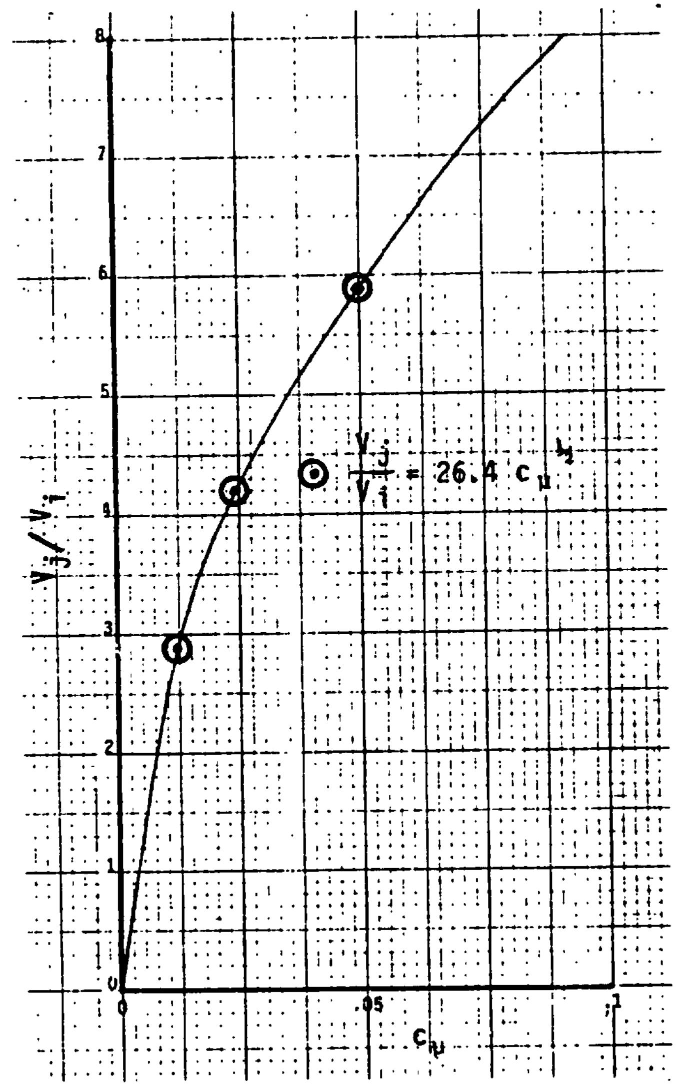


Figure 3, Ratio of Jet Velocity at Ambient Pressure to Reference Velocity with Jet Momentum Coefficient (ref 1)

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The Bernoulli incompressible relationship between velocity and pressure is:

$$P_{t_{j_i}} = 1/2\,\rho_\infty (V_{j_i})^2 + P_\infty \qquad (2)$$

This equation gives the jet velocity when the section plenum total pressure air is expanded to free-stream static pressure.

The plenum pressure at any station is related to the hub pressure as shown below by the isothermal hydrostatic equation which accounts for centrifugal acceleration as:

$$dP_t = \rho\,(2\pi n)^2 r\,dr \qquad (3)$$

$$\frac{d\rho}{dP_t} = \frac{1}{RT} \qquad (4)$$

$$\frac{d\rho}{\rho} = \frac{(2\pi n)^2 r\,dr}{RT} \qquad (5)$$

Integrating from the hub to the radius at station i

$$\frac{P_i}{P_h} = e^{\left[\frac{(2\pi n)^2 r^2}{2RT}\right]} = e^{E_i} \qquad (6)$$

The hub pressure can be adjusted by use of the control valve which operates in series with the compressor.

The local airstream velocity at radius r is the vector sum of the forward and rotational velocities:

$$V_i = \left[V_\infty^{\,2} + (2\pi r_i n)^2\right]^{1/2} \qquad (7)$$

This equation does not take into account the inflow velocities induced by the propeller but the corrections are too small to be of concern.

Combining the above relationships, an expression can be derived between the momentum coefficient and the hub pressure:

$$c_{\mu_i} = \frac{2RT}{(26.4)^2}\left[\frac{P_h e^{E_i}}{P_\infty} - 1\right]\left[\frac{1}{V_\infty^2 + (2\pi r_i n)^2}\right] \qquad (8)$$

The temperature T to be used in this equation is the propeller temperature; however, at the low speed conditions evaluated in this report, the free-stream static temperature can be substituted.

3.2.2 Overall Propeller Characteristics

Propeller thrust and torque are defined by the following relationships:

$$T_i = \frac{dT}{dr} = \frac{1}{2}\rho_\infty V_\infty^2 \left[\frac{1 + a}{\sin\phi}\right]^2 Bc(c_\ell \cos\phi - c_d \sin\phi) \qquad (9)$$

$$Q_i = \frac{dQ}{dr} = \frac{1}{2}r\rho_\infty V_\infty^2 \left[\frac{1 + a}{\sin\phi}\right]^2 Bc(c_\ell \sin\phi + c_d \cos\phi) \qquad (10)$$

These are the conventional propeller section equations and account for the induced flow at each section. To compute the overall thrust and torque, the section contributions are summed using Simpsons rule. The method used for computing the inflow by iteration is described in the Appendix and is adapted from a method developed by Larrabee and French at

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the Massachusetts Institute of Technology.

In addition to the strip integration method described above, use was made of an analytic software program developed by William H. Phillips, (Distinguished Research Associate, LaRC), to secure first appr .imations for efficient propeller chord distributions. These relationships are also based on work by Larrabee (ref 4). In all the computations made, the analytic and strip integrations for the same propeller agreed to within 1 percent.

3.2.3 System Efficiency

The overall efficiency of the propeller system is computed by dividing the useful work done by the sum of the work required to rotate the propeller and the work required to compress the free-stream air to the plenum pressure at each propeller station.

The required mass flow per unit length of propeller is, (ref 1)

$$\dot{m}_i = c_{\mu_i} c_i \left[\frac{\rho_\infty (V_i)^2}{2V_{j_i}} \right] \qquad (11)$$

The horsepower required per foot of propeller radius to pump a mass of air from the hub to a radial station is:

$$HP_{pc_i} = \dot{m}_i \frac{(106.6)\ (32.2)}{(550)} T \left[\left(\frac{P_{t_{j_i}}}{P_{t_{j_h}}} \right)^{0.286} - 1 \right] \qquad (12)$$

For a propeller with B blades, the expression can be written for each radius station r:

$$HP_{pc_i} = 10.92\ \dot{m}_i\ B\ T\left(\left(\frac{P_{t_{j_i}}}{P_{t_{j_h}}}\right)^{0.286} - 1\right) \qquad (13)$$

To find the overall horsepower required, the section horsepower is summed using Simpsons rule. The horsepower for the engine-driven compressor is determined from the requirement that the total mass flow is compressed from the ambient pressure to the pressure at the propeller hub. The total horsepower into the propeller consists of the work for aerodynamic torque plus the work required to centrifugally pump the air, as well as that performed by the compressor to supply hub pressure.

$$HP_{total} = HP_{aero} + HP_{pc} + HP_c$$

$$HP_{total} = \frac{2\pi nQ}{550} + HP_{pc} + HP_c \qquad (14)$$

The useful work done by the propeller is the thrust multiplied by airplane velocity, and in horsepower is:

$$HP_u = \frac{TV_\infty}{550} \qquad (15)$$

The system efficiency is:

$$\eta = \frac{TV_\infty/550}{\frac{2\pi nQ}{550} + HP_{pc} + HP_c} \qquad (16)$$

The above equations, and other ancillary relationships to define atmospheric properties versus altitude, local Reynolds and Mach numbers and other pertinent factors have been mechanized in BASIC and are described in the Appendix. The program is useful for designing any propeller for which the section aerodynamic characteristics can be stated versus angle of attack in a look-up table. In addition, the program is capable of varying parameters such as engine rotational speed or blade helical angle and provides cross-plots for trend analysis. Pertinent results of the computations made for this study are presented below.

3.3 Performance

The design point for all of the propellers was 82.3m/sec (270 ft/sec) at 3.05 km (10,000 ft) altitude and they were then analyzed for low speed flight at sea level. No attempt was made to optimize the propeller diameter or number of blades. A 1.83 m (6 ft) diameter 3 bladed propeller was used for all comparisons. The listing below summarizes the design and off-design flight conditions chosen plus pertinent airplane and engine parameters:

	Design (Cruise)	Off-Design (Sea Level)
Altitude, h	3.05km (10,000 ft)	0
Velocity, V_∞	82.3 m/sec (270 ft/sec)	38.1 m/sec (125 ft/sec)
Thrust required, steady state	1441N (324 lbs)	1544N (347 lbs)
Engine rpm, (full throttle)	2500	2700
Engine HP, (full throttle)	188	285

3.3.1 Airfoil Characteristics

The aerodynamic characteristics measured for S/C-C/C airfoil (configuration 5 of ref 3) are shown in Figure 2 for a range of blowing momentum coefficient and angle-of-attack. The drag coefficients presented are wake drag coefficients that include the momentum of the blown jet. These differ from the coefficients used in the initial study (ref 1), where, for purposes of airfoil comparison, the wake drag coefficients were converted to drag coefficients that included a drag equivalent of the blowing power required. In this study, the power required to blow the air is separately accounted for and charged to the airplane engine. This method takes account of the trigonometric relationships required to compute propeller efficiency.

In the angle-of-attack range of high L/D (about 3^o for the S/C-C/C airfoil), the L/D at no blowing is 53.8 and increases with blowing. The overall efficiency of the airfoil is limited, however, by the energy required to compress the air from ambient pressure to the plenum pressure at the jet. As a typical example of section efficiency, the characteristics of the S/C-C/C section were evaluated at an advance ratio of 0.69 for a fixed 3^o angle of attack with various values of c_μ.

The section efficiency at $c_\mu = 0$ of 0.96 was reduced to 0.95 as the c_μ increased from 0 to 0.02. Larger values of c_μ will further decrease the section efficiency even though the aerodynamic L/D for the section itself is increasing. For applications where the jet velocity is not otherwise limited, it is possible to use momentum coefficients up to about 0.02 without excessive losses in efficiency.

3.3.2 Design Methods and Design Factors Considered

The number of blades and propeller diameter were held constant to study the relative performance of the propellers described below. The diameter was selected to maintain a low tip speed which permitted an additional jet velocity near the tip. In each case, an angle-of-attack distribution was selected and the analytic minimum-loss chord distribution determined. The chord distribution was scaled to achieve the required thrust at the high-speed design point.

Three angle-of-attack distributions were investigated: a nominal 2° and 4°, uniform hub to tip, and a "twisted" distribution of -12° hub to $+5^\circ$ at the tip. The small angles of attack were selected because they were located in the region of maximum section L/D and provided for a large range of operation before stall at low forward speed. The "twisted" distribution was selected to give reasonable performance at the high-speed design point and to minimize stall as much as possible at the off-design point. The summary below outlines the design procedures used to match propeller performance to the airplane thrust requirements.

Propeller Type	Design Point	Off-Design
	3.05 km (10000 ft)	Sea Level Cruise
S/C	Analytic minimum-loss chord distribution	Fixed Pitch - vary engine rpm Variable Pitch- vary hub setting
S/C, C/C, with blowing plenum to 0.7R and no jet velocity restriction	Match c_ℓ at 0.7R to above S/C design. Ratio chords to secure required thrust.	Set $c_\mu = 0$. Vary engine rpm
S/C, C/C with blowing plenum to tip and 0.9 sonic velocity restriction	Analytic minimum loss chord distribution	Set $c_\mu = 0$. Vary engine rpm

Each case in the parametric study (10 total) produced a print out of the propeller characteristics, plus jet characteristics for blown propellers. Table 4 shows a typical printout. In addition, the program generated a number of cross plots. Figure 4 shows examples. The Appendix contains print-outs of propeller characteristics for the various designs studied.

For the off-design condition, the propeller-engine combination was evaluated to determine the excess thrust which could be made available above that required for steady-state flight. The excess thrust, useful for rate of climb or acceleration, was limited by the full-throttle engine horsepower at 2700 rpm or by the maximum thrust capability of the specific propeller at any rpm up to 2700.

3.3.3 Propeller Characteristics

A summary of the operating characteristics of the final C/C and u[illegible] propellers (VP and FP) investigated is presented in Figure 5 and

Table 4, Summary of Calculated Results for a S/C - C/C Propeller*

RESULTS FOR CASE # 4

	PROPELLER CHARACTERISTICS								JET CHARACTERISTICS		
KSI	LIFT COEF	DRAG COEF	L/D RATIO	ALPHA	CHORD/RAD	TWIST	MACH NO.	REYNOLDS	JET VEL.	MOM. COEF	JET PRES.
0.05	-0.03829	0.0058438	-6.55193	-7.8809	0.0083213	73.8220	0.253245	33480.3	528.8270	0.0053905	1701.2000
0.10	0.03814	0.0059304	6.43129	-6.8872	0.0303304	66.9856	0.260972	125756.0	533.9060	0.0051740	1705.9400
0.15	0.0982[illegible]	0.0060540	16.22840	-6.0259	0.0592744	60.6777	0.273365	257435.0	542.2960	0.0048649	1713.8700
0.20	0.14255	0.0063684	22.38430	-5.3354	0.0881325	54.9408	0.289826	405818.0	553.8920	0.0045150	1725.0300
0.25	0.17941	0.0066700	26.89790	-4.7317	0.1122290	49.8795	0.309708	552220.0	568.5610	0.0041661	1739.4900
0.30	0.20940	0.0069389	30.17770	-4.2215	0.1297360	45.4376	0.332396	685131.0	586.1510	0.0038441	1757.3200
0.35	0.24152	0.0071943	33.57160	-3.7117	0.1407890	41.6614	0.357358	799333.0	606.5030	0.0035608	1778.6400
0.40	0.27273	0.0074249	36.73110	-3.2367	0.1464100	38.4189	0.384149	893570.0	629.4600	0.0033191	1803.5500
0.45	0.30582	0.0076760	39.84110	-2.7400	0.1478110	35.6926	0.412414	968495.0	654.8720	0.0031169	1832.2100
0.50	0.34587	0.0079719	43.38600	-2.1569	0.1460620	33.4[illegible]79	0.441870	1025390.0	682.6040	0.0029501	1864.7700
0.55	0.39595	0.0082934	47.74300	-1.4713	0.1419750	31.7[illegible]61	0.472294	1065330.0	712.5380	0.0028137	1901.4400
0.60	0.45548	0.0086408	52.71360	-0.6874	0.1361260	30.4959	0.503511	1088950.0	744.5760	0.0027032	1942.4300
0.65	0.52353	0.0091233	57.38380	0.1707	0.1288710	29.5536	0.535381	1096160.0	778.6390	0.0026147	1987.9900
0.70	0.59973	0.0100916	59.42790	1.0517	0.1203650	28.8519	0.567796	1085980.0	814.6670	0.0025448	2038.3900
0.75	0.68339	0.0111301	61.40000	2.0054	0.1106810	28.4097	0.600666	1056240.0	852.6190	0.0024907	2093.9500
0.80	0.77519	0.0122445	63.30910	3.0450	0.0995943	28.2107	0.633921	1003060.0	892.4740	0.0024502	2155.0200
0.85	0.86452	0.0132035	65.47650	4.1473	0.0867200	28.2031	0.667504	919667.0	934.2250	0.0024215	2221.9900
0.90	0.95528	0.0141670	67.43010	5.2604	0.0711664	28.3182	0.701367	793008.0	977.8840	0.0024031	2295.2900
0.95	1.05017	0.0157221	66.79590	6.3984	0.0505656	28.5604	0.735472	590852.0	1023.4800	0.0023939	2375.4100
1.00	0.40979	0.0083100	49.31320	0.0000	0.0000000	28.9565	0.769786	0.0	0.0000	0.0000000	0.0000

OPERATING CONDITIONS

VEL=270.0 F/S ENG SPD= 41.60 RPS ALT= 10000.00 FEET AIR DEN=0.001756 SL/CUFT TEMP= 483.01 DEG-R AMB PRES=1455.6 PSF

PROPELLER DATA

DIA= 6.0 FT BLDS= 3 TH= 322.69 LBS EFF=0.8799 LAM= 0.344 ROD HP= 180.03 AVL HP= 263.19

COMPRESSOR

MASS FLOW= 0.0024 SL/SEC COMP HP= 0.5727 COMPRESSOR RATIO= 1.1676

* See Appendix For Definition of terms and techniques for calculation

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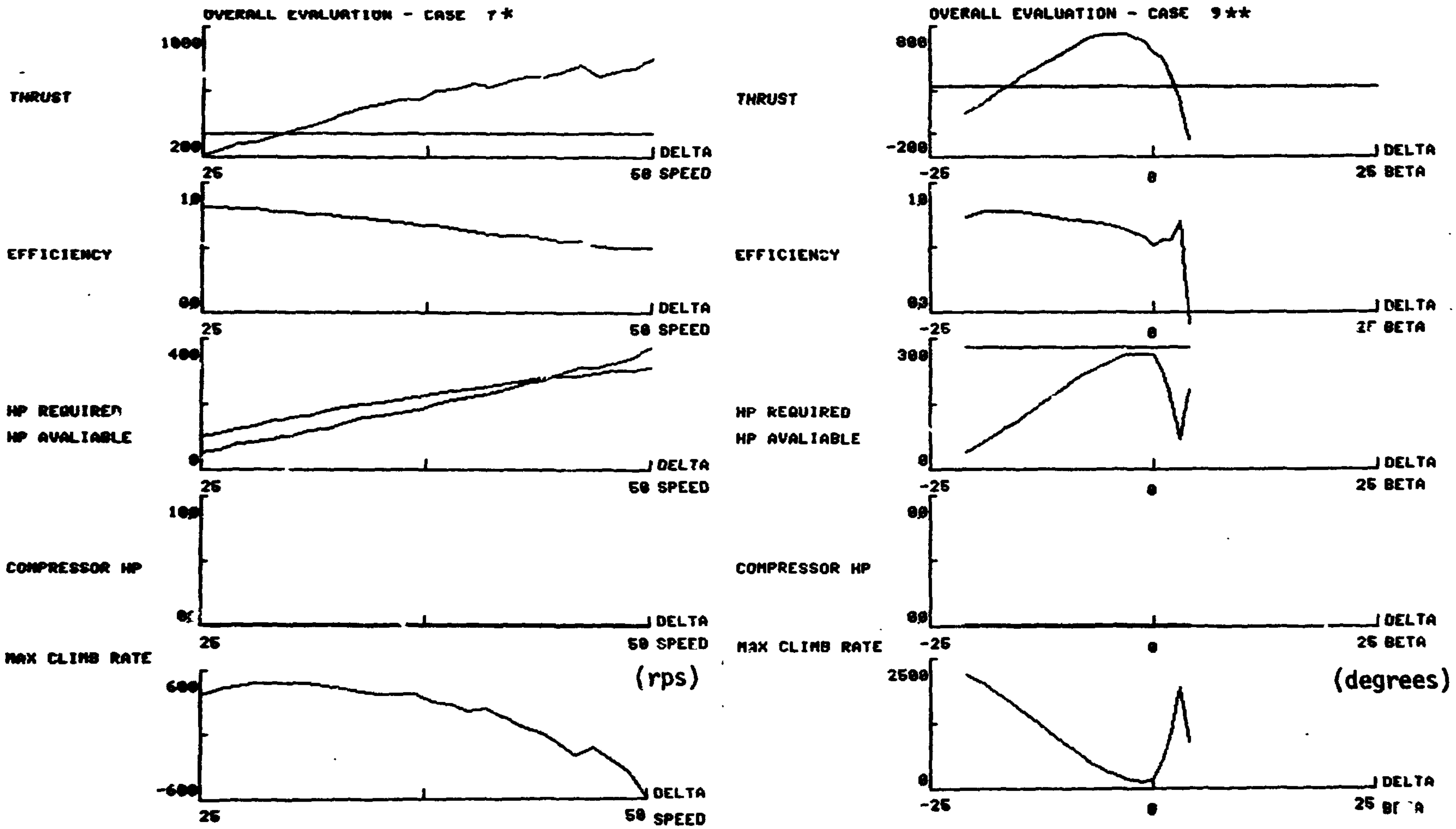

* Evaluation of a Fixed Pitch Propeller at various engine speeds

** Evaluation of a Variable Pitch Propeller at various blade settings

Figure 4. Computer Generated data for Comparison Evaluation of Propellers

the propeller efficiencies in steady-state cruise are presented in Table 5 for both the high-speed and low-speed flight conditions selected.

Table 5. Calculations of Propeller Efficiency

Propeller Type	Design Point 82.3 m/sec at 3.05 km (270 ft/sec at 10,000ft)	Off Design Point 38.1 m/sec at Sea Level (125 ft/sec at Sea Level)
Variable Pitch Narrow Chord	0.897 at 2500rpm	0.784 at 2700rpm
Fixed Pitch Narrow Chord	0.897 at 2500rpm	0.620 at 2100rpm
S/C-C/C Wide Chord with blowing to tip, subsonic jet	0.886 at 2500rpm	0.777 at 1800rpm

For the high-speed cruise design condition (Figure 5a), the chord of each propeller (C/C and unblown) was established as described above (section 3.3.2) to provide the thrust required for cruise at the recommended engine rpm of 2500 for sustained steady-state flight, (indicated as ⊙). A value of $c_\mu = 0.0025$ at 0.7 R was selected for the C/C propeller prior to establishment of the C/C chord to maintain subsonic blowing. The printout as Table 4 shows the variation of c_μ (and jet velocity when expanded to ambient pressure) along the span. The efficiencies at high-speed cruise are nearly the same (about 0.89) for all three propellers (see Table 5). This is not unexpected as all are operating at a selected angle of attack that provides high L/D ratios.

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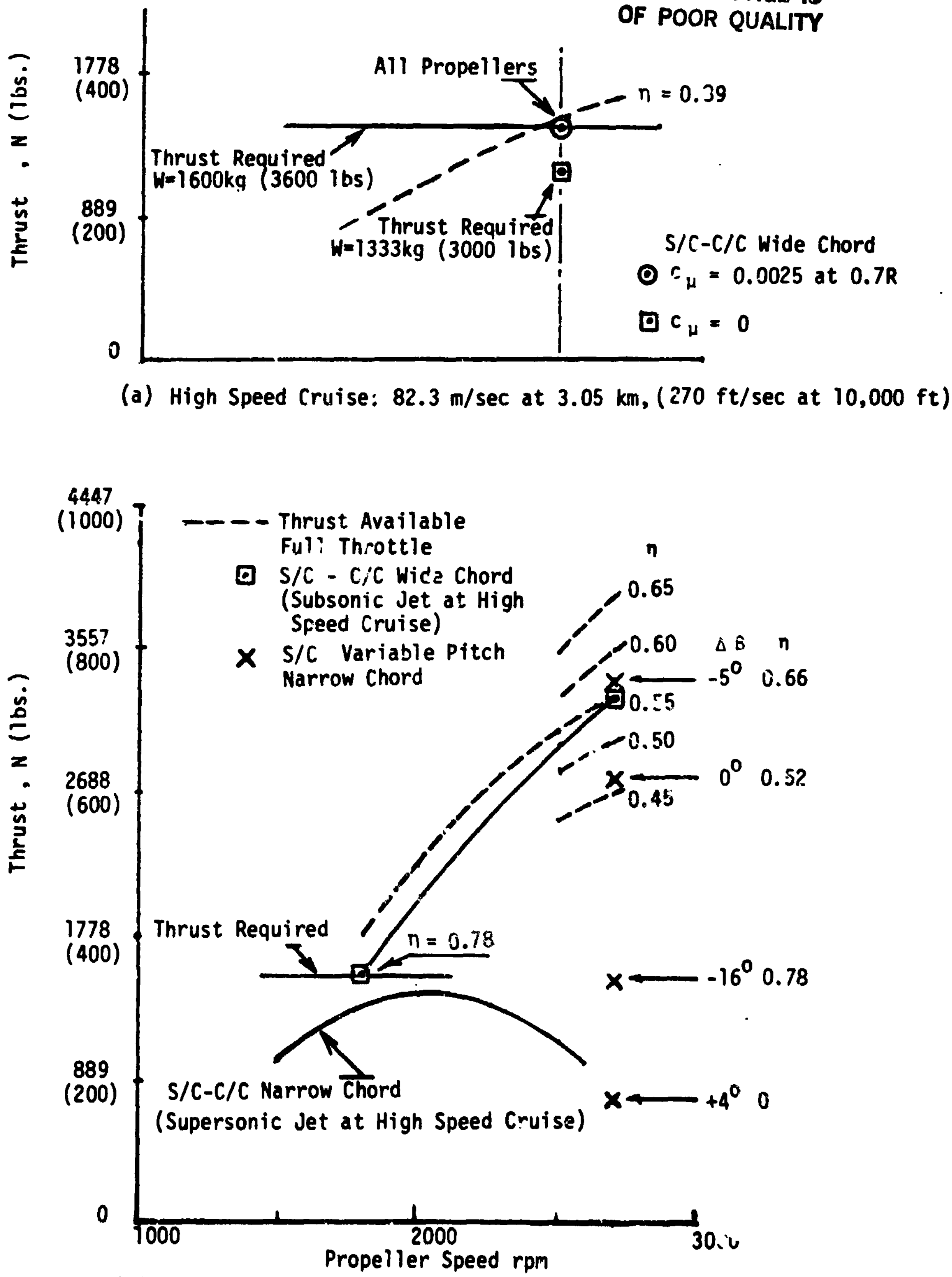

(a) High Speed Cruise: 82.3 m/sec at 3.05 km, (270 ft/sec at 10,000 ft)

(b) Low Speed Cruise: 38.1 m/sec. at Sea level, (125 ft/sec)

Figure 5, Propeller Operating Characteristics

With this propeller efficiency assumed, the thrust available with the engine operating at full throttle was calculated and plotted against rpm as the dashed line in Figure 5a. Each propeller is capable of providing the thrust required at about the maximum horsepower available from the selected airplane engine at cruise rpm. Blowing control can be used for steady-state high-speed flight at a constant engine rpm to accommodate some decrease in airplane weight below the design weight (shown as ⊡ in Figure 5a, to W =1333kg, 3000 lbs). A further reduction in weight, of course, will require reduced engine rpm. In contrast, a variable-pitch propeller can operate through a wide range of weight at a constant engine speed.

For the selected low- speed condition, the thrust available with the S/C - C/C propeller designed with a subsonic jet at the high-speed condition is plotted against rpm in Figure 5b as the solid line. The propeller efficiency at the rpm at which the required steady-state thrust is obtained (1800 rpm) and the propeller efficiency at the maximum rpm of 2700 rpm are indicated at the ends of the curve as 0.78 and 0.55, respectively. The dashed lines show the thrust available with the engine operating at full throttle plotted against rpm for various assumed values of propeller efficiency from 0.65 to 0.45.

It is first seen that more than sufficient engine power is available for steady-state cruise at the thrust-required rpm of 1800; i.e., the S/C - C/C propeller efficiency is greater than that necessary (<0.55) for the engine at full throttle to provide the required thrust for steady-state flight. The engine, therefore, would be operated at reduced throttle for steady-state cruise at this low speed. A margin is then available for climb or acceleration.

The maximum rate of climb at constant speed is directly proportional to the difference in thrust available at the maximum engine power or the maximum thrust available from the propeller from that required for steady-state flight. From Figure 5b, it is seen that the S/C - C/C propeller efficiency is high enough (0.55) at the maximum rpm of 2700 to absorb the maximum engine power at that rpm. The thrust margin for climb or acceleration which results is 1779N (400 lbs).

The thrust produced with the S/C propeller operating as a variable pitch propeller at 2700 rpm for various changes in hub blade angle, are indicated "x" and the corresponding propeller efficiencies are listed. The maximum thrust available with a fixed-pitch propeller ($\Delta\beta = 0$) is less than that obtainable with the S/C -C/C propeller. The thrust is limited by blade stall and not by engine power availability as indicated by comparison of the FP propeller efficiency (0.52) with the full-throttle thrust-available curves. The VP propeller with a hub blade angle change of -5^{o} produces the largest excess thrust. For this case also, the engine would be operated at part throttle, whereas the S/C - C/C propeller operates at full throttle because of a lower efficiency (0.55 vs 0.66).

The results shown in Table 5 indicate that, to match the required thrust for steady-state cruise with a fixed pitch narrow chord propeller at the selected low speed, an engine rpm of 2100 is required. Although the analysis was done at an rpm of 2700 for the VP propeller, it is clear from Figure 5b that the VP propeller can be adjusted to operate at any preferred rpm.

Also plotted on Figure 5b are results for a S/C - C/C propeller with a narrow chord similar to the S/C FP and VP propeller chords. The

C/C propeller with narrow chord was unable to achieve the required low-speed steady-state flight thrust at any engine speed because of blade stall at angles of attack less than that for stall of the thin trailing edge S/C airfoil. Even if some change in design could permit achievement of the required thrust (at about 2100 rpm), no excess thrust for climb or acceleration would exist.

3.4 Operating Boundaries

The aerodynamic data used (reference 3) were measured over a limited Reynolds number and Mach number range. For this study, the c_d,c_ℓ and c_μ vs α relationships were assumed to be invariant. Extrapolation of the experimental data over a range of negative angle of attack was required for a portion of the study. Operating boundaries that should be observed are illustrated in Figure 6 and discussed as follows.

3.4.1 Use of Positive Lift Coefficient

It is possible to operate over a small range of negative c_ℓ for the S/C - C/C airfoils and secure positive c_ℓ by blowing. This should be avoided to prevent loss of propeller effectiveness in event the blowing is disrupted by equipment malfunction.

3.4.2 Use of Low Angle of Attack

On the blown airfoil, the degree of control of c_ℓ with changes in the momentum coefficient varies widely with angle of attack. For example, at zero degrees angle-of-attack, a change of c_μ from 0 to .01 produces a change in c_ℓ from 0.38 to 0.90, a ratio of 2.37:1 increase. At an angle of attack of +9 , for the same c_μ change, the c_ℓ varies from 1.16 to 1.48, a ratio of 1.28:1. This is almost a 2:1 change in effective control by blowing. Because of the desire to work at low angles, it was necessary to provide wide chords to provide the required

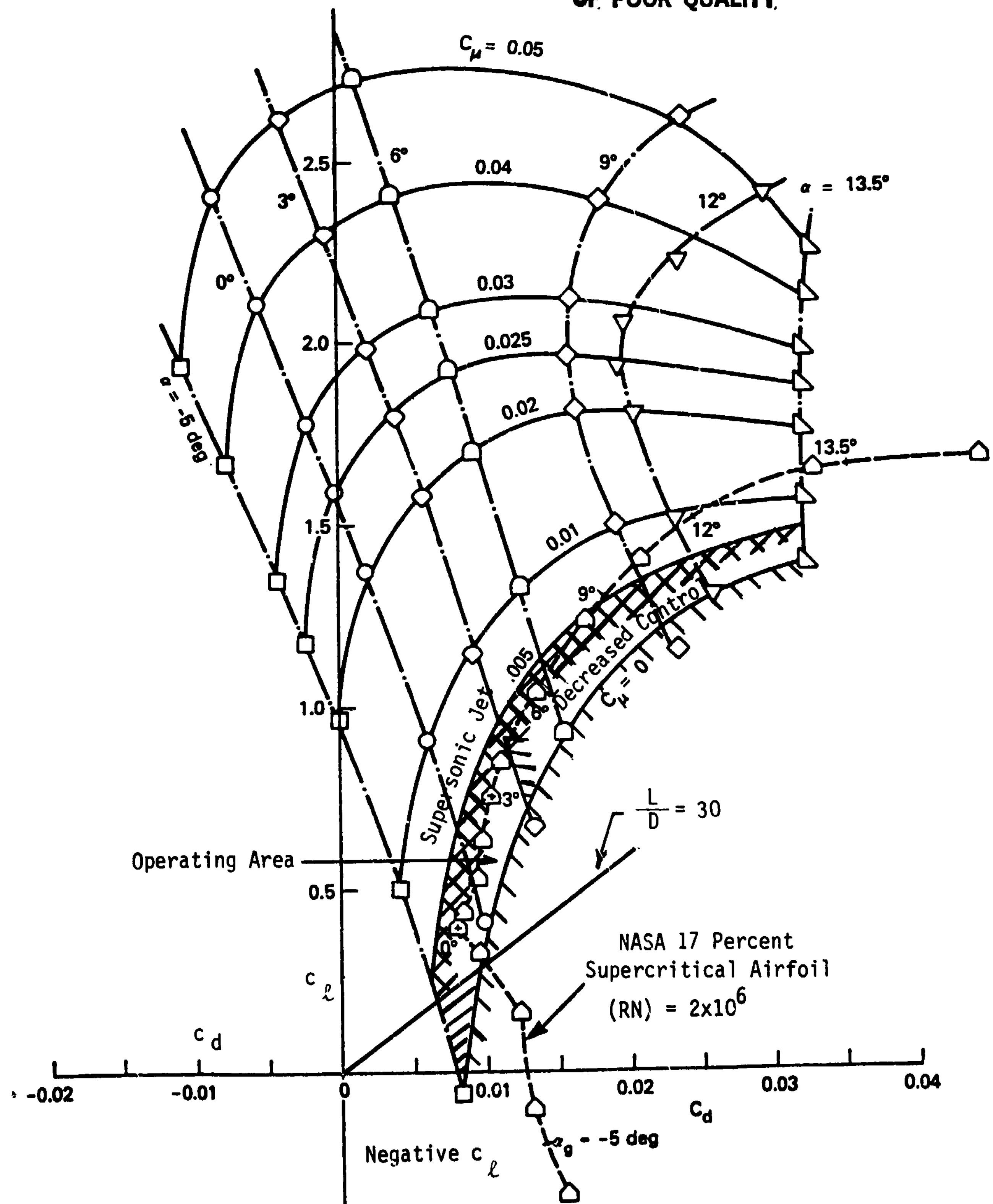

Figure 6, Drag Polars for S/C and S/C-c/c Airfoils (configuration 5 of ref 3) with Propeller Operating Boundaries thrusts. As shown above (3.3.3,) only the wide chord C/C propellers provide reasonable performance.

3.4.3 Avoidance of Supersonic Jet Velocity

For the airplane and propellers studied, propeller tip velocities were subsonic, and it was possible to design propellers with circulation control out to the tip. Although some computations were made which resulted in supersonic jet velocities (e.g., results presented in Figure 5b), there are no data regarding the aerodynamic performance with high jet velocities. To keep the jet velocities subsonic, the momentum coefficients had to range from no more than 0.002 at the tip to 0.004 inboard. The approximate boundary for sonic momemtum coefficient is shown in Figure 6 for the single-plenum propeller.

3.4.4 Section Efficiency

The c_ℓ/c_d plot indicates that maximum L/D is secured for the S/C airfoil at angle of attack of about 5°, and for the S/C - C/C at about 4°. The L/D does not linearly affect propeller performance as it does for wings on aircraft. In fact, until the L/D decreases to about 30, there are only small effects on propeller performance. The L/D for the S/C-C/C is above 30 for angles-of-attack down to zero degrees. Lower angles will have significant adverse effects on propeller performance.

Momentum coefficients below 0.02 are desired, (sec.3.3.1), to prevent excessive deterioration of section efficiency. In general, the supersonic jet boundary restricts operation to below $c_\mu = 0.005$; however, with multi-plenum systems, it should be possible to operate with somewhat higher momentum coefficients than 0.005 near the hub as a means to improve propeller performance.

3.5 System Design Considerations

In this limited study, only aerodynamic performance was computed and analyzed. Other design considerations such as noise, structural analysis and design, system weight, ducting and seal design, and type of compressor were considered but not in enough depth to warrant many conclusions; however, no large technical problems were apparent.

Because of the small slot size, it is judged that the noise energy would be located at high frequency and therefore not be a problem. Also, blowing is only used for the high-altitude high-speed condition and not at low altitudes. The structural problems were only examined to the extent that it appears reasonable to make the trailing edge assembly as a sub-assembly of the main propeller blade. The small size and dimensions of the slot lead to concerns regarding nicks, distortion and structural failure under concentrated loads. The design of pneumatic shaft seals is believed to be straightforward.

The compressor requirements to compress the ambient air to the hub pressures required for a typical propeller are listed on Table 6. While the compression ratio is higher than that required for supercharging the airplane engine, the mass flow is small and the compression horsepower only about one fourth of that required for the engine alone. Valving of the charger outputs would be suitable to control the hub pressure. If the airplane engine is not supercharged, it is possible to operate an automotive type positive displacement unit (vane or Roots type) as a belt-driven accessory. The cruise intake air pumping requirement is 0.92 liters (56 in ^{3}) per crankshaft revolution and is comparable to the pumping volume rates available from the automotive market.

Table 6. Air Flow Requirements For a S/C-C/C Propeller Driven by a Supercharged Engine

	Propeller*	Engine	Total
Air Flow Required	0.038 kg/sec (0.0026 sl/sec)	0.0159 kg/sec (0.0310 sl/sec)	0.097 kg/sec (0.0336 sl/sec)
Compression Ratio	1.22	1.078	-
Compressor Horse-power Required	1.214	5.02	6.23
Compressor Horse-power Available			18.2

Note: Operating conditions for 3.06 km,(10,000 ft), at 2500 rpm with a Turbocharged engine of 8.52 liters, (520 in^3), displacement, (ref 2)

*The propeller requirements include an allowance for leakage and losses within the ducting.

4.0 CONCLUDING REMARKS

A specially-developed computer program (presented in the Appendix) has been used to compare the aerodynamic performance of circulation-control (C/C) propellers with variable-pitch and fixed-pitch propellers. The comparisons were made for a 1600 kg (3600 lb) single-engine general aviation airplane with a maximum speed of about 300 km/hr (186 miles/hr), the approximate limit for a fixed-pitch propeller.

The study indicated that, on an aerodynamic performance basis, the circulation-control propeller is feasible. Increased speed decreases the potential feasibility. Inability to feather and reverse thrust limits applicability to single- engine airplanes or multi-engine configurations where engine failures can not produce a disturbing torque (e.g. on-axis configurations). Economic feasibility requires analysis of manufacturing and maintenance costs of C/C propellers as well as appraisal of mission requirements for specific airplane applications.

All of the propellers investigated had approximately the same efficiency at the high-speed cruise design condition. At low-speed, the C/C propeller performance (cruise, rate of climb, and acceleration) was better than that of an unblown fixed-pitch propeller but not as good as that of a variable-pitch propeller. Although blowing at high-speed permits operation through a wider range of angle of attack than for an unblown fixed-pitch propeller, performance is constrained by the amount of blowing permissible. The amount of blowing is limited by decreases in efficiency with increases in blowing power and by the desire to maintain the blown jet velocity to subsonic values. The latter constraint was imposed in the interest of conservatism because no experimental data are available with supersonic jet velocities. It appeared reasonable to expect that the aerodynamic effectiveness of the Coanda jet would deteriorate with supersonic blowing. Improved performance, however, appears possible through compartmentation of the blowing plenum along the propeller span to provide increased subsonic blowing at the lower-speed inboard sections. The flexibility of operation for a variable-pitch propeller will likely yield superior performance at all off-design low-speed conditions. The possible overall advantages of C/C propellers, therefore, depend upon economic comparisons.

A limited appraisal of other than aerodynamic design considerations, such as noise, structure, weight, ducting, and seals, indicated no large technical problems for C/C propellers. The compressor requirements can be met with automotive-type compressors or by a small amount of valve-controlled bleed from an engine supercharger.

APPENDIX

A BASIC Computer Program For The Aerodynamic Design of Aircraft Propellers as Fixed Pitch, Variable Pitch or Circulation Controlled.

By Wayne H. Bryant
NASA Langley Research Center

CONTENTS

APPENDIX

by
Wayne H. Bryant
NASA Langley Research Center

Introduction

This appendix describes the computer program developed to generate the data in the present study. This aerodynamic propeller design program can accommodate minimum loss (ref. 4) fixed- or variable-pitch propellers, and circulation-controlled propellers with a single plenum extending from the root to any given radius. The program was implemented in BASIC so that only a minimal computer investment is required to use it to design propellers. The present work was accomplished using a Digital Equipment Corporation VAX-11/780 superminicomputer, and the BASIC language elements conform to those used in VAX BASIC. An effort was made to develop as much of the program as possible in "standard" BASIC to ease its transition to other machines. To test this, the program was transferred to a CDC Cyber 175 computer at LaRC where approximately two hours were required to obtain successful operation. Comments on probable coding changes required/desired appear at the end of this appendix.

The results obtained using the computer program described here have been examined and appear reasonable. While there are no known problems or "bugs" remaining in this program, there may yet be problems that will surface for new input cases. Additionally, the program makes no structural analysis of the designed propellers; the structural integrity must be ascertained by the propeller builder using some other technique.

This appendix is organized into seven main sections. These are:

- Introduction
- General Description of Major Program Sections
- Case Table Identification for the Present Study
- Program Variable Definitions and Program Listing
- Detailed Program Description (keyed to listing line numbers)
- Suggestions for Tailoring Program
- Concluding Remarks

General Description of Major Program Sections

The purpose here is to give a brief description of each major area encountered in the program. This will be done first in the order the sections are found in the listing itself without regard to the program execution flow. Next, a specific case will be given to illustrate typical program flow, and appears in the Detailed Program Description section.

There are eight main program sections:

(1) Case selection
(2) Minimum induced loss propeller design (analytic) and output
(3) Strip integration propeller design (Part 1), both non-blown and blown (circulation controlled)
(4) Induced velocity iterative calculations
(5) Strip integration propeller design (completion) including thrust matching iterative calculations
(6) Miscellaneous calculations (e.g., efficiency, Mach number, etc.)
(7) Line printer and cross plot file output
(8) Subroutines

The main purpose of each section is given in the text that follows. The line numbers listed correspond to the program listing found later in this appendix. While this program was developed to generate data for the study presented in the main body of this paper, it should be remembered that relatively simple modifications to the listed program render it useful for evaluating a variety of propeller designs. The data contained in the program, and the logic statements controlling the program flow, are those used for the last part of the study.

(1) Case Selection

After the array declarations and opening output files, the first part of the program consists of initializing variables for a specific run. This occurs between lines 170 and 1820. A number of DATA statements contain information for the blown propeller lift and drag coefficient lookup table as well as that for ten pre-defined evaluation cases. These DATA entries are identified in the Detailed Program Description section following the program listing and cross Reference table. Table A1 in the next part of this appendix shows the main characteristics of these pre-defined cases. If a run is desired for which no case exits, all required data can be manually entered from the keyboard during program execution. All propeller designs using manually entered data will be evaluated as "on design point" cases; that is, the propeller's performance in some arbitrary off-design point cannot be made. The "off-design point" evaluation feature is built in with the use of pre-defined cases.

The engineering units for each input parameter is displayed as the value is requested. These same units are used for pre-loading the defined cases in the data statements. The data order for the defined cases will be given in more detail later. In addition to data for the actual propeller design, the program inquires whether either of two forms of diagonistic output is required for the current run (both predefined or manual input cases). The first set of output is routed to the printer and is useful for observing the convergence during induced velocity and thrust matching iterations; the second set routes the inflow iteration data to the console display device (CRT) so that the user can observe convergence in real-time.

(2) Minimum induced loss propeller design and output (Analytic)

The next section designs a non-blown propeller at the given operating condition using the technique described by Larrabee in reference 4. This section is based almost entirely on a propeller design program developed by W. Hewitt Phillips and E. Eugene Larrabee for an HP 9830 desktop computer. The code implemented ranges from line 1820 to line 3860; equations noted in the REMark statements refer to the numbered equations of (ref. 4), and are all contained in the listing within angle brackets (e.g. <EQN 21>).

After loading data required for the non-blown propeller table look-up subroutine, this section obtains the lift and drag coefficients for the angle of attack spanwise distribution previously entered. This is accomplished through a subroutine call to the non-blown propeller lift/drag subroutine. After these quantities are calculated, this section determines the spanwise chord distribution, efficiency, required horsepower and torque, the local Mach and Reynolds numbers, and other pertinant data. These data are then output to the line printer file.

At the end of this section, chord and beta spanwise distributions are saved for later predefined case analysis. A more complete description of this mechanism is given in the detailed program description.

(3) Strip integration propeller design (Part 1)

This section is coded in lines 3870 through 4590 and implements equations found in the main body of this report. These references are denoted within the REMark statements using square brackets (e.g. [EQN. 7] at line 3900). The strip integration section can design either blown or non-blown minimum induced-loss propellers; this feature is controlled by the designer at program setup time.

The strip integration designs were checked against the analytic designs and gave results identical within a few percent although there were small changes in the spanwise chord and angle of attack distribution. These changes in angle of attack result in an increased thrust which is compensated for (in a later program section) by scaling the spanwise chords to achieve the required thrust. Comparison of the output from the (non-blown) analytic design with that of the (non-blown) strip integration design shows small changes in the spanwise chord and angle of attack distributions.

(4) Induced velocity iteration calculations

This section implements the iterative equations necessary to determine the true spanwise blade angle of attack which is different from the nominal because of induced velocity. Lines 4600 through 5420 realize this procedure. The technique used here is derived from (Ref. 5) and is listed here in full for convenience. References to equations in the comment portion of the individual statements or in REMark statements are enclosed in square brackets and have an "A" (for appendix) prefix. For example, line 4710 has a comment (the text following the "!") indicating that line implements equation A1 ([EQN. A1]); that equation itself follows.

The induced velocity components are evaluated at each radial blade station, i, by the iterative procedure listed below. To start the iterations

$$\phi_i = \tan^{-1}\left(\frac{\lambda}{\xi}\right) \tag{A1}$$

is used to find the initial estimate of α_i as

$$\alpha_i = \beta_i - \phi_i \tag{A2}$$

The procedure continues by finding the multiplier

$$K_i = \frac{\dfrac{Bc_i}{8\pi\xi R}}{\dfrac{2}{\pi}\cos^{-1}\left(e^{-\left[\dfrac{B(1-\xi)\ (1+\lambda^2)^{1/2}}{2\lambda}\right]}\right)} \tag{A3}$$

which is then used in the calculation of

$$a_i = \frac{K_i\left(\dfrac{C_{\ell_i}\ (\cos\phi_i)}{\sin^2\phi_i}\right)}{(1-K_i)\left(\dfrac{C_{\ell_i}(\cos\phi_i)}{\sin^2\phi_i}\right)} \tag{A4}$$

and

$$a'_i = \frac{K_i\left(\dfrac{C_{\ell_i}}{\cos\phi_i}\right)}{(1+K_i)\left(\dfrac{C_{\ell_i}}{\cos\phi_i}\right)} \tag{A5}$$

The induced velocity components a_i and a'_i are next used to calculate an updated ϕ as

$$\phi_{c_i} = \tan^{-1}\left(\frac{\lambda}{\xi}\bullet\frac{1+a_i}{1-a'_i}\right) \tag{A6}$$

which is used in obtaining a corrected α in

$$\alpha_{c_i} = \alpha_i + \tfrac{1}{2}(\phi_i - \phi_{c_i}) \tag{A7}$$

The corrected angle-of-attack is used to calculate a corrected ϕ as

$$\phi_{c_i} = \beta_i - \alpha_{c_i} \tag{A8}$$

which is used if further iterations are necessary.

The convergence tests consists of comparing the current iteration value of α_{c_i} with the previous iteration value of α_i at each blade station and declaring a converged solution if the absolute difference at every blade station is less than that of 0.05°. Stated mathematically, the test is

$$(\alpha_i - \alpha_{c_i}) < 0.05^\circ \quad \text{For all blade stations, i.} \tag{A9}$$

If any station fails to meet this criteria, the procedure iterates starting with Equation A3; if the corrected angle-of-attack at all blade stations pass the test, program flow is to the second part of the strip integration design. In either case, new lift and drag coefficients, based on the most recently corrected angle-of-attack, are calculated for both blown and non-blown designs as appropriate.

(5) Strip Integration propeller design (completion), and thrust matching

This section is coded between lines 5430 and 6520, with the thrust matching part between 5660 and 6510. After the initial induced velocity corrections are made to each blade station's angle of attack, the differential thrust and torque are determined. The total thrust is obtained by numerical integration and is compared to the required thrust for the indicated flight condition. If the developed thrust does not match the required thrust within 1%, then some form of adjustment is employed. This is accomplished in an iterative fashion, with the adjustment parameter selected by a combination of case identification and control variables. After the adjustment has been made, program flow returns to the induced velocity iterations to account for the present thrust matching changes. This sequence is repeated until the developed thrust is within limits indicated above, or the designer manually terminates the run.

This program section largly controls the manner in which cases are interpreted, i.e., the sequence in which cases must be run to obtain meaningful results. (This sequence is discussed in the detailed examination of the listing.) For the current program, alpha, beta, engine speed, or the propeller chord is scaled obtaining desired thrust according to case under evaluation. To modify the program for one's particular needs, a good understanding of this section is required, since most changes will be made here.

(6) Miscellaneous calculations

This section starts at line 6530 and ends at line 7290. Differential torque is numerically integrated to obtain total torque. If the designed propeller uses Coanda blowing, then the total air mass flow, and the centrifugal and compressor engine horsepower for this air flow are obtained. Next, aerodynamic torque is converted to horsepower using

$$Q_{aero} = \frac{2\pi n Q}{550} \qquad \text{(A10)}$$

and the total useful work (in horsepower) is calculated. From this data, propeller efficiency is then calculated. Finally, at each blade station; (a) local Mach number as

$$(MN)_i = \frac{V_i}{V_s} \qquad \text{(A11)}$$

with V_s = velocity of sound at current altitude,

(b) Reynold's number

$$(RN)_i = \frac{\rho_\infty C_i V_i}{\mu_\infty} \qquad \text{(A12)}$$

with ρ_∞ = air density and μ_∞ = viscosity

and (c) the Drag/Lift ratio

$$\frac{C_{d_i}}{C_{\ell_i}} \qquad \text{(A13)}$$

are calculated.

The section ends with the determination of the available horsepower at the current engine speed for the aircraft selected in this study, and the possible rate-of-climb for the propeller/engine/aircraft system.

(7) Line printer and cross-plot file output

The next program section runs from line 7300 to line 8400. If the case under examination calls for off-design point evaluation, the program saves pertinent information in a disk file for later processing. The saved data and the file format are discussed in the detailed program description. Next, data for the appropriate design technique is output. Three forms of printer output are available: (a) analytic (non-blown), (b) strip integration (non-blown), and (c) strip integration (blown). The particular combination of output printed is determined by case number and control variables.

After the output is complete, the final beta and chord values for the design case propellers are saved for use in the off-design case evaluation. This section ends with a query to either examine another case or stop the program.

(8) Subroutines

The program subroutines can be found starting at line number 8410 and running to the end of the program at line 9710. Aerodynamic coefficients for the non-blown propeller are obtained from a lookup table subroutine between lines 8410 and 8770. A Simpson's Rule integration scheme is found starting at line 8780 and ending at line 8920. An atmospheric characteristics subroutine, reproducing the values given in the 1962 NASA standard atmosphere report (Ref. 6), is next, running from lines 8930 to 9190.

The Coanda effect, blown trailing edge propeller aerodynamic coefficients subroutine is located starting at line 9200 and ending at line 9460. The subroutine between 9470 and 9630 is used to calculate rank intervals for this lookup table. The final subroutine runs from 9640 to 9710 and calculates the available engine horsepower as a function of engine speed at full throttle for the engine used in this study.

Case Table Identification for the Present Study

The current program is structured to design six propellers in cases 1, 2, 3, and 4. These propellers are denoted A, A', B, C, C', and D. Cases 5 - 10 are for off-design point evaluation. Table A1 lists the characteristics and control parameters for each case. Definitions of the variables and control parameters listed at the bottom of each column, and in the text that follows the table can be found in the list of symbols that preceeds the program listing.

Table A1. Propeller Design Program Case Identification

			Evaluate (?)	Fixed During Thrust Correction (?)				
Case #	Alpha	Design	Blown/Non-blown	Blowing	Chord	Beta	Alpha	RPM
1 (A/A')	+4	On	Y(A)/Y(A')	On	Y/N	Y	N/Y	Y
2 (B)	-12,5	On	Y(B)/N	On	Y/-	Y	N/-	Y
3 (C/C')	+2	On	Y(C)/Y(C')	On	Y/N	Y	N/Y	Y
4 (D)	-12,5	On	Y(D)/N	On	Y/-	Y	N/-	Y
5 (A)	+4	Off	Y(A)/N	Off	Y/-	Y	Y/-	N
6 (B)	-12,5	Off	Y(B)/N	Off	Y/-	Y	Y/-	N
7 (C)	+2	Off	Y(C)/N	Off	Y/-	Y	Y/-	N
8 (D)	-12,5	Off	Y(D)/N	Off	Y/-	Y	Y/-	N
9 (A')	+4	Off	N/Y(A')	-	-/Y	N	-/Y	Y
10 (C')	+2	Off	N/Y(C')	-	-/Y	N	-/Y	Y
T8	A(1,I)	*	C7	*	C5	B7	C6	*

Parameter variation by case number identification is controlled by the variable listed at the bottom of each column. For those columns with *, the parameter is embeded within the program itself, and cannot be changed without modifying the source code. The propeller identification for the ten cases set up in the accompanying listing are shown under the "Case #" column in parenthesis (e.g. (A/A')).

An example is helpful in understanding this table. For Case #1, (T8=1) two propellers are designed, denoted A and A'. Both propellers have a nominal value of alpha of +4 degrees (A(1,I)), and are considered to be designed for the operating conditions specified in the Q(1,*) array as indicated by the "On" in the Design column. Both a blown and a non-blown propeller will be evaluated (C7=3), and for the blown propeller, the trailing edge jets will be active (Blowing?). The propellers are designed to match the available thrust to the required thrust specified in the Q(1,3) element. This can be done several ways. The next four columns specify for each propeller/case which scheme is used to match the available thrust to the required thrust. For the blown propeller, the alpha values are scaled to accomplish the matching (as can be seen by the N(o) in the first part of the entry under "Alpha".) For the non-blown propeller, the chords are scaled, as can be seen from the /N(o) under the "Chord" column. The variables C5, B7, and C6 are used to set up the Chord, Beta, and Alpha columns, and program logic is used to setup the RPM column.

The predefined cases must be run in a specific sequence to make certain that necessary data is available for each case. For the current program logic, the sequences are as follow:

```
          Case #1                      Case #3
          /     \                      /     \
     Case #2   Case #9            Case #4   Case #10
        |                            |
     Case #5                      Case #7
        |                            |
     Case #6                      Case #8
```

Case #1 designs two propellers, A' (non-blown) and A (blown) at the design point. A' is designed first, and the chords are scaled to match the required thrust. A is then designed using the final chords obtained from propeller A'; thrust matching is achieved by changing the nominal angle of attack. Case #2 designs one propeller, B (blown). The chords used in this design are those obtained from the A' propeller, and thrust matching is carried out by changing the nominal angle of attack.

In a similar manner, Case #3 designs two propellers, C' (non-blown) and C (blown), also at the design point. Again, C' is designed first and the final chords obtained during the thrust matching is used at the design chord values for the blown propeller (C) with nominal angle of attack modified to obtain the required thrust. Case #4 designs the sixth propeller, D (blown) which uses the chords from the C' propeller, and also changes the nominal angle of attack to secure the required thrust.

Cases #5, 6, 7, and 8 evaluate the four blown propeller designs (A, B, C, and D) at an off-design point. For these cases, the blowing is shut off, and thrust matching is achieved by changing engine speed. Cases #9 and 10 evaluate the two non-blown propeller designs (A' and C') at some off-design condition, and vary the propeller pitch to secure the required thrust.

Engineering and Program Variable Definition, and Program Listing

ENGINEERING	PROGRAM	USAGE
α_i	A(1,I)	Alpha at each blade station, degrees
	A(2,I)	Non-blown propeller lookup routine interval constants
	A(3,I)	Non-blown propeller lookup routine alpha increment, degrees
	A(4,I)	Not used
	A$	Output format string
α_i	A1	Alpha at each blade station during manual setup of spanwise distribution, degrees
$\Delta\beta$	A2	beta increment/iteration during off-design analysis, degrees
$\Delta\beta_{total}$	A3	Total beta change during off-design analysis, degrees
	A4	Logical: -1 = forced case end during off-design analysis
	A5	Square of jet velocity (temporary variable)
$\Delta\alpha$	A6	Alpha increment/iteration during off-design analysis, degrees

ENGINEERING	PROGRAM	USAGE
$\Delta\alpha_{total}$	A7	Cumulative alpha change during off-design analysis, degrees
	A8	Logical: Available thrust within 1% of required thrust (A8=0); otherwise A8=1
B	B	Number of propeller blades
	B$	Output format string variable
β_i	B(I)	Beta at each blade station, degrees
T_c (Ref. 4)	B1	Thrust coefficient, $2T/\rho V^2 \pi R^2$
λ	B2	Advance ratio
P_c	B3	Power Coefficient, $2P/\rho V^3 R^2$
η	B5	Efficiency
η	B6	Blown propeller efficiency
	B7	Logical: Beta fixed? 1=yes, 0=no
$(C_\ell)_i$	C(1,I)	Lift Coefficient
$(C_d)_i$	C(2,I)	Drag Coefficient
c/R_i	C(3,I)	Chord/span ratio
	C(4,I)	Unused
	C$	Output format string variable
	C1	Temporary variable
V_s	C2	Velocity of sound (f/s) at current altitude
	C5	Case data: Chord fixed this run? 1=yes, 0=no
	C6	Case data: Momentum coefficients fixed this run? 1=yes, 0=no
	C7	Case data: Evaluate which propellers? 0=none, 1=non-blown only, 2=blown only, 3=both
	C8	Logical: Cross plot this run? 1=yes, 0=no
	C9	Temporary variable: maximum alpha, degrees
D	D	Propeller diameter, feet
	D(1,I)	Unused
	D(2,I)	Unused
	D(3,I)	Lookup table drag interval coefficients
$(c_d/c_\ell)_i$	D(4,I)	Drag to lift coefficient ratio
	D$	Output format string variable
	D3	Temporary variable

ENGINEERING	PROGRAM	USAGE
f_i (Ref. 4)	E(I)	Vortex sheet spacing parameter
F_i (Ref. 4)	F(I)	Ratio of average velocity increment in the slipstream to the sheet velocity
	F1	Temporary variable
	FOR1$	Output format string variable
	FOR2$	Output format string variable
	FOR3$	Output format string variable
	FOR4$	Output format string variable
	FOR5$	Output format string variable
	FTEM$	Output format string variable
G_i (Ref. 4)	G(I)	Circulation distribution function
V_{ji}	H(1,I)	Jet velocity at each blade station, f/s
$(P_{T_j})_i$	H(2,I)	Jet pressure at each blade station, PSF
V_i	H(3,I)	Local velocity at each blade station, f/s
T	H(4,I)	Differential thrust; also total thrust, lbs.
Q	H(5,I)	Differential torque; also total torque, ft-lbs.
$\sin \phi_i$	H(6,I)	Sin Phi-i
$\cos \phi_i$	H(7,I)	Cos Phi-i
$\dot{m}$	H(8,I)	Mass flow/foot, slugs/sec/foot
HP_{pci}	H(9,I)	Horsepower/foot
ρ_∞	H	Air density, slugs/f**3
h	H2	Altitude, km
	I	Program loop control variable; maximum value is number of blade stations
	I8	Program termination control variable
	J	Program loop control variable
	J( )	Blown propeller lookup table interval lift and drag coefficients
	K	Program loop control variable
ξ	K(I)	Blade station radius to blade radius ratio
	K2	Temporary variable
	L(1,I)	Non-blown propeller table lookup interval lift coefficients
	L(2,I)	Unused

ENGINEERING	PROGRAM	USAGE
	M	Temporary variable
$(MN)_i$	M(I)	Local blade station Mach number
	MO	Total mass flow, slugs/second
	N	Temporary variable
n	N1	Engine speed, revolutions/second
	N2	Engine speed change/iteration required to match required thrust, revolutions/second
	N3	Cumulative engine speed change in matching thrust, revolutions/second
	O	Temporary variable
	P	Temporary variable
HP_{total}	P1	HP; Engine power; also, Required power
P_∞	P2	Static Pressure, lbs/f**2
Π	P3	Pi (3.14159...)
	Q	Temporary variable
V_∞	Q(Case#,0)	Airspeed, f/s
n	Q(Case#,1)	Engine speed, rev./sec
D	Q(Case#,2)	Propeller diameter, feet
T	Q(Case#,3)	Thrust, lbs.
h	Q(Case#,4)	Altitude, feet
B	Q(Case#,5)	Number of propeller blades
HP_{avail}	Q(Case#,6)	Engine power, HP
	Q(Case#,7)	Logical: Alpha fixed during thrust matching? 1=yes, 0=no
	Q(Case#,8)	Logical: Beta fixed during thrust matching? 1=yes, 0=no
	Q(Case#,9)	Logical: Momentum coefficients fixed during thrust matching? 1=yes, 0=no.
	Q(Case#,10)	Propeller type selection: 1=non-blown, 2=blown, 3=both
α_1	Q(Case#,11)	Alpha at blade station 1, degrees
α_2	Q(Case#,12)	Alpha at blade station 2, degrees
	.	.
α_{20}	Q(Case#,30)	Alpha at blade station 20, degrees

ENGINEERING	PROGRAM	USAGE
Q	Q6	Torque, ft-lbs
$(RN)_i$	R(I)	Reynolds number at each blade station
	R	Temporary variable
R	R6	Propeller tip radius, feet
a_i (Ref. 4)	T(1,I)	Induced velocity equations parameter a-i
a_i' (Ref. 4)	T(2,I)	Induced velocity equations parameter a'-i
ϕ_{ci} "	T(3,I)	Induced velocity equations corrected Phi
α_{ci} "	T(4,I)	Induced velocity equations corrected Alpha
β_i	T(5,I)	Final Beta for Case 1, analytic propeller (A')
β_i	T(6,I)	Final Beta for Case 2 propeller (B)
β_i	T(7,I)	Final Beta for Case 3, analytic propeller (C')
β_i	T(8,I)	Final Beta for Case 4 propeller (D)
β_i	T(9,I)	Final Beta for Case 1, blown propeller (A)
β_i	T(10,I)	Final Beta for Case 3, blown propeller (C)
$(C/R)_i$	T(11,I)	Final Chord ratio for propeller A'
$(C/R)_i$	T(12,I)	Final Chord ratio for propeller B
$(C/R)_i$	T(13,I)	Final Chord ratio for propeller C'
$(C/R)_i$	T(14,I)	Final Chord ratio for propeller D
$(C/R)_i$	T(15,I)	Final Chord ratio for propeller A
$(C/R)_i$	T(16,I)	Final Chord ratio for propeller C
T	T	Thrust, lbs.
HP_c	T0	Compressor power required to pump from P-static to required hub jet pressure, HP
HP_{pc}	T1	Total centrifugal horsepower requirement, HP
T	T2	Ambient temperature, Degrees R
	T3	Total useful work, ft-lbs
HP_{aero}	T4	Aerodynamic torque, HP
HP_{total}	T5	Total power required, HP
T	T6	Thrust developed, lbs.
	T7	Logical: 1=both blown & non-blown evaluation, 0=either blown or non-blown evaluation
Case	T8	Case identification: 0=manual input, 1-10 predefined in data statements
HP_{avail}	T9	Available horsepower @ current engine speed, HP
$(C_\mu)_i$	U(1,I)	Momentum Coefficents at each blade station

ENGINEERING	PROGRAM	USAGE
	U(2-7,I)	Not used
ϕ_i	U(8,I)	Phi at each blade station, degrees
α_i	U(9,I)	Alpha at each blade station, degrees
ξ	U(10,I)	K(I) in the Induced velocity iterative equation
α	U0	Angle of Attack in lift/drag lookup subroutine
	U1	Temporary (lookup subroutine)
μ_∞	U2	Viscosity of air
	U4	Temporary variable
$(P_t)_h$	U5	Total hub pressure, lbs/ft**2
	U6	Temporary variable (Induced velocity equations)
	U9	Temporary variable (ATAN argument)
V_∞	V	Free stream velocity, f/s
V_i	V(I)	Local velocity at each blade station, f/s
	V1	Temporary variable (Induced velocity equations)
	V2	Temporary variable (Induced velocity equations)
	V3	Identification number of first blade station used in calculation of non-blown propeller lift and drag coefficients
	V4	Logical: 0=Blown, 1=Non-blown
	V7	Logical: Induced velocity iterations complete? 1=yes, 0=no.
	V8	Logical: Diagonistic printer output desired? 1=yes, 0=no
	V9	Logical: Analytic output complete? 1=yes, 0=no
	W2	Logical: Want CRT iterative output? 1=yes
	X(I)	x-i, Omega*R/V
	Y	Temporary variable
	Z(I)	Simpson's rule transfer parameter array. (Value of integrand at each station.)
	Z	Simpson's rule integral (Integral of Z(I))
ζ (Ref. 4)	Z0	Displacement Velocity Ratio
	Z9	Degrees/Radian conversion factor.

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Program Listing and Cross References

```
10 REM**************************************************************
20 REM*                                                            *
30 REM*          PROPELLOR DESIGN PROGRAM FOR USE IN               *
40 REM*  THE DESIGN OF A FULL-BLOWN PROP OR A NON-BLOWN PROP       *
50 REM*                  WHB LARC 1/18/83                          *
55 REM*                                                            *
60 REM**************************************************************
70 DIM E(20),X(20),F(20),G(20),R(20),H(9,20),T(16,20),Q(10,30)
80 DIM M(20),K(20),U(10,20),J(9,8)
90 DIM L(2,20),D(4,20),A(4,20),Z(20),C(4,20),B(20),V(20)
100 REM ********************************************************
110 REM          START INPUT OF VALUES
120 REM*********************************************************
130 OPEN "OUTPUT.DAT" FOR OUTPUT AS FILE #1%
140 MARGIN #1%,132%
150 OPEN "CRPLOT.DAT" FOR OUTPUT AS FILE #2%
160 MARGIN #2%,80%
170 DATA -.68,53.5,.26,-1.0,.009,-.40,-.001,0.
180 DATA -.42,52.5,.27,-1.0,.008,-.40,0.,0.
190 DATA -.15,51.5,.28,-2.0,.008,-.40,.0009,-.025
200 DATA .13,49.5,.25,-.50,.0089,-.425,.0011,.02
210 DATA .38,49.0,.28,-3.50,.01,-.405,.0031,.04
220 DATA .66,45.5,.26,-5.50,.0131,-.365,.0024,.075
230 DATA .92,40.0,.24,08.00,.0155,-.29,.0069,.0
240 DATA 1.16,32.0,.17,-9.50,.0224,-.29,.0035,.02
250 DATA 1.33,22.5,.07,-5.50,.0259,-.27,.0077,.27
260 FOR I=1 TO 9
270 FOR J=1 TO 8
280 READ J(I,J)
290 NEXT J
300 NEXT I
310 DATA 270.,41.6,6.,324.,10000.,3.,0.,0,1,0,3,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4
320 DATA 4,4,4,4,4
330 DATA 270.,41.6,6,324.,10000.,3.,0,1,1,0,2,-12.,-11.49,-10.92,-10.38,-9.82
340 DATA -9.29,-8.7,-8.12,-7.5,-6.76,-5.89,-4.9,-3.82,-2.72
350 DATA -1.55,-.3,1.0,2.3,3.62,5.
360 DATA 270.,41.6,6.,324.,10000.,3.,0.,0,1,0,3,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2
370 DATA 2,2,2,2,2
380 DATA 270,41.6,6,324,10000,3,0,1,1,0,2,-12.,-11.49,-10.92,-10.38,-9.82
390 DATA -9.29,-8.7,-8.12,-7.5,-6.76,-5.89,-4.9,-3.82,-2.72
400 DATA -1.55,-.3,1.0,2.3,3.62,5.
410 DATA 125,45,6,347,0,3,0,1,1,1,2,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4
420 DATA 125,45,6,347,0,3,0,1,1,1,2,-12.,-11.49,-10.92,-10.38,-9.82
430 DATA -9.29,-8.7,-8.12,-7.5,-6.76,-5.89,-4.9,-3.82,-2.72
440 DATA -1.55,-.3,1.0,2.3,3.62,5.
450 DATA 125,45,6,347,0,3,0,1,1,1,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2
460 DATA 125,45,6,347,0,3,0,1,1,1,2,-12.,-11.49,-10.92,-10.38,-9.82
470 DATA -9.29,-8.7,-8.12,-7.5,-6.76,-5.89,-4.9,-3.82,-2.72
480 DATA -1.55,-.3,1.0,2.3,3.62,5.
490 DATA 125,45,6,347,0,3,0,1,0,1,1,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4
500 DATA 125,45,6,347,0,3,0,1,0,1,1,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2,2
```

```
510 FOR I=1 TO 10
520 FOR J=0 TO 30
530 READ Q(I,J)
540 NEXT J
550 NEXT I
560 REM ----------------- CLEAR THE 'ANALYTIC OUTPUT COMPLETE' FLAG -----------
570 V9=0
580 REM ---------------RESET THE THRUST MATCHING PARAMETERS -----------
590 A3=0
600 A7=0
610 N3=0
620 PRINT ," DATE : ";DATE$(0)
630 REM ---------ENTER THE CASE IDENTIFICATION FOR THE CURRENT RUN----
640 PRINT "INPUT 'CASE #' (1-10) FOR THIS RUN, OR '0' FOR MANUAL INPUT ";
650 INPUT T8
660 IF T8<=0 THEN GOTO 810
670 IF T8>10 THEN T8=10
680 V=Q(T8,0)
690 N1=Q(T8,1)
700 D=Q(T8,2)
710 T=Q(T8,3)
720 H2=Q(T8,4)
730 B=Q(T8,5)
740 P1=Q(T8,6)
750 C5=Q(T8,7)
760 B7=Q(T8,8)
770 C6=Q(T8,9)
780 C7=Q(T8,10)
790 IF T8<>0 THEN GOTO 990
800 REM ---------- INPUT AIRSPEED ----------
810 PRINT "ENTER AIRSPEED , V , IN FT/SEC";
820 INPUT V
830 REM ---------- INPUT ROTATIONAL SPEED ----------
840 PRINT "ENTER ROTATIONAL SPEED , N1 , IN RPS";
850 INPUT N1
860 REM ---------- INPUT PROP DIAMETER ----------
870 PRINT "ENTER PROP. DIAMETER , D , IN FEET";
880 INPUT D
890 REM ---------- INPUT THRUST ----------
900 PRINT "ENTER THRUST , T , IN POUNDS";
910 INPUT T
920 REM ---------- INPUT ALTITUDE (IN FEET) ----------
930 PRINT "ENTER ALTITUDE , H , IN FEET";
940 INPUT H2
950 REM***********************************************************
960 REM        FIRST SET OF INPUT VALUES ARE COMPLETE
970 REM***********************************************************
980 REM        ----- Z9 = DEGREES/RADIAN -----
990 P3=3.1415927
1000 Z9=180.0/P3
1010 REM       ----- H2 IS CONVERTED TO METRIC UNITS (KM) -----
1020 H2=(3.048E-04)*H2
1030 IF H2<47 THEN 1070
```

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```
1040 PRINT "ALTITUDE ENTERED AT SETUP TIME IS TOO LARGE"
1050 GO TO 930
1060 REM       ----- ATMOSPHERIC DENSITY SUBROUTINE IS CALLED -----
1070 GOSUB 2930
1080 IF T8<>0 THEN GOTO 1210
1090 REM*****************************************************
1100 REM        INPUT SECOND SET OF VALUES
1110 REM*****************************************************
1120 REM ---------- INPUT NUMBER OF BLADES ON PROP ----------
1130 PRINT "ENTER NUMBER OF BLADES ON PROP , B";
1140 INPUT B
1150 REM ---------- INPUT HORSEPOWER ----------
1160 PRINT "ENTER ENGINE HORSEPOWER , P";
1170 INPUT P1
1180 REM*************************************************
1190 REM         SECOND SET OF INPUT VALUES ARE COMPLETE
1200 REM*************************************************
1210 REM       ----- R6 = TIP RADIUS OF PROP -----
1220 R6=D/2
1230 REM       ----- B1 = THRUST COEFFICIENT <EQN. 15> -----
1240 B1=8*T/(H*V**2*D**2*P3)
1250 REM       ----- B2 = ADVANCE ANGLE <EQN. 9> -----
1260 B2=V/(P3*N1*D)
1270 REM       ----- B3 = POWER COEFFICIENT  -----
1280 B3=2*P1*550/(H*V**3*R6**2*P3)
1290 FOR I=1 TO 20
1300 REM       ----- K(I) = RATIO OF RADIUS DISTANCE FROM I TO TIP <EQN. 17>---
1310 K(I)=0.05*I
1320 NEXT I
1330 REM ---------- BLOWN OR NON-BLOWN DESIGN------------------
1340 IF T8<>0 THEN GOTO 1420
1350 REM ********** MANUAL INPUT FOR BLOWN/NON-BLOWN EVALUATION **************
1360 PRINT"ENTER '1' FOR NON-BLOWN PROPELLER DESIGN, '2' FOR BLOWN DESIGN,"
1370 PRINT"OR '3' FOR BOTH.... ";
1380 INPUT C7
1390 IF C7<1 THEN C7=1
1400 IF C7>3 THEN C7=3
1401 PRINT
1402 PRINT"ENTER CODE FOR PARAMETER YOU WISH TO VARY IN MATCHING THRUSTS."
1403 PRINT"ENTER '1' FOR CHORD SCALING, '2' FOR BETA SCALING, AND "
1404 PRINT"'3' FOR ALPHA SCALING.   ";
1405 INPUT C1
1406 IF C1<1 OR C1>3 THEN GOTO 1402
1407 IF C1=1 THEN C5=0 ELSE C5=1
1408 IF C1=2 THEN B7=0 ELSE B7=1
1409 IF C1=3 THEN C6=0 ELSE C6=1
1410 REM ****** NOW SET UP CONTROL PARAMETERS FOR SELECTED EVALUATION ********
1420 IF C7=2 THEN V4=0 ELSE V4=1
1430 IF C7>=3 THEN T7=1 ELSE T7=0
1440 IF V4=0 THEN V9=1
1450 REM************************************************************
1460 REM     WANT DIAGONISTIC OUTPUT??? 1=YES, 0=NO INTO V8
1470 REM************************************************************
```

```
1480 PRINT"ENTER 1 TO INCLUDE DIAGONISTIC PRINTER OUTPUT, ";
1490 PRINT "OTHERWISE ENTER '0'.. ";
1500 INPUT V8
1510 IF V8< 0 THEN V8=0
1520 IF V8>1 THEN V8=1
1530 PRINT "ENTER '1' FOR INFLOW ITERATION CRT OUTPUT, OTHERWISE '0'  ";
1540 INPUT W2
1550 IF W2>1 THEN W2=1
1560 IF W2< 0 THEN W2=0
1570 REM
1580 IF T8<>0 THEN GOTO 1790
1590 IF(T7=1) AND (V4=0) THEN GOTO 1820
1600 REM**************************************************************
1610 REM           MANUAL INPUT OF ALPHA AT EACH BLADE STATION
1620 REM
1630 REM      A(1,I) = BLADE ANGLE OF ATTACK
1640 REM      A(2,I) = INTERVAL CONSTANTS
1650 REM      A(3,I) = INTERVAL INCREMENTAL ALPHA
1660 REM
1670 REM**************************************************************
1680 I=1
1690 PRINT "ALPHA(";I;")";
1700 INPUT A1
1710 PRINT "HOW MANY VALUES OF";A1;
1720 INPUT K
1730 FOR J=I TO K+I-1
1740 A(1,J)=A1
1750 IF J=20 THEN 1820
1760 NEXT J
1770 I=J+1
1780 GOTO 1690
1790 FOR I=1 TO 20
1800 A(1,I)=Q(T8,I+10)
1810 NEXT I
1820 REM***********************************************************
1830 REM       NOW HAVE 20 VALUES FOR A(1,I)
1840 REM       A(1,I)=20 ALPHA VALUES
1850 REM       ASSIGN LOOKUP TABLE INTERVALS
1860 REM***********************************************************
1870 A(2,1)=-3
1880 A(2,2)=0
1890 A(2,3)=3
1900 A(2,4)=6
1910 A(2,5)=9
1920 A(2,6)=12
1930 A(2,7)=14
1940 A(2,8)=17
1950 REM****************************************************************
1960 REM   NOW ASSIGN LIFT AND DRAG VALUES TO LOOKUP TABLE COEFFICIENTS
1970 REM****************************************************************
1980 REM
1990 L(1,1)=0.001
2000 L(1,2)=0.37
2010 L(1,3)=0.73
```

```
2020 L(1,4)=1.01
2030 L(1,5)=1.3
2040 L(1,6)=1.52
2050 L(1,7)=1.66
2060 L(1,8)=1.66
2070 L(1,9)=0.001
2080 D(3,1)=0.0123
2090 D(3,2)=0.0081
2100 D(3,3)=0.01
2110 D(3,4)=0.0127
2120 D(3,5)=0.0181
2130 D(3,6)=0.0242
2140 D(3,7)=0.0365
2150 REM***********************************************************************
2160 REM    WE NOW HAVE INTERVAL LIMITS AND LINEAR COEFFICIENTS FOR THE LIFT *
2170 REM       AND DRAG COMPUTATIONS-----NOW COMPUTE LIFT                    *
2180 REM***********************************************************************
2190 IF V4=0 THEN GOTO 2540
2200 FOR I=1 TO 20
2210     T(4,I)=A(1,I)
2220 NEXT I
2230    V3=1
2240    GOSUB 8410
2250 IF V9=1 THEN GOTO 2540
2260 REM**************************************************************
2270 REM          OUTPUT VALUES TO PRINTER
2280 REM**************************************************************
2290 PRINT #1 ,CHR$(12%)        !FORM FEED
2300 PRINT #1%,TAB(40);"ANALYTIC RESULTS FOR CASE #";T8
2310 PRINT #1 ,"   V";V;  !FREE STREAM VELOCITY
2320 PRINT #1 ,"   N";N1; !ENGINE SPEED, REV/SEC
2330 PRINT #1 ,"   D";D; !PROPELLER DIAMETER, FEET
2340 PRINT #1 ,"   T";T; !REQUIRED THRUST, LBS
2350 PRINT #1 ,"   RHO";H !AIR DENSITY, RHO
2360 PRINT #1
2370 PRINT #1 ,"   B";B; !NUMBER OF PROPELLER BLADES
2380 PRINT #1 ,"   H,KM";H2; !ALTITUDE, KM
2390 PRINT #1 ,"   P";P1; !AVAILABLE ENGINE HORSEPOWER
2400 PRINT #1 ,"   V/ND";V/(N1*D) !ADVANCE ANGLE, LAMBDA, DEGREES
2410 PRINT #1
2420 PRINT #1 ,"   LAMBDA";B2; !ADVANCE RATIO
2430 PRINT #1 ,"   TC";B1; !THRUST COEFFICIENT
2440 PRINT #1 ,"   PC";B3 !POWER COEFFICIENT
2450 PRINT #1
2460 PRINT #1 ,"KSI            CL            D/L            ALPHA"
2470 PRINT #1
2480 FOR I=1 TO 20
2490 PRINT #1 ,K(I),C(1,I),D(4,I),A(1,I)
2500 NEXT I
2510 REM**************************************************************
2520 REM          FIRST OUTPUT COMPLETE, COMPUTE FOR SECOND OUTPUT
2530 REM**************************************************************
```

```
2540 FOR I=1 TO 20
2550 REM *************** <EQN. 8> *************************************
2560 E(I)=0.5*B*SQR(B2**2+1)*(1-K(I))/B2
2570 REM *************** <EQN 5>  *************************************
2580 X(I)=K(I)/B2
2590 REM *************** <EQN 7>  *************************************
2600 Y=EXP(-E(I))
2610 F(I)=2*ATN(SQR(1-Y**2)/Y)/P3
2620 REM *************** <EQN 6>  *************************************
2630 G(I)=F(I)*X(I)**2/(X(I)**2+1)
2640 REM *************** <EQN 20> INTEGRAND *************************
2650 M(I)=4*K(I)*G(I)*(1-D(4,I)/X(I))
2660 NEXT I
2670 FOR I=1 TO 20
2680 Z(I)=M(I)
2690 NEXT I
2700 GOSUB 8830
2710 REM *************** <EQN 20> INTEGRAL **************************
2720 M=Z
2730 FOR I=1 TO 20
2740 REM *************** <EQN 21> INTEGRAND *************************
2750 Z(I)=M(I)/(2*(X(I)**2+1))
2760 NEXT I
2770 GOSUB 8830
2780 REM *************** <EQN 21> INTEGRAL **************************
2790 N=Z
2800 FOR I=1 TO 20
2810 REM *************** <EQN 16> INTEGRAND, FIRST PART ************
2820 Z(I)=4*K(I)*G(I)*(1+D(4,I)*X(I))
2830 NEXT I
2840 GOSUB 8830
2850 REM *************** <EQN 16> INTEGRAL, FIRST PART *************
2860 O=Z
2870 FOR I=1 TO 20
2880 REM *************** < EQN 16> INTEGRAND, SECOND PART ***********
2890 Z(I)=4*K(I)*G(I)*(1+D(4,I)*X(I))*X(I)**2/(2*(X(I)**2+1))
2900 NEXT I
2910 GOSUB 8830
2920 REM *************** < EQN 16> INTEGRAL, SECOND PART ************
2930 P=Z
2940 IF T=0 THEN 3070
2950 REM **************************************************************
2960 REM          THE REQUIRED THRUST WAS SPECIFIED
2970 REM **************************************************************
2980 REM
2990 REM *************** < EQN 19> ************************************
3000 Z0=M*(1-SQR(1-(4*B1*N/M**2)))/(2*N)
3010 REM *************** < EQN 29> NUMERATOR *************************
3020 B3=O*Z0+P*Z0**2
3030 REM *************** < EQN 29> ************************************
3040 B5=B1/B3
3050 GOTO 3160
```

```
3060 REM***********************************************************
3070 REM          THE ENGINE HORSEPOWER WAS SPECIFIED
3080 REM***********************************************************
3090 Z0=0*(SQR(1+(4*B3*P)/0**2)-1)/(2*P)
3100 B1=M*Z0-N*Z0**2
3110 REM ************** <EQN 29> **********************************
3120 B5=B1/B3
3130 REM***********************************************************
3140 REM          BEGIN SECOND SET OF OUTPUTS
3150 REM***********************************************************
3160 IF V9=1 THEN 3210
3170 PRINT #1
3180 PRINT #1 ,"    Z";Z0;
3190 PRINT #1 ,"    ETA";B5
3200 REM *************** REQUIRED TORQUE FOR CURRENT PROPELLER ****
3210 Q6=V**3*B1*H*D**2/(16*N1*B5)
3220 REM *************** REQUIRED HORSEPOWER FOR CURRENT PROPELLER *
3230 P1=2*P3*N1*Q6/550
3240 REM *************** THRUST PRODUCED BY CURRENT PROPELLER ******
3250 T=2*P3*N1*Q6*B5/V
3260 IF V9=1 THEN GOTO 3370
3270 PRINT #1
3280 PRINT #1 ,"   TORQUE";Q6;
3290 PRINT #1 ,"   HP";P1;
3300 PRINT #1 ,"   THRUST";T
3310 REM*********************************************************************
3320 REM**                                                                 **
3330 REM**      BYPASS ANALYTIC CHORD AND BETA CALCULATIONS                **
3340 REM**      IF OFF DESIGN EVALUATION (T8>4)                            **
3350 REM**                                                                 **
3360 REM*********************************************************************
3370 FOR I=1 TO 20
3380 REM ************* <EQN 24> *********************************************
3390 IF T8<5 THEN C(3,I)=4*P3*B2*G(I)*Z0/(B*SQR(X(I)**2+1)*C(1,I))
3400 REM ************* <EQN 25B> ********************************************
3410 IF T8<5 THEN B(I)=Z9*ATN(B2*(1+Z0/2)/K(I))+A(1,I)
3420 REM ********* SAVE CALCULATED ANALYTIC VALUES FOR SUBSEQUENT CASE USE ***
3430 IF (T8=1) AND (V4=1) THEN T(5,I)=B(I)
3440 IF (T8=2) THEN C(3,I)=T(15,I)
3450 IF (T8=3) AND (V4=1) THEN T(7,I)=B(I)
3460 IF (T8=4) THEN C(3,I)=T(16,I)
3470 IF (T8=5) THEN B(I)=T(9,I)
3480 IF (T8=5) THEN C(3,I)=T(15,I)
3490 IF (T8=6) THEN B(I)=T(6,I)
3500 IF (T8=6) THEN C(3,I)=T(12,I)
3510 IF (T8=7) THEN B(I)=T(10,I)
3520 IF (T8=7) THEN C(3,I)=T(16,I)
3530 IF (T8=8) THEN B(I)=T(8,I)
3540 IF (T8=8) THEN C(3,I)=T(14,I)
3550 IF (T8=9) THEN B(I)=T(5,I)
3560 IF (T8=9) THEN C(3,I)=T(11,I)
3570 IF (T8=10) THEN B(I)=T(7,I)
3580 IF (T8=10) THEN C(3,I)=T(13,I)
3590 NEXT I
```

```
3600 IF V9=1 THEN GOTO 3670
3610 PRINT #1
3620 PRINT #1 ,"C/R            .5(C/R)COSB   .5(C/R)SINB    B"
3630 PRINT #1
3640 FOR I=1 TO 20
3650 PRINT #1 ,C(3,I),0.5*C(3,I)*COS(B(I)/Z9),0.5*C(3,I)*SIN(B(I)/Z9),B(I)
3660 NEXT I
3670 GOSUB 8930
3680 REM---------- VELOCITY OF SOUND (IN FT/SEC) ----------
3690 C2=SQR(2403.0*T2)
3700 REM---------- VISCOSITY (LB*SEC/FT**2) ----------
3710 U2=(340.8+0.548*(T2-453.0))*(10**(-9))
3720 FOR I=1 TO 20
3730 REM ********** LOCAL VELOCITY, F/S ************************
3740 V(I)=SQR(V**2+(2*P3*K(I)*R6*N1)**2)
3750 REM---------- MACH NUMBER ----------
3760 M(I)=V(I)/C2
3770 REM---------- REYNOLDS NUMBER ----------
3780 R(I)=H*V(I)*C(3,I)*D/(2*U2)
3790 NEXT I
3800 IF V9=1 THEN GOTO 3870
3810 PRINT #1
3820 PRINT #1 ,"MACH NO         REYNOLDS NO"
3830 PRINT #1
3840 FOR I=1 TO 20
3850 PRINT #1 ,M(I),R(I)
3860 NEXT I

3870 REM--------SET 'ANALYTIC OUTPUT COMPLETE' FLAG TO 1 ----------------
3880 V9=1
3890 REM*********************************************************************
3900 REM*     CALCULATE EACH BLADE STATIONS LOCAL VELOCITY [EQN. 7]
3910 REM*********************************************************************
3920 REM
3930 FOR I=1 TO 20
3940 H(3,I)=(V**2+(P3*K(I)*D*N1)**2)**.5
3950 NEXT I
3960 REM*********************************************************************
3970 REM**                                                                 **
3980 REM**     ROUTE PROGRAM FLOW BASED ON BLOWN OR NON-BLOWN OPTION       **
3990 REM**      (BLOWN, V4=0; NON-BLOWN, V4=1)                             **
4000 REM**                                                                 **
4010 REM*********************************************************************
4020 REM********** SET THE JET VELOCITY AT THE TIP TO .95 MACH ***********
4030 REM********** IF BLOWN AND THE DESIGN POINT EVALUATION *************
4040 REM********** OTHERWISE, SHUT BLOWING OFF    ***********************
4050 REM
4060 IF (V4=0) AND (T8<5) THEN H(1,19)=.95*C2 ELSE H(1,19)=0.
4070 REM
4080 REM********** THE REQUIRED JET PRESSURE AT STATION 19 IS [EQN 2] ******
4090 REM
4100 H(2,19)=0.5*H*H(1,19)**2.+P2
4110 REM
```

```
4120 REM********** THE HUB PRESSURE TO GIVE THIS STATION 19 IS [EQN 6] *****
4130 REM
4140 U4=((P3*N1*K(19)*D)**2)/(3432*T2)
4150 U5=H(2,19)/EXP(U4)
4160 REM
4170 REM******************************************************************
4180 REM*           CALCULATE JET PRESSURE AT EACH BLADE STATION  [EQN. 6]
4190 REM******************************************************************
4200 REM
4210 FOR I=1 TO 19
4220 U4=((P3*N1*K(I)*D)**2)/(3432*T2)
4230 H(2,I)=U5*EXP(U4)
4240 REM
4250 REM******************************************************************
4260 REM*           CALCULATE JET VELOCITY AT EACH STATION ALSO  [EQN. 2]
4270 REM******************************************************************
4280 REM
4290 A5=(H(2,I)-P2)*2/H
4300 IF A5<=0 THEN A5=0.
4310 H(1,I)=A5**.5
4320 REM
4330 REM******************************************************************
4340 REM*                                                                *
4350 REM*       CALCULATE EACH BLADE STATIONS LOCAL VELOCITY [EQN. 7]    *
4360 REM*                                                                *
4370 REM******************************************************************
4380 H(3,I)=(V**2+(P3*K(I)*D*N1)**2)**.5
4390 V(I)=SQR(V**2+(2*P3*K(I)*R6*N1)**2)
4400 REM
4410 REM******************************************************************
4420 REM*     ... AND FINALLY, CALCULATE THE MOMENTUM COEFFICIENT
4430 REM*                      AT EACH BLADE STATION  [EQN. 1]
4440 REM******************************************************************
4450 REM
4460 REM
4470 U(1,I)=((H(1,I)/H(3,I))**2)/696.96
4480 REM******************************************************************
4490 REM*                            END OF LOOP
4500 REM
4510 NEXT I
4520 REM *****************************************************************
4530 REM *  RECALCULATE [EQN 7] FOR CORRECT LOCAL VELOCITY DURING THE      *
4540 REM *  THRUST MATCHING ITERATIVE PORTION OF THIS PROGRAM.             *
4550 REM *****************************************************************
4560 FOR I=1 TO 20
4570 H(3,I)=(V**2+(P3*K(I)*D*N1)**2)**.5
4580 V(I)=SQR(V**2+(2*P3*K(I)*R6*N1)**2)
4590 NEXT I
4600 REM*********************************************************************
4610 REM
4620 REM  MAKE INFLOW CORRECTIONS FOR ALPHA, PHI, & RECALCULATE CL, CD, & CD/CL
4630 REM
4640 REM*********************************************************************
4650 REM
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4660 REM
4670 REM        DEFINE PHI(I) AND OTHER QUANTITIES TO START ITERATION
4680 REM
4690 B2=V/(P3*N1*D)              ! LAMBDA
4700 FOR I=1 TO 20
4710 U(8,I)=ATN(B2/K(I))         ! PHI(I)  [EQN A1]
4720 A(1,I)=B(I)-U(8,I)*180./P3  ! CALCULATED ALPHA [EQN A2]
4730 T(4,I)=A(1,I)               ! ALPHA(I), CORRECTED
4740 NEXT I
4750 T(2,20)=0.                  ! a' AT EACH STATION
4760 T(3,20)=0.                  ! PHI, CORRECTED
4770 T(4,20)=U(8,20)             ! ALPHA, CORRECTED
4780 T(1,20)=0.                  ! a AT EACH STATION
4790 A(1,20)=0.                  ! ALPHA AT BLADE TIP
4800 REM
4810 REM        INITIALIZE ITERATIVE EQUATIONS
4820 REM
4830 V7=1
4835 REM ************** [EQN A3] **********************************
4840 FOR I=1 TO 19
4850 H(6,I)=SIN(U(8,I))
4860 H(7,I)=COS(U(8,I))
4870 V1=(((B/2)*(B2**2+1.)**.5)/B2)*(1.-K(I))
4880 U6=EXP(-V1)
4890 U9=ATN(SQR(1-U6**2)/U6)
4910 U(10,I)=B*C(3,I)/(8*P3*K(I))*1./(2/P3*U9)
4920 NEXT I
4930 V3=1
4940 IF V4=0 THEN GOSUB 9200 ELSE GOSUB 8410
4950 FOR5$="## ## ###.## ###.##  ###.##  ###.## #.###### #.######"
4960 REM ***********************************************************
4970 REM *    LIMIT ALPHA TO 17 DEG (NON-BLOWN) OR 14 DEG (BLOWN) *
4980 REM ***********************************************************
4990 FOR I=1 TO 19
5000 IF V4=0 THEN C9=14.0 ELSE C9=17.0
5010 IF I>19 THEN C9=17.0
5020 IF (V4=0) AND (I<20) THEN C1=1.4 ELSE C1=1.66
5030 IF A(1,I)>C9 THEN C8=C1 ELSE C8=C(1,I)
5040 REM *********** [EQN A4] & [EQN A5] *****************************
5050 V1=C8*H(7,I)/H(6,I)**2
5060 V2=C8/H(7,I)
5070 T(1,I)=(U(10,I)*V1)/(1.-U(10,I)*V1)
5080 T(2,I)=(U(10,I)*V2)/(1.+U(10,I)*V2)
5090 REM ************ [EQN A6] *****************************************
5100 T(3,I)=ATN((B2/K(I)*((1+T(1,I))/(1-T(2,I)))))
5110 REM ************ [EQN A7] *****************************************
5120 T(4,I)=A(1,I)+28.65*(U(8,I)-T(3,I))
5130 REM ************ IF REQUESTED, OUTPUT CRT DIAGONISTIC DATA ****
5139 IF W2<>1 THEN GOTO 5150
5140 IF I>1 THEN GOTO 5143
5141 PRINT
5142 PRINT "V4   I  AOA-I   AOA-C    PHI-I   PHI-C    C-MU      CHORD/RAD"
5143 PRINT USING FOR5$,V4,I,A(1,I),T(4,I),U(8,I)*Z9,(B(I)-T(4,I)),U(1,I),C(3,I)
5150 NEXT I
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5170 REM ***** DIAGONSTIC PRINTER OUTPUT ******
5180 IF V8<>1 THEN GOTO 5270
5190 PRINT #1%," I   AOAI    AOAC     PHII     PHIC     A(I)    A'(I)"
5200 FOR I=13 TO 15
5210 PRINT #1% USING '##  ##.###  ##.###   ##.###  ##.###  ##.###  ##.####',&
      I,A(1,I),T(4,I),U(8,I)*180/P3,T(3,I)*180/P3,T(1,I),T(2,I)
5220 NEXT I
5230 REM ***** END OF DIAGONISTIC OUTPUT AT THIS POINT *******
5240 REM
5250 REM        TEST ALPHA-ALPHAC FOR CONVERGENCE
5260 REM
5270 FOR I=1 TO 19
5280 REM ******** [EQN A9] ****************************************************
5290 IF ABS(A(1,I)-T(4,I))>0.5 THEN V7=0
5300 IF V8<>1 THEN GOTO 5330
5310 IF ABS(A(1,I)-T(4,I))>.5 THEN PRINT "I,A(1,I),T(4,I) = ";I, A(1,I),T(4,I)
5320 REM ********* [EQN A8] UPDATE CURRENT PHI AT EACH BLADE STATION *******
5330 U(8,I)=(B(I)-T(4,I))*P3/180.
5340 REM ********* UPDATE CURRENT ALPHA GUESS ******************************
5350 A(1,I)=T(4,I)
5360 NEXT I
5370 V3=1
5380 REM *********** GET NEW Cl & Cd VALUES FOR BLOWN OR NON-BLOWN PROPELLER***
5390 IF V4=0 THEN GOSUB 9200 ELSE GOSUB 8410
5400 IF V7=0 THEN GOTO 4830 ELSE GOTO 5430
5410 REM
5420 REM        END OF ITERATIVE SECTION.
5430 REM
5440 REM        CALCULATE DIFFERENTIAL THRUST AT EACH STATION, I, AND
5450 REM        DIFFERENTIAL TORQUE AT EACH STATION.....
5460 REM
5470 FOR I=1 TO 20
5480 H(6,I)=SIN(U(8,I))
5490 H(7,I)=COS(U(8,I))
5500 REM ************* [EQN 9] DIFFERENTIAL THRUST ******************************
5510 H(4,I)=0.5*H*V**2*((1+T(1,I))/H(6,I))**2*B*C(3,I)*D/2
5520 H(4,I)=H(4,I)*(C(1,I)*H(7,I)-C(2,I)*H(6,I))
5530 REM ************* [EQN 10] DIFFERENTIAL TORQUE ******************************
5540 H(5,I)=D*K(I)/4*H*V**2*((1+T(1,I))/H(6,I))**2*B*C(3,I)*D/2
5550 H(5,I)=H(5,I)*(C(1,I)*H(6,I)+C(2,I)*H(7,I))
5560 Z(I)=H(4,I)
5570 NEXT I
5580 REM
5590 REM        INTEGRATE DT/DR TO FIND TOTAL THRUST, T6
5600 REM
5610 GOSUB 8830
5620 T6=Z*D*0.5
5630 REM *********** TEST FOR CONVERGENCE OF ACTUAL THRUST TO REQUIRED THRUST **
5640 IF ABS(T-T6)<T/100. THEN A8=0 ELSE A8=1
5650 IF (T8>4) OR (A8=0) THEN GOTO 6520
5655 PRINT
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```
5660 REM ************************************************************************
5670 REM **                                                                    **
5680 REM **     SCALE ALPHA, BETA, OR MOMENTUM COEFFICIENTS DEPENDING          **
5690 REM **     ON CASE BEING RUN... THE CONTROL VARIABLES ARE AS FOLLOW:      **
5700 REM **     C5=1 (CASES 2,4-10, & BLOWN CASES)  DO NOT RESCALE CHORDS      **
5710 REM **     B7=1 (CASES 1-8)    DO NOT RESCALE BETA                        **
5720 REM **     C6=1 (CASES 1N,3N, 5-10) DO NOT RESCALE ALPHA                  **
5730 REM **     ALL QUANTITIES ARE RESCALED BY REQUIRED THRUST/AVAIL. THRUST**
5740 REM **                                                                    **
5750 REM ************************************************************************
5760 REM
5770 REM ***** PRINT DIAGONISTICS HERE IF V8=1 ****************
5780 IF V8<>1 THEN GOTO 5860
5790 PRINT #1%,"REQUIRED THRUST = ";T;" AVAILABLE THRUST = ";T6
5800 FOR I=13 TO 15
5810 IF C5<>1 THEN PRINT #1%, "ALPHA VALUES ARE ";I,A(1,I)
5820 IF B7<>1 THEN PRINT #1%, "BETA VALUES ARE ";I,B(I)
5830 REM
5840 NEXT I
5850 REM ********** END OF DIAGONISTIC OUTPUT AT THIS POINT *****
5860 IF B7=1 THEN 6030
5870 REM ************************************************************************
5880 REM *         RESCALE BETA TO MATCH AVAILABLE THRUST TO REQUIRED THRUST   *
5890 REM ************************************************************************
5900 A2=.005*(T-T6)
5910 PRINT"REQUIRED THRUST=";T;" AVAILABLE THRUST=";T6;"AUTODELTA BETA=";A2
5920 PRINT"TOTAL CHANGE IN BETA SO FAR THIS RUN IS ";A3
5930 PRINT"ENTER '0' IF OK, '1' TO ENTER MANUAL CHANGE IN BETA,"
5940 PRINT "OR '-1' TO FORCE END OF RUN...";
5950 INPUT A4
5960 IF A4=-1 THEN GOTO 6520
5970 IF A4=0 THEN GOTO 6000
5980 PRINT "ENTER NEW CHANGE IN BETA (DEGREES) ";
5990 INPUT A2
6000 A3=A3+A2
6010 PRINT "TOTAL CHANGE IN BETA NOW IS ";A3
6030 IF (C6=1) OR (V4=1 AND T8>0)  THEN GOTO 6200
6040 REM ************************************************************************
6050 REM *   RESCALE ALPHA TO MATCH AVAILABLE THRUST TO REQUIRED THRUST        *
6060 REM ************************************************************************
6070 A6=.035*(T-T6)
6080 PRINT"REQUIRED THRUST=";T;" AVAILABLE THRUST=";T6;"AUTODELTA ALPHA=";A6
6090 PRINT"TOTAL CHANGE IN ALPHA SO FAR THIS RUN IS ";A7
6100 PRINT"ENTER '0' IF OK, '1' TO ENTER MANUAL CHANGE IN ALPHA,"
6110 PRINT "OR '-1' TO FORCE END OF RUN...";
6120 INPUT A4
6130 IF A4=-1 THEN GOTO 6520
6140 IF A4=0 THEN GOTO 6170
6150 PRINT "ENTER NEW CHANGE IN ALPHA ";
6160 INPUT A6
6170 A7=A7+A6
6180 PRINT"TOTAL CHANGE IN 'ALPHA' IS NOW ";A7
6200 IF (T8<5) OR (T8>8) THEN GOTO 6390
```

```
6210 REM ***********************************************************************
6220 REM *  RESCALE ENGINE RPM TO MATCH AVAILABLE THRUST TO REQUIRED THRUST  *
6230 REM ***********************************************************************
6240 N2=0.015*(T6-T)
6250 PRINT"REQUIRED THRUST=";T;" AVAILABLE THRUST=";T6;" AUTODELTA SPEED=";N2
6260 PRINT "TOTAL CHANGE IN SPEED SO FAR THIS RUN IS ";N3
6270 PRINT "ENTER '0' IF OK, '1' TO ENTER MANUAL CHANGE IN SPEED,"
6280 PRINT "OR '-1' TO FORCE END OF RUN.... ";
6290 INPUT A4
6300 IF A4=-1 THEN GOTO 6520
6310 IF A4=0 THEN GOTO 6340
6320 PRINT "ENTER NEW CHANGE IN SPEED (RPS) ";
6330 INPUT N2
6340 N3=N3+N2
6350 PRINT "TOTAL CHANGE IN SPEED IS NOW ";N3
6360 N1=N1+N2
6370 GOSUB 9640
6380 PRINT "AVAILABLE HORSEPOWER IS ";T9
6390 FOR I=1 TO 20
6400 REM *********************************************************************
6410 REM *  RESCALE CHORDS TO OBTAIN REQUIRED THRUST                          *
6420 REM *********************************************************************
6422 IF B7<>1 THEN B(I)=B(I)+A2
6424 IF (C6<>1) AND (V4=0) THEN B(I)=B(I)+A6
6430 IF (C5<>1) AND (V4=1) THEN C(3,I)=T/T6*C(3,I)
6431 IF (C5<>1) AND (T8=0) THEN C(3,I)=T/T6*C(3,I)
6440 NEXT I
6450 REM *******************************************************************
6460 REM **                                                               **
6470 REM **     FOR SCALED VALUES, PROGRAM FLOW GOES TO INFLOW            **
6480 REM **     ITERATIONS                                                **
6490 REM **                                                               **
6500 REM *******************************************************************
6501 IF W2<>1 THEN GOTO 4560
6502 IF (C5<>1) AND (V4=1 OR T8=0) THEN PRINT"      CHORDS HAVE BEEN RESCALED"
6510 GOTO 4560
6520 REM
6530 REM        INTEGRATE DQ/DR TO FIND TOTAL TORQUE, Q6
6540 REM
6550 FOR I=1 TO 20
6560 Z(I)=H(5,I)
6570 NEXT I
6580 GOSUB 8830
6590 Q6=Z*D*0.5
6600 REM
6610 REM        SET BLOWING HP VALUES TO ZERO FOR NON-BLOWING CASE
6620 REM
6630 T0=0.
6640 T1=0.
6650 REM
6660 REM        SKIP BLOWING CALCULATIONS FOR NON-BLOWN CASE (V4=1)
6670 REM
6680 IF V4=1 THEN GOTO 7030
```

```
6690 REM
6700 REM          CALCULATE THE MASS FLOW PER FOOT (H(8,I)) AND THE
6710 REM          HORSEPOWER PER FOOT (H(9,I)) REQUIRED...
6720 REM
6730 FOR I=1 TO 20
6740 IF I>19 THEN GOTO 6820
6750 IF H(1,I)>0. THEN GOTO 6790
6760 H(8,I)=0
6770 GOTO 6810
6780 REM ************************ [EQN 11] *****************************
6790 H(8,I)=U(1,I)*C(3,I)*D/4*H*H(3,I)**2/H(1,I)
6800 REM ************************ [EQN 12] *****************************
6810 H(9,I)=H(8,I)*6006.*T2*((H(2,I)/U5)**.286-1)/550.
6820 IF I>19 THEN H(9,I)=0
6830 IF I>19 THEN H(8,I)=0.
6840 Z(I)=H(9,I)
6850 NEXT I
6860 REM
6870 REM          INTEGRATE HP REQUIRED/FOOT TO FIND TOTAL HP, T1
6880 REM
6890 GOSUB 8830
6900 T1=Z*B*D*.05
6910 REM
6920 REM          INTEGRATE MASS FLOW/FOOT TO FIND TOTAL MASS FLOW
6930 REM
6940 FOR I=1 TO 20
6950 Z(I)=H(8,1)
6960 NEXT I
6970 GOSUB 8830
6980 M0=Z*B*D*0.5
6990 REM ********************************************************************
7000 REM *        CALCULATE COMPRESSOR HP REQUIRED [EQN. 13]                *
7010 REM ********************************************************************
7020 T0=M0*6006./550.*T2*((U5/P2)**.286-1)
7030 REM ********************************************************************
7040 REM *        CALCULATE TOTAL USEFUL WORK [EQN. 15]                     *
7050 REM ********************************************************************
7060 T3=T6*V/550.
7070 REM ********************************************************************
7080 REM *        CONVERT AERODYNAMIC TORQUE TO HORSEPOWER [EQN. A10]       *
7090 REM *        AND THEN FIND THE TOTAL HORSEPOWER REQUIRED [EQN. 14]     *
7100 REM ********************************************************************
7110 T4=2.*P3*N1*Q6/550.
7120 T5=T0+T1+T4
7130 REM ********************************************************************
7140 REM *        CALCULATE EFFICIENCY [EQN. 16]                            *
7150 REM ********************************************************************
7160 B6=T3/T5
7170 REM ********************************************************************
7180 REM *        CALCULATE LOCAL MACH NUMBER [EQN. A11], REYNOLD'S NUMBER  *
7190 REM *        [EQN. A12], AND DRAG-TO-LIFT RATIO [EQN. A13]             *
7200 REM ********************************************************************
7210 FOR I=1 TO 20
7220 Q(0,I)=H(3,I)/C2
7230 R(I)=H*C(3,I)*D/2*H(3,I)/U2
```

```
7240 D(4,I)=C(2,I)/C(1,I)
7250 NEXT I
7260 REM **************** DETERMINE AVAILABLE HP AT THE CURRENT RPM **********
7270 GOSUB 9640
7300 REM **********************************************************************
7310 REM *     THE NEXT SECTION SAVES DATA FOR POST-PROCESS CROSS PLOTTING  *
7320 REM **********************************************************************
7330 IF (T8<5) OR (A4=-1) OR (A8=0) THEN GOTO 7580
7340 FOR1$="00 ## ###.## ###.## ###.## ###.## #####. ###.## ####.## ##.# ## "
7350 FTEM$="####.## ###.####"
7360 FOR1$=FOR1$+FTEM$
7370 FOR2$="01 ## ###.#### ###.#### ###.#### ###.### #.##### ####.##"
7380 FOR3$="02 ## #.## ###.#### ###.#### #####.## ####.### #.##### ##.### "
7390 FTEM$="#.##### ########."
7400 FOR3$=FOR3$+FTEM$
7410 FOR4$="03 ## ####.### #.####### ######.#"
7420 PRINT #2% USING FOR1$, T8,A3,A7,V,N1,H2/(3.048E-4),T2,P2,D,B,T6,B6
7430 PRINT #2% USING FOR2$,T8,T0,T1,T5,T9,U5/P2,T
7440 FOR I =1 TO 20
7450 PRINT #2% USING FOR3$,T8,K(I),C(1,I),C(2,I),1./D(4,I),A(1,I),&
       C(3,I),B(I),Q(0,I),R(I)
7460 NEXT I
7470 IF V4=1 THEN GOTO 7510
7480 FOR I = 1 TO 20
7490 PRINT #2% USING FOR4$,T8,H(1,I),U(1,I),H(2,I)
7500 NEXT I
7510 PRINT #2%, "99 99 9999.999 9.9999999 9999.999"
7520 GOTO 5780
7530 REM *****************************************************************
7540 REM **                                                             **
7550 REM **      FORMATTED LINE PRINTER OUTPUT FOR ALL CASES            **
7560 REM **                                                             **
7570 REM *****************************************************************
7580 A4=0
7590 PRINT #1, CHR$(12%)                     !FORM FEED
7600 PRINT #1,TAB(60%);"RESULTS FOR CASE #";T8
7610 IF V4=1 THEN GOTO 7640                  !NON-BLOWN CASE
7620 PRINT #1,TAB(35%);"PROPELLER CHARACTERISTICS";TAB(105%);&
       "JET CHARACTERISTICS"
7630 GOTO 7650
7640 PRINT #1,TAB(35%);"PROPELLER CHARACTERISTICS"
7650 PRINT #1
7660 PRINT #1," KSI    LIFT COEF  DRAG COEF  L/D RATIO    ALPHA    ";&
       "CHORD/RAD   TWIST     MACH NO.   REYNOLDS";
7670 IF V4=1 THEN 7690
7680 PRINT #1,TAB(101%);"JET VEL.   MOM. COEF  JET PRES.";
7690 PRINT #1
7700 FOR I=1 TO 20
7710 PRINT #1 USING ' #.##     ###.#####  #.######  ###.#####    ###.####',&
       K(I),C(1,I),C(2,I),1/D(4,I),A(1,I);
7720 PRINT #1 USING '  #.#######  ###.####   #.######  ########.#',&
       C(3,I),B(I),Q(0,I),R(I);
7730 IF V4=1 THEN 7750
```

```
7740 PRINT #1 USING '     ####.####  #.#######  ####.####',&
        H(1,I),U(1,I),H(2,I);
7750 PRINT #1
7760 NEXT I
7770 PRINT #1
7780 PRINT #1
7790 PRINT #1
7800 PRINT #1, TAB(37);"OPERATING CONDITIONS"
7810 PRINT #1
7820 A$='  VEL=###.# F/S   ENG SPD= ##.## RPS   '
7830 B$='ALT=######.## FEET    AIR DEN=#.###### SL/CU FT '
7840 C$='TEMP=####.## DEG-R    AMB PRES=####.# PSF'
7850 D$=A$+B$+C$
7860 PRINT #1
7870 PRINT #1 USING D$,V,N1,H2/(3.048E-4),H,T2,P2
7880 PRINT #1
7890 PRINT #1, TAB(40);"PROPELLER DATA"
7900 PRINT #1
7910 A$='  DIA=##.# FT  BLDS=##  TH=####.## LBS  '
7920 B$='EFF=#.####  LAM=##.###  RQD HP=####.## AVL HP=####.## '
7930 C$=A$+B$
7940 PRINT #1 USING C$,D,B,T6,B6,B2,T5,T9
7950 IF V4=1 THEN GOTO 8040
7960 PRINT #1
7970 PRINT #1
7980 PRINT #1, TAB(42);"COMPRESSOR"
7990 PRINT #1
8000 A$='  MASS FLOW=###.#### SL/SEC     COMP HP=###.####   '
8010 B$='COMPRESSOR RATIO=###.####'
8020 C$=A$+B$
8030 PRINT #1 USING C$,M0,T0,U5/P2
8040 PRINT #1
8050 REM ********************************************************************
8060 REM **                                                                **
8070 REM **      END OF OUTPUT FOR THE PRESENT CASE                        **
8080 REM **                                                                **
8090 REM **                                                                **
8100 REM ********************************************************************
8110 REM*************************************************************************
8120 REM **      SAVE BETA, B(I), AND FINAL CHORDS, C(3,I) FOR PROPELLERS      **
8130 REM**       A, A', B, C, C', AND D ACCORDING TO SCHEME IN NOTES...        **
8140 REM*************************************************************************
8150 IF T8>4 THEN GOTO 8280
8160 FOR I=1 TO 20
8170 IF (T8=1) AND (V4=1) THEN T(11,I)=C(3,I)
8180 IF (T8=1) AND (V4=0) THEN T(15,I)=C(3,I)
8190 IF (T8=1) AND (V4=0) THEN T(9,I)=B(I)
8200 IF (T8=2) THEN T(12,I)=C(3,I)
8210 IF (T8=2) THEN T(6,I)=B(I)
8220 IF (T8=3) AND (V4=1) THEN T(13,I)=C(3,I)
8230 IF (T8=3) AND (V4=0) THEN T(16,I)=C(3,I)
8240 IF (T8=3) AND (V4=0) THEN T(10,I)=B(I)
8250 IF (T8=4) THEN T(14,I)=C(3,I)
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```
8260 IF (T8=4) THEN T(8,I)=B(I)
8270 NEXT I
8280 IF (T7=0) OR (V4=0) THEN GOTO 8320
8290 V4=0
8300 GOTO 1790
8310 REM ***************** "EXAMINE NEXT CASE?" DECISION POINT ******************
8320 PRINT "ENTER OPTION NUMBER";TAB(30);"0 = STOP"
8330 PRINT TAB(30);"1 = RESTART PROGRAM "
8340 PRINT TAB(30);"CONTROL-C OR CONTROL-Y = EXIT TO MONITOR"
8350 PRINT "ENTER OPTION...";
8360 INPUT I8
8370 IF I8<=0 THEN STOP
8380 IF I8>3 THEN STOP
8390 GOTO 570
8400 STOP

8410 REM ******************************************************************
8420 REM **                                                             **
8430 REM **     CALCULATE LIFT, DRAG, AND DRAG/LIFT RATIO FOR THE NON-  **
8440 REM **     BLOWN PROPELLER                                         **
8450 REM **     INPUTS: V3=STARTING LOOP VALUE (FIRST BLADE STATION)    **
8460 REM **             T(4,I)=ALPHA'S                                  **
8470 REM **             A(2,I)=INTERVAL CONSTANTS                       **
8480 REM **             L(1,I)=LIFT CONSTANTS                           **
8490 REM **             D(3,I)=DRAG CONSTANTS                           **
8500 REM **     OUTPUTS:C(1,I)=LIFT COEFFICIENTS                        **
8510 REM **             C(2,I)=DRAG COEFFICIENTS                        **
8520 REM **            D(4,I)=DRAG/LIFT RATIO                           **
8530 REM **                                                             **
8540 REM ******************************************************************
8550 FOR I=V3 TO 20
8560 D(3,8)=SIN(T(4,I))
8570 D(3,9)=SIN(T(4,I))
8580 IF T(4,I)<=12 THEN F1=6 ELSE F1=7
8590 IF T(4,I)>17. THEN GOTO 8720
8600 REM
8610 REM        J= RANK INDEX FOR LIFT AND DRAG
8620 REM
8630 J=INT((T(4,I)+F1)/3)
8640 REM
8650 REM        A(3,I)=DELTA ALPHA
8660 REM
8670 K2=L(1,J+1)
8680 D3=A(2,J+1)-A(2,J)
8690 C(1,I)=L(1,J)+((K2-L(1,J))/D3)*(T(4,I)-A(2,J))
8700 C(2,I)=D(3,J)+((D(3,J+1)-D(3,J))/D3)*(T(4,I)-A(2,J))
8710 GOTO 8740
8720 C(1,I)=.001
8730 C(2,I)=SIN(T(4,I)/Z9)
8740 IF ABS(C(2,I))<0.0001 THEN C(2,I)=0.0001
8750 D(4,I)=C(2,I)/C(1,I)
8760 NEXT I
8770 RETURN
```

```
8780 REM ****************************************************
8790 REM **                                               **
8800 REM **      SIMPSON'S RULE INTEGRATION               **
8810 REM **                                               **
8820 REM ****************************************************
8830 Q=0
8840 FOR J=1 TO 10
8850 Q=Q+Z(1+2*(J-1))
8860 NEXT J
8870 R=0
8880 FOR J=1 TO 10
8890 R=R+Z(2*J)
8900 NEXT J
8910 Z=0.05*(4*Q+2*R)/3
8920 RETURN
```

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```
8930 REM ****************************************************
8940 REM **                                               **
8950 REM **     ATMOSPHERIC CHARACTERISTICS SUBROUTINE    **
8960 REM **                                               **
8970 REM ****************************************************
8980 IF H2<11 THEN 9070
8990 IF H2<20 THEN 9100
9000 IF H2<32 THEN 9130
9010 IF H2<47 THEN 9160
9020 REM***********************************************************
9030 REM          H  = DENSITY IN SLUGS/FT**3
9040 REM          P2 = AMBIENT PRESSURE IN LB/FT**2
9050 REM          T2 = AMBIENT TEMPERATURE IN DEGREES 'R'
9060 REM***********************************************************
9070 P2=2116.6792*(288.15/(288.15-6.5*H2))**(-5.255876)
9080 T2=(288.15-6.5*H2)*1.8
9090 GOTO 9180
9100 P2=472.78248*EXP(-0.157688*(H2-11))
9110 T2=389.97
9120 GOTO 9180
9130 P2=114.37003*(216.65/(216.65+(H2-20)))**34.163195
9140 T2=(216.65+(H2-20))*1.8
9150 GOTO 9180
9160 P2=18.132812*(228.65/(228.65+2.8*(H2-32)))**12.201141
9170 T2=(288.65+2.8*(H2-32))*1.8
9180 H=0.0005827*P2/T2
9190 RETURN

9200 REM **********************************************************
9210 REM **                                                     **
9220 REM **     BLOWN PROPELLER LINEARIZED LOOKUP SUBROUTINE    **
9230 REM **           * * * *  I N P U T S * * * *              **
9240 REM **     MOMENTUM COEFFICIENTS AT STATION I, U(1,I)      **
9250 REM **     BLADE ANGLE OF ATTACK AT STATION I, T(4,I)      **
9260 REM **                                                     **
9270 REM **  ************************************************** **
```

```
9280 REM **       LIFT COEFFICIENTS AT STATION I, C(1,I)          **
9290 REM **       DRAG COEFFICIENTS AT STATION I, C(2,I)          **
9300 REM **     DRAG/LIFT COEFFICIENTS AT STATION I, D(4,I)       **
9310 REM **                                                       **
9320 REM *********************************************************
9330 FOR I=1 TO 19
9340 GOSUB 9470
9350 IF (T(4,I)< -12.0)AND (W2=1) THEN PRINT "I,AOA,U0,U1=";I,T(4,I),U0,U1
9360 IF U0>=14.0 THEN GOTO 9400
9370 C(1,I)=J(U0,1)+J(U0,2)*U(1,I)+U1*(J(U0,3)+J(U0,4)*U(1,I))
9380 C(2,I)=J(U0,5)+J(U0,6)*U(1,I)+U1*(J(U0,7)+J(U0,8)*U(1,I))
9390 GOTO 9420
9400 C(1,I)=0
9410 C(2,I)=SIN(T(4,I)/Z9)
9420    IF ABS(C(1,I))< 0.001 THEN C(1,I)=0.001
9430    IF ABS(C(2,I))< 0.0001 THEN C(2,I)=0.0001
9440    D(4,I)=C(2,I)/C(1,I)
9450    NEXT I
9460 RETURN

9470 REM********************************************************
9480 REM**                                                    **
9490 REM**     SUBROUTINE TO CALCULATE LOOKUP TABLE INTERVAL  **
9500 REM**             RANK U0 AND AOA FRACTION U1            **
9510 REM**                                                    **
9520 REM********************************************************
9530 U0=T(4,I)-.0001
9540 IF U0 -12. THEN 9580
9550 IF U0>14.0 THEN 9620
9560 U0=INT((U0+12)/3.0)+1.0
9570 GOTO 9590
9580 U0=1
9590 U1=(T(4,I)-(3*U0-15))/3.0
9600 IF U0=9 THEN U1=U1*1.5
9610 GOTO 9630
9620 U1=0
9630 RETURN

9640 REM *********************************************************
9650 REM **                                                     **
9660 REM **     SUBROUTINE TO CALCULATE AVAILABLE HORSEPOWER    **
9670 REM **     AS A FUNCTION OF ENGINE RPM @ FULL THROTTLE     **
9680 REM **                                                     **
9690 REM *********************************************************
9700 T9=(-.1667)*N1**2+20.8332*N1-314.99
9710 RETURN
```

Symbol Cross Reference Table

The following table lists for each program symbol (variable name) the number (label) of every statement in which that symbol can be found. Symbols that end with the dollar sign ($) are string variables, and are used here to store formatting information for printer, terminal, or disk file output. All other symbols are used for numberic data, with no differentiation made for integer or floating-point data. The Class column contains only the letter 'I' or a blank; if an 'I' is present, the corresponding Symbol is an array variable, otherwise, it is a scalar variable.

The 'References' column lists the statement labels for those statements in which each symbol is found. The statement label is the integer portion of the Reference number; the fractional portion indicates which element of the statement contains the symbol, and is most often '.001' indicating the first part. The fractional portion will be other values when the symbol is found in the 'IF...THEN...ELSE...' type statement, with the occurrance found after 'THEN' or 'ELSE'. The pound sign (#) indicates the statement in which array variables are dimensioned.

Symbol	Class	References				
A	I	90.001#	1740.001	1800.001	1870.001	1880.001
		1890.001	1900.001	1910.001	1920.001	1930.001
		1940.001	2210.001	2490.001	3410.002	4720.001
		4730.001	4790.001	5030.001	5120.001	5143.001
		5210.001	5290.001	5310.001	5310.002	5350.001
		5810.002	7450.001	7710.001	8680.001	8690.001
		8700.001				
A$		7820.001	7850.001	7910.001	7930.001	8000.001
		8020.001				
A1		1700.001	1710.001	1740.001		
A2		5900.001	5910.001	5990.001	6000.001	6422.002
A3		590.001	5920.001	6000.001	6010.001	7420.001
A4		5950.001	5960.001	5970.001	6120.001	6130.001
		6140.001	6290.001	6300.001	6310.001	7330.001
		7580.001				
A5		4290.001	4300.001	4300.002	4310.001	
A6		6070.001	6080.001	6160.001	6170.001	6424.002
A7		600.001	6090.001	6170.001	6180.001	7420.001
A8		5640.002	5640.003	5650.001	7330.001	

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Symbol	Class	References				
B		730.001	1140.001	2370.001	2560.001	3390.002
		4870.001	4910.001	5510.001	5540.001	6900.001
		6980.001	7420.001	7940.001		
B	I	90.001#	3410.002	3430.002	3450.002	3470.002
		3490.002	3510.002	3530.002	3550.002	3570.002
		3650.001	4720.001	5143.001	5330.001	5820.002
		6422.002	6424.002	7450.001	7720.001	8190.002
		8210.002	8240.002	8260.002		
B$		7830.001	7850.001	7920.001	7930.001	8010.001
		8020.001				
B1		1240.001	2430.001	3000.001	3040.001	3100.001
		3120.001	3210.001			
B2		1260.001	2420.001	2560.001	2580.001	3390.002
		3410.002	4690.001	4710.001	4870.001	5100.001
		7940.001				
B3		1280.001	2440.001	3020.001	3040.001	3090.001
		3120.001				
B5		3040.001	3120.001	3190.001	3210.001	3250.001
B6		7160.001	7420.001	7940.001		
B7		760.001	1408.002	1408.003	5820.001	5860.001
		6422.001				
C	I	90.001#	2490.001	3390.002	3440.002	3460.002
		3480.002	3500.002	3520.002	3540.002	3560.002
		3580.002	3650.001	3780.001	4910.001	5030.003
		5143.001	5510.001	5520.001	5540.001	5550.001
		6430.002	6431.002	6790.001	7230.001	7240.001
		7450.001	7710.001	7720.001	8170.002	8180.002
		8200.002	8220.002	8230.002	8250.002	8690.001
		8700.001	8720.001	8730.001	8740.001	8740.002
		8750.001	9370.001	9380.001	9400.001	9410.001
		9420.001	9420.002	9430.001	9430.002	9440.001
C$		7840.001	7850.001	7930.001	7940.001	8020.001
		8030.001				
C1		1405.001	1406.001	1407.001	1408.001	1409.001
		5020.002	5020.003	5030.002		
C2		3690.001	3760.001	4060.002	7220.001	
C5		750.001	1407.002	1407.003	5810.001	6430.001
		6431.001	6502.001			
C6		770.001	1409.002	1409.003	6030.001	6424.001

Symbol	Class	References				
C7		780.001	1380.001	1390.001	1390.002	1400.001
		1400.002	1420.001	1430.001		
C8		5030.002	5030.003	5050.001	5060.001	
C9		5000.002	5000.003	5010.002	5030.001	
D		700.001	880.001	1220.001	1240.001	1260.001
		2330.001	2400.001	3210.001	3780.001	3940.001
		4140.001	4220.001	4380.001	4570.001	4690.001
		5510.001	5540.001	5620.001	6590.001	6790.001
		6900.001	6980.001	7230.001	7420.001	7940.001
D	I	90.001#	2080.001	2090.001	2100.001	2110.001
		2120.001	2130.001	2140.001	2490.001	2650.001
		2820.001	2890.001	7240.001	7450.001	7710.001
		8560.001	8570.001	8700.001	8750.001	9440.001
D$		7850.001	7870.001			
D3		8680.001	8690.001	8700.001		
E	I	70.001#	2560.001	2600.001		
F	I	70.001#	2610.001	2630.001		
F1		8580.002	8580.003	8630.001		
FOR1$		7340.001	7360.001	7420.001		
FOR2$		7370.001	7430.001			
FOR3$		7380.001	7400.001	7450.001		
FOR4$		7410.001	7490.001			
FOR5$		4950.001	5143.001			
FTEM$		7350.001	7360.001	7390.001	7400.001	
G	I	70.001#	2630.001	2650.001	2820.001	2890.001
		3390.002				
H	I	70.001#	3940.001	4060.002	4060.003	4100.001
		4150.001	4230.001	4290.001	4310.001	4380.001
		4470.001	4570.001	4850.001	4860.001	5050.001
		5060.001	5480.001	5490.001	5510.001	5520.001
		5540.001	5550.001	5560.001	6560.001	6750.001
		6760.001	6790.001	6810.001	6820.002	6830.002
		6840.001	6950.001	7220.001	7230.001	7490.001
		7740.001				

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Symbol	Class	References			
H	1240.001	1280.001	2350.001	3210.001	3780.001
	4100.001	4290.001	5510.001	5540.001	6790.001
	7230.001	7870.001	9180.001		
H2	720.001	940.001	1020.001	1030.001	2380.001
	7420.001	7870.001	8980.001	8990.001	9000.001
	9010.001	9070.001	9080.001	9100.001	9130.001
	9140.001	9160.001	9170.001		
I	260.001	280.001	300.001	510.001	530.001
	550.001	1290.001	1310.001	1320.001	1680.001
	1690.001	1730.001	1770.001	1790.001	1800.001
	1810.001	2200.001	2210.001	2220.001	2480.001
	2490.001	2500.001	2540.001	2560.001	2580.001
	2600.001	2610.001	2630.001	2650.001	2660.001
	2670.001	2680.001	2690.001	2730.001	2750.001
	2760.001	2800.001	2820.001	2830.001	2870.001
	2890.001	2900.001	3370.001	3390.002	3410.002
	3430.002	3440.002	3450.002	3460.002	3470.002
	3480.002	3490.002	3500.002	3510.002	3520.002
	3530.002	3540.002	3550.002	3560.002	3570.002
	3580.002	3590.001	3640.001	3650.001	3660.001
	3720.001	3740.001	3760.001	3780.001	3790.001
	3840.001	3850.001	3860.001	3930.001	3940.001
	3950.001	4210.001	4220.001	4230.001	4290.001
	4310.001	4380.001	4390.001	4470.001	4510.001
	4560.001	4570.001	4580.001	4590.001	4700.001
	4710.001	4720.001	4730.001	4740.001	4840.001
	4850.001	4860.001	4870.001	4910.001	4920.001
	4990.001	5010.001	5020.001	5030.001	5030.003
	5050.001	5060.001	5070.001	5080.001	5100.001
	5120.001	5140.001	5143.001	5150.001	5200.001
	5210.001	5220.001	5270.001	5290.001	5310.001
	5310.002	5330.001	5350.001	5360.001	5470.001
	5480.001	5490.001	5510.001	5520.001	5540.001
	5550.001	5560.001	5570.001	5800.001	5810.002
	5820.002	5840.001	6390.001	6422.002	6424.002
	6430.002	6431.002	6440.001	6550.001	6560.001
	6570.001	6730.001	6740.001	6750.001	6760.001
	6790.001	6810.001	6820.001	6820.002	6830.001
	6830.002	6840.001	6850.001	6940.001	6950.001
	6960.001	7210.001	7220.001	7230.001	7240.001
	7250.001	7440.001	7450.001	7460.001	7480.001
	7490.001	7500.001	7700.001	7710.001	7720.001
	7740.001	7760.001	8160.001	8170.002	8180.002
	8190.002	8200.002	8210.002	8220.002	8230.002
	8240.002	8250.002	8260.002	8270.001	8550.001
	8560.001	8570.001	8580.001	8590.001	8630.001
	8690.001	8700.001	8720.001	8730.001	8740.001
	8740.002	8750.001	8760.001	9330.001	9350.001
	9350.002	9370.001	9380.001	9400.001	9410.001
	9420.001	9420.002	9430.001	9430.002	9440.001
	9450.001	9530.001	9590.001		

Symbol	Class			References		
I8		8360.001	8370.001	8380.001		
J		270.001	280.001	290.001	520.001	530.001
		540.001	1730.001	1740.001	1750.001	1760.001
		1770.001	8630.001	8670.001	8680.001	8690.001
		8700.001	8840.001	8850.001	8860.001	8880.001
		8890.001	8900.001			
J	I	80.001#	280.001	9370.001	9380.001	
K		1720.001	1730.001			
K	I	80.001#	1310.001	2490.001	2560.001	2580.001
		2650.001	2820.001	2890.001	3410.002	3740.001
		3940.001	4140.001	4220.001	4380.001	4390.001
		4570.001	4580.001	4710.001	4870.001	4910.001
		5100.001	5540.001	7450.001	7710.001	
K2		8670.001	8690.001			
L	I	90.001#	1990.001	2000.001	2010.001	2020.001
		2030.001	2040.001	2050.001	2060.001	2070.001
		8670.001	8690.001			
M		2720.001	3000.001	3100.001		
M	I	80.001#	2650.001	2680.001	2750.001	3760.001
		3850.001				
MO		6980.001	7020.001	8030.001		
N		2790.001	3000.001	3100.001		
N1		690.001	850.001	1260.001	2320.001	2400.001
		3210.001	3230.001	3250.001	3740.001	3940.001
		4140.001	4220.001	4380.001	4390.001	4570.001
		4580.001	4690.001	6360.001	7110.001	7420.001
		7870.001	9700.001			
N2		6240.001	6250.001	6330.001	6340.001	6360.001
N3		610.001	6260.001	6340.001	6350.001	
O		2860.001	3020.001	3090.001		
P		2930.001	3020.001	3090.001		
P1		740.001	1170.001	1280.001	2390.001	3230.001
		3290.001				
P2		4100.001	4290.001	7020.001	7420.001	7430.001
		7870.001	8030.001	9070.001	9100.001	9130.001
		9160.001	9180.001			

Symbol	Class	References				
P3		990.001	1000.001	1240.001	1260.001	1280.001
		2610.001	3230.001	3250.001	3390.002	3740.001
		3940.001	4140.001	4220.001	4380.001	4390.001
		4570.001	4580.001	4690.001	4720.001	4910.001
		5210.001	5330.001	7110.001		
Q		8830.001	8850.001	8910.001		
Q	I	70.001#	530.001	680.001	690.001	700.001
		710.001	720.001	730.001	740.001	750.001
		760.001	770.001	780.001	1800.001	7220.001
		7450.001	7720.001			
Q6		3210.001	3230.001	3250.001	3280.001	6590.001
		7110.001				
R		8870.001	8890.001	8910.001		
R	I	70.001#	3780.001	3850.001	7230.001	7450.001
		7720.001				
R6		1220.001	1280.001	3740.001	4390.001	4580.001
T	I	70.001#	2210.001	3430.002	3440.002	3450.002
		3460.002	3470.002	3480.002	3490.002	3500.002
		3510.002	3520.002	3530.002	3540.002	3550.002
		3560.002	3570.002	3580.002	4730.001	4750.001
		4760.001	4770.001	4780.001	5070.001	5080.001
		5100.001	5120.001	5143.001	5210.001	5290.001
		5310.001	5310.002	5330.001	5350.001	5510.001
		5540.001	8170.002	8180.002	8190.002	8200.002
		8210.002	8220.002	8230.002	8240.002	8250.002
		8260.002	8560.001	8570.001	8580.001	8590.001
		8630.001	8690.001	8700.001	8730.001	9350.001
		9350.002	9410.001	9530.001	9590.001	
T		710.001	910.001	1240.001	2340.001	2940.001
		3250.001	3300.001	5640.001	5790.001	5900.001
		5910.001	6070.001	6080.001	6240.001	6250.001
		6430.002	6431.002	7430.001		
T0		6630.001	7020.001	7120.001	7430.001	8030.001
T1		6640.001	6900.001	7120.001	7430.001	
T2		3690.001	3710.001	4140.001	4220.001	6810.001
		7020.001	7420.001	7870.001	9080.001	9110.001
		9140.001	9170.001	9180.001		
T3		7060.001	7160.001			
T4		7110.001	7120.001			

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Symbol	Class	References				
T4		7110.001	7120.001			
T5		7120.001	7160.001	7430.001	7940.001	
T6		5620.001	5640.001	5790.001	5900.001	5910.001
		6070.001	6080.001	6240.001	6250.001	6430.002
		6431.002	7060.001	7420.001	7940.001	
T7		1430.002	1430.003	1590.001	8280.001	
T8		650.001	660.001	670.001	670.002	680.001
		690.001	700.001	710.001	720.001	730.001
		740.001	750.001	760.001	770.001	780.001
		790.001	1080.001	1340.001	1580.001	1800.001
		2300.001	3390.001	3410.001	3430.001	3440.001
		3450.001	3460.001	3470.001	3480.001	3490.001
		3500.001	3510.001	3520.001	3530.001	3540.001
		3550.001	3560.001	3570.001	3580.001	4060.001
		5650.001	6030.001	6200.001	6431.001	6502.001
		7330.001	7420.001	7430.001	7450.001	7490.001
		7600.001	8150.001	8170.001	8180.001	8190.001
		8200.001	8210.001	8220.001	8230.001	8240.001
		8250.001	8260.001			
T9		6380.001	7430.001	7940.001	9700.001	
U	I	80.001#	4470.001	4710.001	4720.001	4770.001
		4850.001	4860.001	4910.001	5070.001	5080.001
		5120.001	5143.001	5210.001	5330.001	5480.001
		5490.001	6790.001	7490.001	7740.001	9370.001
		9380.001				
U0		9350.002	9360.001	9370.001	9380.001	9530.001
		9540.001	9550.001	9560.001	9580.001	9590.001
		9600.001				
U1		9350.002	9370.001	9380.001	9590.001	9600.002
		9620.001				
U2		3710.001	3780.001	7230.001		
U4		4140.001	4150.001	4220.001	4230.001	
U5		4150.001	4230.001	6810.001	7020.001	7430.001
		8030.001				
U6		4880.001	4890.001			
U9		4890.001	4910.001			

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Symbol	Class	References				
V		680.001	820.001	1240.001	1260.001	1280.001
		2310.001	2400.001	3210.001	3250.001	3740.001
		3940.001	4380.001	4390.001	4570.001	4580.001
		4690.001	5510.001	5540.001	7060.001	7420.001
		7870.001				
V	I	90.001#	3740.001	3760.001	3780.001	4390.001
		4580.001				
V1		4870.001	4880.001	5050.001	5070.001	
V2		5060.001	5080.001			
V3		2230.001	4930.001	5370.001	8550.001	
V4		1420.002	1420.003	1440.001	1590.001	2190.001
		3430.001	3450.001	4060.001	4940.001	5000.001
		5020.001	5143.001	5390.001	6030.001	6424.001
		6430.001	6502.001	6680.001	7470.001	7610.001
		7670.001	7730.001	7950.001	8170.001	8180.001
		8190.001	8220.001	8230.001	8240.001	8280.001
		8290.001				
V7		4830.001	5290.002	5400.001		
V8		1500.001	1510.001	1510.002	1520.001	1520.002
		5180.001	5300.001	5780.001		
V9		570.001	1440.002	2250.001	3160.001	3260.001
		3600.001	3800.001	3880.001		
W2		1540.001	1550.001	1550.002	1560.001	1560.002
		5139.001	6501.001	9350.001		
X	I	70.001#	2580.001	2630.001	2650.001	2750.001
		2820.001	2890.001	3390.002		
Y		2600.001	2610.001			
Z	I	90.001#	2680.001	2750.001	2820.001	2890.001
		5560.001	6560.001	6840.001	6950.001	8850.001
		8890.001				
Z		2720.001	2790.001	2860.001	2930.001	5620.001
		6590.001	6900.001	6980.001	8910.001	
Z0		3000.001	3020.001	3090.001	3100.001	3180.001
		3390.002	3410.002			
Z9		1000.001	3410.002	3650.001	5143.001	8760.001
		9410.001				

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Detailed Program Description

This section describes in more detail the program operations, keyed to the line numbers given above. Generalized descriptions are provided where a combination of the previous description and the comments embeded in the listing appear adequate; for the less obvious functions, more detail is provided here. To facilitate the description, it will be assumed that the program is memory resident, ready for execution. Program flow for Case #1 will be examined to illustrate operation.

After the array declaration statements at line numbers 70 - 90, two output files are opened and margins are defined for each (lines 130 - 160). File "OUTPUT.DAT" is used for 132 column printer data, and "CRPLOT.DAT" is an 80 column file used for cross-plot data accumulation in the off-design point analysis.

DATA statements 170 - 250 contain the 9 X 8 coefficient matrix elements used in the blown propeller aerodynamic coefficient lookup table subroutine. The matrix itself, J(9,8), is filled during the execution of statements 260 - 300. The rows of J( ) represent angle of attack intervals of three degrees each. They start with the interval (-12,-9) degrees and end with the interval (12,14) degrees. The first four columns of J( ) represent linearized coefficients used in the lift coefficient equation and the second four columns represent the coefficients for the drag coefficient equation. The subroutines at 9200 - 9630 calculate the lift and drag coefficients as a function of angle of attack and momentum coefficient as

$$C_{\ell_\alpha} = J(*,1) + J(*,2)C_\mu + \left(J(*,3) + J(*,4)C_\mu\right)\left(\frac{\alpha - \alpha_\ell}{\alpha_u - \alpha_\ell}\right) \tag{A14}$$

$$C_{d_\alpha} = J(*,5) + J(*,6)C_\mu + \left(J(*,7) + J(*,8)C_\mu\right)\left(\frac{\alpha - \alpha_\ell}{\alpha_u - \alpha_\ell}\right) \tag{A15}$$

with C_μ = momentum coefficients,

α_ℓ = angle-of-attack interval lower limit

α_u = angle-of-attack interval upper limit

For $\alpha > 14$ degrees, $C_{\ell_\alpha} = 0.001$ and $C_{d_\alpha} = \sin\alpha$.

The DATA statements between lines 310 - 500 are used to define the programmed cases 1 - 10. Each case requires thirty-one data elements. The data defined here is read into a 10 X 31 array Q(10,0:30) with statements 510 - 550 in the order specified by the symbols list preceeding this program listing.

Program lines 560 - 610 reset certain flags and accumulators specified in the comment statements. Lines 620 - 640 starts user interaction by asking for either a predefined case (1 - 10) or a signal for manual input (0). If a non-zero case is entered, airspeed, engine RPM, etc. are loaded from the Q( ) matrix at lines 680 - 780; if a zero is entered, the program interactively obtains the required data at lines 800 - 950. For the example Case #1, lines 680 - 780 make V = 270, N1 = 41.6, D = 6, T = 324, H2 = 10000, B = 3, P1 = 0, C5 = 0, B7 = 1, C6 = 0, and C7 = 3. Between lines 950 - 1070, radian/degree conversion factors are defined and the atmospheric characteristics subroutine is invoked. Lines 1090 - 1200 interactivly query for additional case data; this information has already been supplied for the cases 1-10, so program flow jumps to line 1210 for the Case #1 example.

The section from line 1210 to line 1330 calcuates run data based on the specific case under analysis. Variable descriptions are given in the REMark statements and equation references are also provided there. As mentioned earlier, equation references enclosed with angle brackets < > are from Reference 4, while those enclosed with square brackets [ ] are from this report. Line 1340 branches around the case examination question at lines 1350 - 1400, and lines 1420 - 1440 set up the control variables V4, T7, and V9 according to which propellers are to be designed/evaluated. For Case #1, both non-blown and blown propellers will be designed (C7 = 3); in this situation, V4 = 1, T7 = 1, and V9 is left at its value of 0 defined at line 570. From the program variable list prior to the program itself, the control variables can be interpreted as (1) the current case is non-blown (V4 = 1), (2) both non-blown and blown propellers will be evaluated (T7 = 1), and (3) output from the Analytic design section has not been completed (V9 = 0). When both non-blown/blown analysis is conducted in a single Case, the non-blown evaluation is always done first.

Lines 1450 - 1570 inquire as to whether certain diagonistic output is to be included in the print file "OUTPUT.DAT", and whether during the induced velocity iterations (inflow calculations) certain data is to be routed to the user terminal (CRT). Responses to the two questions cause control variables V8 and W2 to be set to either a 1 (include output) or a 0 (no output). The selectable output can easily be located in the listing by first referring to the Symbol Cross-Reference Table just after the program listing. In this table the control variables V8 and W2 can be located, and all line numbers that include them can be found.

Lines 1580 and 1590 route program flow around interactive entry for blade angle of attack distribution (lines 1600 - 1780) if either a defined entry has been made, or if a manual entry non-blown/blown case is in progress and the first part (non-blown) has been completed (V4 = 0). For defined cases, lines 1790 - 1810 load the AOA distribution from the Q( ) matrix. Lines 1820 - 2140 set up the angle of attack intervals and the linearized coefficients for the lift and drag coefficient equations used in the non-blown propeller aerodynamic coefficient subroutine (located at lines 8410 - 8770). The equations realized in this subroutine are similar to those used in the blown propeller lookup table, and can readily be determined by inspection of the code.

At line 2190, program flow is diverted to line 2540 for the blown propeller examination. For the example Case #1, the non-blown propeller is first designed so flow continues to lines 2200 - 2240 where the non-blown propeller aerodynamic coefficients are obtained. Both analytic and strip integration design is effected for the non-blown propeller; if the analytic design has been completed (V9 = 1), line 2250 routes execution to line 2540 to avoid the first set of analytic printer output (lines 2270 - 2530). Between lines 2540 and 3120, the analytical design is made based on equations listed in the REMark statements. This design is carried out for both analytic and strip integration evaluation since some of the results obtained in the analytic calculations are used later by the strip integration section. Lines 3120 - 3300 send more analytic output to the printer; control statements at lines 3160 and 3260 route flow around PRINT statements if the analytic output is complete.

Lines 3370 - 3410 do the analytic chord and beta distribution calcuations for all cases 1, 2, 3, or 4. Lines 3430 - 3590 save or restore these chord and beta distributions for later case use. For the example Case #1, line 3430 saves the beta distributions in the 5th column of the T( ) array if the non-blown propeller is being analyzed (V4 = 1). For Case #2 (line 3440), the chord distributions used are obtained from the 15th column of the T( ) array, which was saved at line 8180 during a Case #1 blown propeller design run. The current scheme for saving and restoring data can be seen in the accompanying table; data is stored/read in the vicinity of lines 3430 - 3590 or 8160 - 8270. The rationale for this placement is that the 3400 locations occur before any strip integration calculations take place that are impacted by the chord or beta distributions, and that the 8100 locations occur after all strip integration calculations have taken place and the data can be used by later cases.

Case #	Blown ?	Action @3400's	Action @8100's
1	no	T(5,I)=Beta	T(11,I)=Chord
1	yes	none	T(15,I)=Chord, T(9,I)=Beta
2	yes	Chords=T(15,I)	T(12,I)=Chord, T(6,I)=Beta
3	no	T(7,I)=Beta	T(13,I)=Chord
3	yes	none	T(16,I)=Chord, T(10,I)=Beta
4	yes	Chords=T(16,I)	T(14,I)=Chord, T(8,I)=Beta
5	yes	Beta=T(9,I), Chords=T(15,I)	none
6	yes	Beta=T(6,I), Chords=T(12,I)	none
7	yes	Beta=T(10,I),Chords=T(16,I)	none
8	yes	Beta=T(8,I), Chords=T(14,I)	none
9	no	Beta=T(5,I), Chords=T(11,I)	none
10	no	Beta=T(7,I), Chords=T(13.I)	none

Lines 3600 - 3860 consists of the rest of the analytic calculations (described in the REMark statements) and the last of the analytic print statements. Control statements at 3600 and 3800 route flow around these output statements if the analytic output for this case has already been done. Statement 3880 sets the control variable V9 = 1 to indicate the analytic output has been completed for this example Case #1.

Lines 3890 - 5620 implement the strip integration equations contained in the main part of this report or (for the induced velocity iterations) in this appendix. Details found in the REMark statements should prove ample to follow the program flow through this section. Two areas will be expanded here for clarity. First, at line 4060 is the mechanism to have either a blown or a non-blown propeller. If the case identification is 1, 2, 3, or 4, and if the propeller under evaluation is blown (V4 = 0), then the jet velocity at the tip (station 19) is set to 95% of the speed of sound; otherwise, the jet velocity is set to 0 and the propeller is non-blown.

Secondly, if the propeller is blown, it is blown from root to tip (station 1 to station 19). If partial span blowing is desired, then coding changes in this section are necessary to (1) reduce the last blade station number at which blowing will occur, and (2) match the lift coefficient at the transition between the blown and non-blown blade sections. The following code replacement could be used as a basis for a partial span evaluation, with the inner 2/3 (root to station 14) blown, and the outer 1/3 (station 15 to 20) non-blown.

Replacement Code for Evaluation of Partial Span Blowing

```
3960 REM**********************************************************************
3970 REM**                                                                  **
3980 REM**     ROUTE PROGRAM FLOW BASED ON BLOWN OR NON-BLOWN OPTION        **
3990 REM**      (BLOWN, V4=0; NON-BLOWN, V4=1)                              **
4000    IF V4=1 THEN GO TO 4670
4010 REM**                                                                  **
4020 REM**********************************************************************

4030 REM********** DETERMINE MOMENTUM COEFFICIENTS AT STATION 14 ************
4040 REM**********    NECESSARY TO MATCH LIFT OF S/C AIRFOIL    ************
4050 REM
4060 I=14
4070 GOSUB 9470
4080 U3=(C(1,14)-U(U0,1)-U1*U(U0,3))/(U(U0,2)+U1*U(U0,4))
4090    REM
4100 REM********** U3 IS THE MOMENTUM COEFFICIENT AT STATION 14 ************
4110 REM
4120 REM********** NOW CALCULATE THE JET VELOCITY AT STATION 14 ************
4130 REM
4140 H(1,14)=V(14)*26.4*U3**.5
4150 REM
4160 REM********** THE REQUIRED JET PRESSURE AT STATION 14 IS   ************
4170 REM
4180 H(2,14)=0.5*H*H(1,14)**2.+P2
4190 REM
4200 REM********** THE HUB PRESSURE TO GIVE THIS STATION 14 IS  ************
4210 REM
4220 U4=((PI*N1*K(14)*D)**2)/(3432*T2)
4230 U5=H(2,14)/EXP(U4)
4240 REM
4250 REM********   IF REQUIRED HUB PRESSURE IS LESS THAN STATIC ************
4260 REM********         PRESSURE, USE STATIC PRESSURE AT HUB!   ************
4270 REM
4280 IF (U5<P2) AND (C6<>1)
     THEN PRINT "REQUIRED HUB PRESSURE IS LESS THAN STATIC FOR CASE #";T8
4290 IF (U5<=P2) AND (C6<>1) THEN N1=N1*(T/T6)**.5
4300 IF U5<P2 THEN U5=P2
4310 REM
4320 REM**********************************************************************
4330 REM*           CALCULATE JET PRESSURE AT EACH BLADE STATION [EQN. 6]
4340 REM**********************************************************************
4350 REM
4360 FOR I=1 TO 14
```

```
4370 U4=((PI*N1*K(I)*D)**2)/(3432*T2)
4380 H(2,I)=U5*EXP(U4)
4390 REM
4400 REM*********************************************************************
4410 REM*           CALCULATE JET VELOCITY AT EACH STATION ALSO  [EQN. 2]
4420 REM*********************************************************************
4430 REM
4440 H(1,I)=(((H(2,I)-P2)*2)/H)**.5
4450 REM
4460 REM*********************************************************************
4470 REM*                                                                   *
4480 REM*       CALCULATE EACH BLADE STATIONS LOCAL VELOCITY [EQN. 7]       *
4490 REM*                                                                   *
4496 REM*********************************************************************
4497 H(3,I)=(V**2+(PI*K(I)*D*N1)**2)**.5
4498 V(I)=SQR(V**2+(2*PI*K(I)*R6*N1)**2)
4499 REM
4500 REM*********************************************************************
4501 REM*     ... AND FINALLY, CALCULATE THE MOMENTUM COEFFICIENT
4502 REM*                     AT EACH BLADE STATION   [EQN. 1]
4503 REM*********************************************************************
4504 REM
4505 REM
4506 U(1,I)=((H(1,I)/H(3,I))**2)/696.2
4507 REM*********************************************************************
4508 REM*                            END OF LOOP
4509 REM
4510 NEXT I
```

Other changes may be required to the program depending on the method used to match developed thrust to required thrust. For example, if the momentum coefficients are scaled to achieve the required thrust, then program flow after jet adjustment must return to statement 4120 to recalculate the required hub pressure and other affected quantities. In addition, the blown propeller aerodynamic coefficient subroutine must be modified at line 9330 to account for the partial span blowing to station 14. Calls to the non-blown propeller aero coefficient routine must set V3 to station 15, the first non-blown location.

Lines 5630 - 6510 test the developed thrust against the required thrust, and if they do not match within 1% of the required thrust, some form of adjustment is implemented. The specific form of adjustment employed was discussed earlier, in the Case Table Identification of Table A1. For this program, Alpha, Beta, engine speed, or chord scaling is used to obtain the required values of thrust, with the specific parameter controlled by the values of B7, C5, C6, or Case #. For the non-blown propeller of example Case #1, the chords are scaled at line number 6430, because (1) B7 = 1 causes program flow to skip the Beta adjustment (line 5860), (2) V4 = 1 causes a skip of the Alpha adjustment (line 6030), (3) Case #1 (T8 = 1) causes a skip of the engine speed adjustment (line 6200), and (4) C5 <> 1 and Case # < 5 results in the execution of line 6430, which is the chord adjustment. Similar logic can be applied to verify the form employed by other cases. After any adjustment is made, program flow returns to line 4560 to recalculate the induced velocity component. This iterative process occurs until either a satisfactory thrust match has been obtained, or the user terminates the case evaluation.

Lines 6520 - 7290 calculate torque, air mass flow, compressor power requirements, etc. This section has ample comments to follow the operations with references as appropriate. Line 7270 calls a subroutine to determine the horsepower available at a specific engine speed and full throttle for a **Turbocharged engine of 520 in^3 displacement.**

Lines 7300 - 7520 output cross-plot data to the "CRPLOT.DAT" file for the off-design cases (5 - 10). Each time a thrust adjustment is made in the off-design runs, the cross-plot data file has data added to it. In this fashion, data is accumulated as a function of the parameter making the thrust adjustment. This data is then used to generate plots like Figure 4 in the main report. The variables seen in lines 7420, 7430, 7450, and 7490 are saved at each data point; the interpretation of these variables can be made by referring to the List of Symbols located just before the program listing. There are four record types output to this file; the record type identification is always the first two-digit number in each record. Valid record types are 00, 01, 02, 03, and 99. Record type 99 is a data point delimiter. Data analysis of the cross-plot file requires a knowledge of the output format; the easiest way to obtain that information is to run the program and then type (part of) the cross-plot file. When data is added to this file, no printer file output is generated. This action is controlled by the variable A4, as can be seen in lines 7330 and 7520.

Lines 7530 - 8100 output printer data for the strip integration equations. The printer file is currently set up for a 132 column printer and essentially all columns are required for the blown propeller output quantities. Fewer are needed for the non-blown propeller output, but an 80 column printer is still not adequate. Control variable V1 is used to select the correct output statements (non-blown/blown).

Lines 8110 - 8270 save final chord and beta values as was discussed earlier. Lines 8280 - 8300 control the program flow for the multiple evaluation cases, such as the example Case #1. This case first requires the analytic design of a non-blown propeller, followed by the strip integration design of the same non-blown propeller. After all output is complete (line 8100), and the chord values have been saved, statement 8290 sets control variable V4 (which was 1 for the non-blown propeller) to a 0 (for a blown propeller design). Control then returns to statement 1790 to design/evaluate the blown propeller. When execution returns to statement 8280, V4 = 0 causes the program flow to resume at line 8320.

Lines 8320 - 8400 execute at the end of each case evaluation and allow the user to run another case or to stop the program. If another case is selected, control returns to line 570; otherwise the program stops at line 8400.

Most of the subroutines found between lines 8410 and 9710 have already been discussed. The one exception to this is the Simpson's Rule numerical integration subroutine found at 8780 - 8920. This routine has the integrand passed to it in the Z( ) vector which has 20 elements. Lines 7480 to 7500 sum the odd numbered Z( ) elements into the temporary variable Q, that is

$$Q = Z(1)+Z(3)+Z(5)+Z(7)+Z(9)+Z(11)+Z(13)+Z(15)+Z(17)+Z(19)$$

and lines 7520 - 7540 sum the even numbered Z( ) elements into the temporary variable R, as

$$R = Z(2)+Z(4)+Z(6)+Z(8)+Z(10)+Z(12)+Z(14)+Z(16)+Z(18)+Z(20)$$

These quantities are then formed into the integral by application of

$$Z = 0.05\ (4Q + 2R)\ /\ 3 \quad \text{(where Z is a scalar)}$$

The integral is returned to the calling program in the scalar variable Z.

Suggestions for Tailoring the Program

To start a new effort using this program requires modification of two main program elements: (1) the airfoil and engine characteristics, and (2) the pre-defined case identification, and program logic flow. The case identification and program flow have been discussed earlier. The remaining changes are discussed here.

The main task in adapting this program to use some arbitrary airfoil shape and engine characteristic is to obtain the piecewise-linear coefficients used by the lookup table subroutines (Lines 8410 - 8770, 9200 - 9630, and 9640 - 9710). This data is obtained from airfoil lift/drag polars by first segmenting the lift/drag curve into three degree parts (for the current program), and then obtaining coefficients for the slope-intercept form of a straight line best representing the lift/drag curve over each angle of attack range. This data is then stored in the DATA statements (170 - 250) used to load the J( ) array for the blown propeller, or in statements 1990 - 2140 for the non-blown propeller. Engine characteristics are derived in a similar manner, and the slope-intercept data used in statement 9700 for the horsepower available subroutine.

The remaining comments are intended to assist in the conversion of this program to run on some other machine. Since it is impossible to consider all implementations of BASIC that might be encountered, the statements that appear to be non-standard are discussed. Establishing new cases for evaluation, modification of the thrust matching procedure to account for other parametric variation, reducing the blowing span, and changing the engine characteristics have all been discussed.

Lines 70 - 90 will cause problems with those versions of BASIC that do not allow multiply subscripted arrays. This poses a very difficult problem, and most likely, makes the program unusable. Fortunately, not many versions have such limitations. Lines 130 - 160 may cause problems in the form used to open files. A printer disk file as such may not be required; if not, then replace line 130 with the appropriate type. The MARGIN statement may not be allowed; delete it, or find a suitable replacement to tell the computer how wide the longest line will be in each file.

Line 620 prints the current date on the user's terminal; it can easily be removed if the function is not otherwise available. The majority of the program is "standard" BASIC, so the next possible problem area are in the output sections scattered throughout the program. To a large extent, the PRINT USING statement was utilized to more precisely control the output format. If the selected version of BASIC has a PRINT USING statement, it may not agree exactly with the one used in the current program, but only small changes should be required. If no PRINT USING is available, then all strip integration output will have to be redone to fit whatever PRINT statements are available. The format variable names used (e.g. FOR1$) may also be a problem; if so, change the names. String concatanation is used to achieve long format strings (longer than 30 characters) as can be seen in lines 7360 and 7400. If this cannot be accomplished in this manner, some other scheme must be devised.

It is likely that the program size will cause difficulties in transferring this program to another machine. Since the machine used for the current study compiled the BASIC source program to its own machine code, and used common memory resident run-time libraries, the actual number of bytes of memory required for interpretative machine execution is not known. Obvious techniques to reduce memory requirements include (1) removal of the REMark statements and the comments on each line, and (2) segmentation or chain operation of the program. In an interpretative BASIC computer, REMark statements require available user memory just as executable statements do, but they do not affect program results. If segmentation or chain operation is used, the program can be divided into parts in a fashion similar to the way the program was discussed in the General Description portion of this appendix.

Concluding Remarks

A comprehensive discussion of the propeller design program used in the current study has been given. This discussion first addressed the general characteristics of each major program section, and then described in detail the manner in which predefined cases were set up. A complete program variable list, with the engineering units used by the program (as appropriate), was given just prior to a complete program listing. A symbol table (program variable) cross-reference listing was then given to facilitate program understanding. A detailed program walk-through followed these listings, keyed to the program line numbers, and using an example case for clarity. The appendix ends with some comments on adapting the program to some arbitrary airfoil and engine characteristic and transferring the program to other machines.

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16. Abstract

This study evaluated the feasibility of replacing variable-pitch propeller mechanisms with circulation-control (Coanada effect) propellers on general aviation airplanes. The study used a specially-developed computer program written in BASIC which could compare the aerodynamic performance of circulation-control propellers with conventional propellers. The comparison of aerodynamic performance for circulation-control, fixed-pitch and variable-pitch propellers is based upon the requirements for a 1600 kg (3600 lb) single-engine general aviation aircraft. A circulation-control propeller using a supercritical airfoil was shown feasible over a representative range of design conditions. At a design condition for high speed cruise, all three types of propellers showed approximately the same performance. At low speed, the performance of the circulation-control propeller exceeded the performance for a fixed-pitch propeller but did not match the performance available from a variable-pitch propeller. It appears feasible to consider circulation-control propellers for single engine aircraft or multi-engine aircraft which have their propellers on a common axis (tractor-pusher). The economics of the replacement requires a study for each specific airplane application.

The computer program included as the appendix can be used for general purpose aerodynamic design and comparisons of performance. The calculations are based upon well-established aerodynamic relationships for propellers and will accomodate designs for fixed-pitch, variable-pitch and circulation-control configurations.

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