Enhanced Capabilities and Modified Users Manual for Axial-Flow Compressor Conceptual Design Code CSPAN

Arthur J. Glassman
University of Toledo
Toledo, Ohio

and

Thomas M. Lavelle
Lewis Research Center
Cleveland, Ohio

January 1995
SUMMARY

This report presents modifications made to the computer code CSPAN, which is a conceptual sizing analysis for axial-flow compressors. The CSPAN analysis uses a rapid approximate design methodology based on isentropic simple radial equilibrium to determine the flowpath either for a given number of stages or for a given overall pressure ratio. Calculations are performed at constant span-fraction locations from tip to hub. Stage energy addition is controlled by specifying the maximum allowable values for several aerodynamic design parameters.

Modifications were made to CSPAN to enhance code capabilities, upgrade loss modeling, and improve user convenience. Added to the code were endwall blockage and stall margin predictions. Endwall blockage is calculated using an annulus boundary-layer model. Stall margin is estimated by diffuser analogy. The pressure-loss coefficient model, which had been based on cascade data, was replaced by one that had been successfully tested against several multistage compressors.

Default correlations for rotor and stator solidities and aspect ratios and for stator-exit tangential velocity along with default values for the aerodynamic design limits have been added to the code as an aid for non-expert users in selecting reasonable values for these inputs. The solidity and aspect ratio correlations were based on values used for the design of five transonic core compressors. Aerodynamic design limits for rotor and stator diffusions, rotor hub turning, and stator-hub Mach number were based on design experience.

This report also serves as an updated users manual for the modified CSPAN code. Program input and output are described, and sample cases are included for illustration.

INTRODUCTION

Performing engine studies requires the capability to rapidly produce conceptual designs of the components in order to determine geometry, performance, and weight. The typical compressor "design" code enables a study of the interrelationship of the number of stages, the flowpath radii, the gas velocities, the flow angles, and the resultant variation of compressor efficiency. A computer code capable of performing this function in a rapid approximate manner was presented in reference 1. An updated version of this code (named CSPAN) with
numerous modeling improvements was presented in reference 2, and subsequent blade geometry modeling added to the code was reported in reference 3.

Additional capabilities were recently added to CSPAN. Presented in reference 4 are a method for the calculation of endwall blockage as well as correlations for determining the losses at minimum-loss incidence. Correlations for the calculation of maximum loading capability for a compressor are presented in reference 5. These methods, all based on meanline parameters and thus consistent with a rapid calculation procedure, were added to CSPAN. In addition, it became evident that non-expert users needed guidance in the specification of inputs. Therefore, default correlations were added for rotor and stator solidities and aspect ratios and for stator-exit tangential velocities, and upper limits were included as defaults for the input parameters reflecting aerodynamic design severity.

This report presents the analytical modeling associated with the new capabilities added to the CSPAN code. It also serves as an updated users manual for the code. Program input and output are described and sample cases are included for illustration.

SYMBOLS

A area, ft$^2$
A aspect ratio
B coefficient in tangential velocity equation (eq.(16)), (ft)(in.)/sec
C coefficient in tangential velocity equation (eq.(16)), ft/sec
C$_f$ friction coefficient
c chord, ft
d diffusion factor
D$_{eq}$ equivalent diffusion ratio
D coefficient in tangential velocity equation (eq.(16)), ft/(sec)(in.)
E coefficient in tangential velocity equation (eq.(16)), ft/(sec)(in.$^2$)
F axial blade-force defect, lbm/sec$^2$
g gravitational constant, 32.17 (lbm)(ft)/(lbf)(sec$^2$)
H form factor
h blade height, ft
$\Delta$h stage specific work, Btu/lbm
i stage number
J conversion constant, (ft)(lbf)/Btu
L$_i$ ideal pressure-rise coefficient
M Mach number
n number of stages
PR pressure ratio
p pressure, psi
R reaction
r radius, in.
U  blade speed, ft/sec
V  relative (for rotors) or absolute (for stators) velocity, ft/sec
β  relative (for rotors) or absolute (for stators) flow angle from axial direction, deg
δ  displacement thickness, ft
θ  momentum thickness, ft
ρ  density, lb/ft³
σ  solidity
φ_{eq} equivalent divergence angle, deg
ω  pressure loss coefficient

Subscripts:
ew  endwall
h  hub
i  stage number index
lf  lift forces
m  mean
max  maximum
mid  middle
p  profile
r  rotor
rel  relative
s  stator
sf  streamwise forces
sh  shock
st  stall
t  tip
tot  total
u  absolute tangential component
x  axial component
0  stagnation
1  rotor inlet or cascade inlet
2  rotor exit / stator inlet or cascade exit
3  stator exit

Superscript:
*  at peak efficiency

ANALYTICAL MODELING

The analytical models for the new/modified capabilities added to CSPAN are discussed in this section. These features are endwall blockage, stall margin, loss coefficients, and input defaults. Where the detailed methodologies can be referenced, only the key assumptions
and equations are presented here.

Endwall Blockage

The endwall blockage calculation uses the methodology of Wright and Miller (ref. 4), which is an application of the formulation of De Ruyck and Hirsch (ref. 6). This method is based on a 2D incompressible semi-empirical model for the growth of endwall boundary-layer momentum thickness across a blade row:

$$\theta_2 - \theta_1 = c_x C_f/(2 \cos \beta_m) - \theta_m(2+H_m)(V_{x,2}-V_{x,1})/V_{x,m} + F_{x,sf}/(p V_{x,m}^2) + F_{x,xf}/(p V_{x,m}^2)$$  \hspace{1cm} (1)

The first two terms on the right hand side of this equation are the skin friction and the axial-velocity ratio effects. The last two terms account for changes in the axial component of blade force through the endwall boundary layer due to dissipation forces along the streamlines and lift forces at right angles to the streamlines.

The empirical expressions required to evaluate the blade-force terms of equation (1) are presented in reference 4. To complete the system of equations, Greens entrainment equation (presented in ref. 4) for a simple power-law velocity profile is used.

$$V_{x,2}\theta_2 H_2/(H_2-1) - V_{x,1}\theta_1 H_1/(H_1-1) = 0.0153 c_x V_{x,m}[2H_m/(H_m-1)-3]^{0.653}$$  \hspace{1cm} (2)

Once the exit momentum thickness and the exit form factor are solved for, the exit displacement thickness is found as

$$\delta_2 = H_2 \theta_2$$  \hspace{1cm} (3)

The tip and hub blockage factor inputs are then calculated as

$$DTIP = 1 - \delta_l(2r_t-\delta_l)/(r_t^2-r_h^2)$$  \hspace{1cm} (4a)

and

$$DH = 1 - \delta_h(2r_h+\delta_h)/(r_t^2-r_h^2)$$  \hspace{1cm} (4b)

where (1-DTIP) and (1-DH) are the endwall-area blockages at the tip and hub, respectively.

The total endwall-area blockage (tip plus hub) calculated at stage exit for the five core compressors used as the performance database in reference 2 are plotted against stage number in figure 1. Unfortunately, there seems to be no readily available data against which to compare the predictions. The calculated values are reasonably consistent with general experience. The large blockage for the three-stage compressor reflects a very highly loaded design with turning of the flow back to axial direction in all stators. The large increase
(dashed line) in the last stage of one of the ten-stage compressors results from modeling limitations in CSPAN wherein one stator row is used to model two exit-stator rows in the actual compressor. If desired, this calculation can be bypassed in favor of using default or input blockages.

Stall Margin

A maximum loading prediction system for determining the design-speed stall margin of axial compressors was reported by Schweitzer and Garberoglio (ref. 5). The primary correlations are based on the analogy between a compressor cascade and a diffuser passage. Semi-empirical correlations are used to relate the cascade-derived maximum loading values to the real compressor environment.

Diffuser performance has been shown to depend on geometric parameters reflecting the amount of diffusion, as can be expressed by area ratio, and the rate of diffusion, as can be expressed by divergence angle. For incompressible flow, the area ratio alone sets the ideal loading

\[ L_i = \frac{\Delta p}{(p_{01}-p_1)} = 1 - \left(\frac{A_1}{A_2}\right)^2 \]  

(5)

which for a two-dimensional compressor cascade can be expressed

\[ L_i = 1 - \left(\frac{\cos \beta_1}{\cos \beta_2}\right)^2 \]  

(6)

An equivalent divergence angle for the same cascade can be expressed

\[ \tan \phi_{eq} = \left[\frac{N}{(\pi \sigma)^{1/2}}(\cos^{1/2}\beta_2 - \cos^{1/2}\beta_1)\right] \]  

(7)

Since any given area ratio for a compressor cascade can be attained by different combinations of inlet and exit angles as stagger is varied, blade row turning \((\beta_1-\beta_2)\) was included as an additional correlation parameter.

With the above three parameters as independent variables, cascade data were used to develop a correlation for determining maximum static pressure-rise coefficient

\[ \left[\frac{\Delta p}{(p_{01}-p_1)}\right]_{max} = f(L_i^{*}, \phi_{eq}, \Delta \beta) \]  

(8)

Corrections for several flow and geometry parameters (e.g., Reynolds number, endwall boundary-layer thickness, tip clearance, etc.) affecting pressure-rise capability must be made to obtain the individual blade-row coefficients. The maximum pressure-rise coefficient for each blade row is then used to calculate a relative loading parameter (ratio of actual to maximum pressure-rise coefficient) which is then averaged into a stall indicator for the whole compressor. Finally, a linear correlation of stall margin versus stall indicator, determined from data for numerous compressors, is used to predict the peak-efficiency stall margin. The
correlations and corrections are presented in detail in reference 5.

The stall margin predicted by this method is a constant-flow stall margin

\[ \text{SM} = \frac{(PR_{st} - PR^*)}{PR_{st}} \times 100 \]  

Table 1 presents a comparison between the stall margin predicted by CSPAN using these correlations and experimentally demonstrated values for the five core compressors and one fan used as the reference 2 database. It should be noted that there is a significant degree of uncertainty associated with the experimental values because (1) the compressors are not fully developed and (2) the near-vertical design-speed lines and the data scatter make it difficult to determine accurately the pressure ratio at peak efficiency. In fact, the pressure ratio at peak efficiency could not even be estimated for the five-stage compressor. The comparison, however, does indicate that this prediction calculation can be used as a qualitative measure of stall-margin adequacy.

**Loss Coefficients**

The existing cascade-based pressure-loss coefficient model (ref. 2) was replaced by a meanline model (ref. 4) that was developed and validated using compressor test results. This new model, which accounts for several dependencies (e.g., Mach no., Reynolds no., tip clearance, etc.) not found in the previous model, includes profile loss, endwall loss, and shock loss components.

The profile loss model has its basis in the same classical two-dimensional low-speed correlation method as previously used, but with modifications to account for compressibility and blade-thickness effects. Thickness-to-chord ratio was included by correlation into the definition of equivalent diffusion ratio (ratio of surface maximum velocity to inlet velocity). A second correlation then relates the classical loss parameter to the equivalent diffusion ratio and inlet Mach number.

\[ \frac{\theta_p}{c} = \omega_p \cos \beta_2 \left( \frac{V_1^2}{V_2^2} \right)/(2\sigma) = f(D_{eq}, M_1) \]  

Endwall loss effects have been treated in a similar manner by using the conservation of axial momentum to relate endwall boundary-layer momentum thickness to total-pressure loss. Based on experimental observations, the endwall loss parameter depended on tip clearance and loading, and a correlation of the form

\[ 2 \frac{\theta_{ew}}{c} = \omega_{ew}(h/c)\left( \frac{V_1^2}{V_2^2} \right) = f(D, \epsilon/c) \]  

was used. Both the profile and the endwall loss coefficients are corrected for Reynolds number.

The shock loss calculation methodology is the same as was used in reference 2 except
for the correction to the normal shock loss, which in reference 4 was taken as 0.65 of the normal shock loss rather than as the normal shock loss divided by the square of the average Mach number as used in reference 2. However, the shock loss calculation in reference 4 was extended into the region of subsonic inlet Mach number. A shock loss is taken if the peak Mach number on the suction surface exceeds 1.08. All correlations and methods necessary to determine the total blade-row pressure-loss coefficients

\[ \omega_{\text{tot}} = \omega_p + \omega_{\text{ew}} + \omega_{\text{sh}} \]  

are given in reference 4.

Efficiencies were calculated with this loss model and compared to efficiencies determined from experimental data for the five core compressors and one fan used as database in reference 2. As discussed therein, the experimental values presented for the design-point efficiencies were in some cases adjusted to account for the undeveloped state of these machines. Initial comparison of calculated and experimental efficiencies resulted in the use of a calibration coefficient to increase the profile and endwall losses by ten percent. This calibration amounts to about one point in efficiency. The comparison between calculated (after calibration) and experimental efficiencies is presented in table I. All calculated efficiencies match the experimental values to within one point, which is quite good.

Input Defaults

There are several geometric and aerodynamic inputs for CSPAN that require some user experience in compressor design/analysis to provide "reasonable" values. These include rotor and stator solidities and aspect ratios, stator-exit tangential velocities, and limiting values for rotor-tip and stator-hub diffusion factors, rotor-hub turning, and stator-inlet-hub Mach number. Default correlations/values based on the database compressors have been provided for these parameters and are presented in this section.

**Solidity.**- Within each of the compressors, there was a strong correlation between rotor-tip solidity and rotor-tip-inlet relative Mach number. The following linear equation was found to yield solidities generally within 10 percent of the actual solidities for all the stages of the database compressors.

\[ \sigma_{r,t} = 0.5 M_{t,1,\text{rel}} + 0.7 \] 

This equation should give reasonable estimates over the range of Mach numbers normally encountered in subsonic and transonic designs.

Stator-hub solidity showed a correlation with stator-hub turning, which is a measure of flow diffusion. Very limited data above 45 degrees of turning hints at an increased slope in this region, as is reflected in the following default correlation:
\Delta \beta_{s,h} \leq 44 \text{ deg}: \quad \sigma_{s,h} = 0.0206 \Delta \beta_{s,h} + 0.794 \quad (14a)

44 < \Delta \beta_{s,h} \leq 60 \text{ deg}: \quad \sigma_{s,h} = 0.080 \Delta \beta_{s,h} - 1.82 \quad (14b)

\Delta \beta_{s,h} > 60 \text{ deg}: \quad \sigma_{s,h} = 3.0 \quad (14c)

The stator-hub solidity is limited to a maximum value of 3, which corresponds to a turning of 60 degrees (well above conventional design practice).

**Aspect ratio.** Aspect ratio depends primarily on stage location and also on design practice (i.e., conventional versus low aspect ratio) for high loadings. A linear variation from inlet to exit was adopted. Default conventional aspect ratios for both rotors and stators were based on a value of 2.5 for the first stage and 1.0 for the last stage. Thus,

\[ A = 1.5(n - i)/(n - 1) + 1.0 \quad (15a) \]

for conventional aspect-ratio blading. Low aspect-ratio blading is based on 1.5 for the first stage and 1.0 for the last stage; thus,

\[ A = 0.5(n - i)/(n - 1) + 1.0 \quad (15b) \]

**Stator-exit tangential velocity.** The value of stator-exit tangential velocity and its variation with radius is specified for each stator by

\[ V_{u,3} = B/r + C + Dr + Er^2 \quad (16) \]

where B, C, D, and E are inputs. Setting C=D=E=0.0 yields a free-vortex distribution of tangential velocity, which should suffice for conceptual design studies.

The tangential velocity of the flow leaving a stator is equal to that entering the following rotor and, thus, defines the reaction of that following stage. Combining the definition of reaction (eqn. (2-39) of ref. 7), the Euler work equation (eqn. (2-14) of ref. 7), and the tangential-component vector relationship (eqn. (2-6) of ref. 7) and assuming constant blade speed and axial velocity across the stage along with equal stage work yields an equation for stator-exit tangential velocity as a function of the reaction of the next stage:

\[ V_{u,3,i-1} = (1-R_i)U_i - gJ\Delta h_i/(2nU_i) \quad (17) \]

Applying equation (17) to the tip section, where blade speeds are known from input, assuming a polytropic efficiency of 0.9 to estimate overall specific work from the input pressure ratio, and specifying reaction, either from an input or default parameter, allows the stator-exit tangential velocity for the previous stage to be estimated. With the assumption of free-vortex flow in equation (16), the input variable defining stator-exit tangential velocity can then be found from:
A methodology to determine the stage-exit tangential velocity for all the stages was adopted wherein reaction would decrease from the first stage to a mid stage and then increase from there to the last stage. For the first stage, the rotor-inlet tangential velocity, for free-vortex flow, is defined by the input variable B1. A value for B1 can be input directly or, as newly added to the program, determined from an input or default (10 deg.) value for first-stage-rotor tip inlet absolute angle.

\[ B3(i) = r_{t,3,i}V_{u,t,3,i} \quad (18) \]

The axial velocity is determined by continuity.

The mid stage, for which a tip reaction is specified by input or default (0.6), is defined for an even number of stages as

\[ i_{\text{mid}} = \frac{n}{2} + 1 \quad (20a) \]

and for an odd number of stages as

\[ i_{\text{mid}} = \frac{n+1}{2} \quad (20b) \]

The value of \( B3(i_{\text{mid}}-1) \) is then determined from equations (17) and (18) using the specified tip reaction. Because of the assumptions associated with equation (17), the reaction for stage \( i_{\text{mid}} \) will only approximate the specified value.

Finally, \( B3(n-1) \) is taken as half of \( B3(i_{\text{mid}}-1) \), and \( B3(n) \) is set to zero. The \( B3 \) values for the remaining stages are found by linear interpolation between \( B1 \) and \( B3(i_{\text{mid}}-1) \) for the front half of the compressor and linear interpolation between \( B3(i_{\text{mid}}-1) \) and \( B3(n-1) \) for the rear of the compressor. This default distribution for \( B3 \) is used only in the absence of input values.

**Aerodynamic design limits.** The design calculation is executed with maximum allowable values for rotor-tip and stator-hub diffusion factors, rotor-hub turning, and stator-inlet-hub Mach number for each stage. Default values assigned to these design limits are:
- rotor-tip diffusion factor: 0.5
- stator-hub diffusion factor: 0.6
- rotor-hub turning: 40 deg.
- stator-inlet-hub Mach number: 0.85

These values, which may be overridden by input, reflect current technology limits for good performance.
DESCRIPTION OF INPUT AND OUTPUT

This section presents a complete description of the input and the output for the updated CSPAN program. Included with the input and output are sample cases for a five-stage transonic compressor.

Input

The input, which is read on unit 05, consists of a title line and one NAMELIST dataset. Input for the sample case is presented in table I1. The title, which is printed as a heading on the output file, can contain up to 71 characters located anywhere in columns 2 through 72 on the title line. A title, even if it is left blank, must be the first record of the input data.

The physical data and option switches are input in data sets having the NAMELIST name NAME. The variables that compose NAME are defined herein along with units and default values. They are presented in order as general inputs, inlet inputs, rotor inputs, and stator inputs.

General:

MW molecular weight of working fluid, lb/(lb mol) (default=28.97)
GAM specific heat ratio (default=1.4)
RCLIM limit value for overall pressure ratio
NSLIM limit value for number of stages
N number of calculation locations from tip to hub
ICV pressure ratio convergence switch (default=1)
   0 - accepts overall pressure ratio equal to or greater than RCLIM as a solution
   1 - converges to overall pressure ratio RCLIM
IPR1 debug output switch (default=0)
   0 - no debug output
   1 - minimum debug output
   2 - extensive debug output
IPR2 radial location output switch (default=0)
   0 - output printed for all radial calculation locations
   1 - output printed for tip and hub only
WK loss multiplier, increases total loss for polytropic efficiency correlation and profile/endwall losses for pressure-loss coefficient correlation (default=1.0)

IIT technology-level indicator for polytropic efficiency (default=1)
1 - current technology, equations (8) and (9) of ref. 2
2 - advanced technology, equations (10) and (11) of ref. 2

IPATH flowpath slope switch (default=0)
0 - flowpath slope is average of previous and next blade-row slopes
1 - flowpath slope equals zero

CSTAL stall margin coefficient, larger value reduces stall margin (default=1.0)

VIS gas viscosity, lbm/(sec)(ft) (default=-1.)
<0.0 - internal computation of viscosity for air
>0.0 - value of viscosity

IBLOCK endwall blockage calculation switch (default=0)
0 - blockage is calculated
1 - default or input blockages are used

Inlet:

TTI inlet total temperature, °R

PTI inlet total pressure, psi

RTIP11 tip radius at first-rotor inlet, in.

UTIP11 blade speed at first-rotor inlet tip, ft/sec

RHORT1 hub/tip radius ratio at first-rotor inlet

VZTIPO inlet axial velocity or mass flow
>0 - VZTIPO is the axial velocity at the first-rotor inlet tip, ft/sec
<0 - IVZTIPOI is the mass flow rate, lb/sec

DTIP1 tip blockage factor at first rotor inlet (default=0.99)

DH1 hub blockage factor at first-rotor inlet (default=0.99)
DPPIGV  inlet guide vane total-pressure loss fraction (default=0.0 if B1 is input, 
default=0.005 if B1 is omitted and BETA1T>0.0 and DPPIGV=0.0 or omitted)

BETA1T  absolute flow angle at first-rotor inlet tip; BETA1T is used only if B1 is 
         omitted, deg (default=10.0)

B1      coefficient B for equation (16) at first-rotor inlet, omit to use BETA1T to define 
       B1 per equation (19), (ft)(in.)/sec

C1      coefficient C for equation (16) at first-rotor inlet, ft/sec (default=0.0)

D1      coefficient D for equation (16) at first-rotor inlet, ft/(sec)(in.) (default=0.0)

E1      coefficient E for equation (16) at first-rotor inlet, ft/(sec)(in.²) (default=0.0)

Rotor:  Each subscripted variable requires NSLIM values.

RT2OT1(I)  ratio of exit-tip radius to inlet-tip radius for each rotor (default=NSLIM * 1.0)

VT2OT1(I)  ratio of exit-tip meridional velocity to inlet-tip meridional velocity for each rotor 
           (default=NSLIM * 1.0)

NPR1(I)    efficiency specifier for each rotor 
           > 0.0 - input value is rotor polytropic efficiency 
           = 0.0 - polytropic efficiency correlation is used 
           =-1.0 - pressure-loss coefficient correlation is used

SRTIP(I)   rotor-tip solidity (default=-1.)
           > 0.0 - input value is rotor tip solidity 
           =-1.0 - default correlation (eqn. (13)) is used

ARO(I)     rotor aspect ratio, based on actual chord (default=-1.)
           > 0.0 - input value is rotor aspect ratio 
           =-1.0 - conventional aspect-ratio correlation (eqn. (15a)) is used 
           =-2.0 - low aspect-ratio correlation (eqn. (15b)) is used

DTIP2(I)   tip blockage factor at rotor exit (default=.99,.985,.98,.975,.97,.965,.96,.955,.95 ...
           .95)

DH2(I)     hub blockage factor at rotor exit (default=.99,.985,.98,.975,.97,.965,.96,.955,.95 ...
           .95)

ARHD(I)    rotor-hub ramp angle limit, deg (default=NSLIM * 40.0)
ARTD(I)  rotor-tip ramp angle limit, deg (default=NSLIM * -20.0)

DRT(I)  rotor-tip diffusion factor maximum allowable value (default=NSLIM * 0.5)
   > 0.0 - DRT is used to compute coefficient B (eqn. (16)) at rotor exit
   = 0.0 - BO is used as coefficient B (eqn. (16)) at rotor exit

BO(I)  coefficient B for equation (16) at rotor exit, required only if DRT(I)=0.0,
       (ft)(in.)/sec

C2(I)  coefficient C for equation (16) at rotor exit, ft/sec (default=NSLIM * 0.0)

D2(I)  coefficient D for equation (16) at rotor exit, ft/(sec)(in.) (default=NSLIM * 0.0)

E2(I)  coefficient E for equation (16) at rotor exit, ft/(sec)(in.²) (default=NSLIM * 0.0)

BPSD(I) maximum allowable value for rotor-hub turning, deg (default=NSLIM * 40.)

TCR  rotor maximum thickness to chord ratio (default=0.06)

EHR  rotor tip-clearance to blade-height ratio (default=0.01)

Stator: Each subscripted variable requires NSLIM values.

RT3OT2(I)  ratio of exit-tip radius to inlet-tip radius for each stator (default=NSLIM * 1.0)

VT3OT2(I)  ratio of exit-tip meridional velocity to inlet-tip meridional velocity for each stator
           (default=NSLIM * 1.0)

NPSI(I)  efficiency specifier for each stage
   > 0.0 - input value is stage polytropic efficiency
   = 0.0 - polytropic efficiency correlation is used
   =-1.0 - pressure-loss coefficient correlation is used for stator

SSH(I)  stator-hub solidity (default=-1.)
   > 0.0 - input value is stator hub solidity
   =-1.0 - default correlation (eqns. (14)) are used

ASO(I)  stator aspect ratio, based on actual chord (default=-1.0)
   > 0.0 - input value is stator-hub solidity
   =-1.0 - conventional aspect-ratio correlation (eqn. (15a)) is used
   =-2.0 - low aspect-ratio correlation (eqn. (15b)) is used
DTIP3(I)  tip blockage factor at stator exit (default=.985,.98,.975,.97,.965,.96,.955,.95 ... .95)
DH3(I)  hub blockage factor at stator exit (default=.985,.98,.975,.97,.965,.96,.955,.95 ... .95)
ASHD(I)  stator-hub ramp angle limit, deg (default=NSLIM * 40.0)
ASTD(I)  stator-tip ramp angle limit, deg (default=NSLIM * -20.0)
DSH(I)  maximum allowable value for stator-hub diffusion factor (default=NSLIM * 0.6)
MSH(I)  maximum allowable value for stator-inlet-hub Mach no. (default=NSLIM * 0.85)
B3(I)  coefficient B for equation (16) at stator exit, omit to use a default B3 distribution based on mid-stage reaction (REACT), (ft)(in.)/sec
C3(I)  coefficient C for equation (16) at stator exit, ft/sec (default=NSLIM * 0.0)
D3(I)  coefficient D for equation (16) at stator exit, ft/(sec)(in.) (default=NSLIM * 0.0)
E3(I)  coefficient E for equation (16) at stator exit, ft/(sec)(in.²) (default=NSLIM * 0.0)
REACT  tip reaction used to compute B3 for the middle stage (eqns. (17) and (18)), REACT is used only if B3(1) is omitted (default=0.6)
TCS  stator maximum thickness to chord ratio (default=0.06)
EHS  stator tip-clearance to blade-height ratio (default=0.0)

The sample input file shown in table II contains two cases for a five-stage transonic compressor. Each case begins with a title card. The first case makes use of all the default values and, thus, requires a minimum of additional input. The second case uses input values consistent with those for the actual compressor.

Output

Program output consists of a main output file written to unit 06 and, where convergence to the given overall pressure ratio is specified, a brief convergence file written to unit 08, which is directed to the terminal. The main output presents either the results of a completed design calculation or an error message indicating the nature of the failure.

Outputs corresponding to the sample input of table II are presented in tables III and IV. The pressure-ratio convergence output, shown in table III, is sent to the terminal so that a convergence problem or a failure to meet design requirements can be immediately detected.
Convergence problems are rare, but unsatisfactory or unexpected design solutions can occur in any preliminary study. As seen from table III, the first case could not produce the desired compressor pressure ratio (CPR) of 5 in five stages within the prescribed constraints. A pressure ratio of only 4.74 was obtained due to the stator-inlet-hub Mach number limit constraining the stage energy addition in the first four stages.

For the second case, it can be seen from table III that convergence to a compressor pressure ratio of 5 was achieved in four iterations. Shown in the output are the number of stages followed by one line for each iteration displaying the rotor-tip diffusion reduction factor (DRTK), the compressor pressure ratio (CPR), and the compressor adiabatic efficiency (EFF). The velocity diagram specified for this case had a reduced stator-inlet Mach number and, thus, enabled an increase in stage energy addition without exceeding the prescribed stator Mach number limit.

The main output is presented in table IV. For brevity in displaying the output, calculations were performed at only three radial locations (N=3), and only stages 1 and 5 of the second case are included along with the overall and inlet information. The first line of output in table IV is the title; it is followed by identification of the loss model used for this case. Then, the general inputs and the inlet inputs are printed. The values displayed are clearly identified.

The next output line in table IV states that one of the aerodynamic limits, in this case the stator hub Mach number, was exceeded in the next stage, which in this case is the first stage. As a result, the rotor-tip diffusion factor was reduced from its maximum allowable value until the Mach number limit was just satisfied. The consequence of this, as indicated above, is a reduction in stage pressure ratio.

The next block of output in table IV is the data for stage 1. This includes the rotor input, the stator input, the cumulative and stage performance, the stage flowpath geometry, the detailed aerodynamic results at the rotor inlet, the rotor exit, and the stator exit, and finally the blading geometry. Note that the rotor and stator input sections include the rotor and stage polytropic efficiencies, respectively, which were determined in this case from the internal loss-coefficient correlation. These input sections also include solidities, aspect ratios, and blockage factors, all of which may be either input or determined internally from correlations.

Under stage output data are the overall (i.e., cumulative) values of pressure ratio, temperature ratio, and adiabatic efficiency followed by the stage values, which are here the same since this is the first stage. Also displayed under this heading are the rotor and stator tip and hub radii, the axial lengths, and the tip and hub ramp angles. At each of the three axial stations for the stage (i.e., rotor inlet, rotor exit, and stator exit) are presented among other parameters, the temperatures and pressures, the absolute and relative velocities, the absolute and relative flow angles, the diffusion factors, and the loss coefficients at each of the radial calculation locations.

Finally, the rotor and stator blading geometries are presented for each of the radial sections. Included are numbers of blades, chord lengths, aspect ratios, solidities, camber angles, incidence and deviation angles, and blading angles.
The stage data format is identical for each stage; therefore, the "STAGE DATA" output for stages 2, 3, and 4 were omitted from table IV. Shown next is the data for stage 5. The "STAGE OUTPUT DATA" show that the overall pressure ratio of 5 has been achieved with an overall efficiency of 0.867. For this constant-tip-radius (10 in.) design, the hub radius increased from 5.0 in. at the first-rotor inlet to 8.33 in. at the last-stator exit. For the last stage, the computed stall margin is displayed after the blading geometry data. The last line of output states that the specified overall pressure ratio has been achieved. If the specified pressure ratio had not been achieved, the last-line message would be that the maximum number of stages had been reached.

SUMMARY OF RESULTS

This report presents modifications made to the computer code CSPAN, which is a conceptual sizing analysis for axial-flow compressors. The CSPAN analysis uses a rapid approximate design methodology based on isentropic simple radial equilibrium to determine the flowpath either for a given number of stages or for a given overall pressure ratio. Calculations are performed at constant span-fraction locations from tip to hub. Stage energy addition is controlled by specifying the maximum allowable values for several aerodynamic parameters.

Modifications made to CSPAN and reported herein resulted in additional capabilities, improved modeling, and user convenience. Specifically:

1. An endwall blockage calculation was added. This was based on a semi-empirical model for the growth of endwall boundary-layer momentum thickness across a blade row. Predictions for five core compressors yield results that appear to be reasonable, but there is no readily available data against which to compare the computed results.

2. Stall margin prediction was incorporated into the analysis using diffuser analogy. A cascade-based correlation for maximum static pressure-rise coefficient as a function of area ratio, divergence angle, and turning provides the basis for estimation. Comparison with several experimentally demonstrated values confirmed the adequacy of the prediction as a qualitative measure of stall margin capability.

3. The cascade-based pressure-loss coefficient model was replaced by a model that had been developed and validated using compressor test results. The new model, which accounts for several dependencies not found in the previous model, includes profile loss, endwall loss, and shock loss correlations. Efficiencies calculated for five compressors and one fan all matched experimentally-based values to within one point.

4. Default correlations for rotor and stator solidities and aspect ratios and for stator-exit tangential velocity along with default values for the aerodynamic design limits have been added to the code as an aid to non-expert users in selecting reasonable values for these inputs. Rotor-tip solidity is a function of rotor-tip inlet Mach number and stator-hub solidity.
depends on stator hub flow turning. Aspect ratio depends on stage location. The stator-exit tangential velocities are based on a mid-stage reaction along with an assumed stagewise distribution. Aerodynamic design limits for rotor and stator diffusions, rotor hub turning, and stator-hub Mach number are based on experience.

This report is also an updated users manual for the modified CSPAN code. Program input and output are described, and sample cases are included for illustration.

REFERENCES


### TABLE I. - COMPARISON OF COMPUTED AND EXPERIMENTAL PERFORMANCE

<table>
<thead>
<tr>
<th>Number of stages</th>
<th>Total pressure ratio</th>
<th>Computed efficiency</th>
<th>Experimental efficiency</th>
<th>Computed stall margin</th>
<th>Experimental stall margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>23.0</td>
<td>0.848</td>
<td>0.855</td>
<td>22.9</td>
<td>16.4</td>
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<tr>
<td>10</td>
<td>14.0</td>
<td>0.865</td>
<td>0.862</td>
<td>17.7</td>
<td>16.7</td>
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<tr>
<td>8</td>
<td>10.3</td>
<td>0.884</td>
<td>0.875</td>
<td>14.9</td>
<td>14.3</td>
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<tr>
<td>5</td>
<td>5.0</td>
<td>0.868</td>
<td>0.867</td>
<td>27.1</td>
<td>---</td>
</tr>
<tr>
<td>3</td>
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<td>0.851</td>
<td>0.860</td>
<td>20.4</td>
<td>16.3</td>
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<td>0.894</td>
<td>0.886</td>
<td>13.5</td>
<td>15.0</td>
</tr>
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### TABLE II. - SAMPLE INPUT

#### 5 STAGE TRANSONIC COMPRESSOR WITH DEFAULT INPUT

```
&NAME TTI=518.7,PTI=14.7,RCLIM=5.0,RTIP1I=10.,
UTIP1I=1100.,RHORT1=5.0,VTIPO=-67.5,NPRI=5*-1.,N=3,NSLIM=5,NPSI=5*-1.,
&END
```

#### NACA 5 STAGE TRANSONIC COMPRESSOR

```
&NAME MW=29.,GAM=1.4,TTI=518.7,PTI=14.7,RCLIM=5.0,RTIP1I=10.,
UTIP1I=1100.,RHORT1=5.0,VTIPO=-67.5,NPRI=5*-1.,N=3,NSLIM=5,
RT2OT1=5*1.0,SRTIP=0.98,1.17,1.30,1.14,0.99,B1=0.0,
VT2OT1=.918, .885, .916, .909, .916,
ARHD=5*40.,ARTD=5*-20.,ARO=2.,1.52,1.11,0.99,0.92,DRT=5*.45,
ASHD=5*40.,ASTD=5*-20.,VT30T2=1.094,1.071,1.053,1.057,0.992,NPSI=5*-1.,
SSH=1.8,1.9,1.6,1.5,1.4,ASO=2.15,1.63,1.24,1.01,0.88,
DSD=5*.55,MSH=5*.75,BPSD=5*45.,B3=5*0.0,RT3OT2=5*1.0,
&END
```

### TABLE III. - CONVERGENCE OUTPUT FOR SAMPLE CASE

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<thead>
<tr>
<th>CPR= 5.0000000000 NOT ACHIEVED IN 5 STAGES: CPR= 4.738175869</th>
</tr>
</thead>
<tbody>
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<td>STAGES= 5</td>
</tr>
<tr>
<td>DRTK= 1.00000000000  CPR= 5.550810337 EFF= 0.8655098081</td>
</tr>
<tr>
<td>DRTK= 0.9007693529   CPR= 4.878148556 EFF= 0.8671319485</td>
</tr>
<tr>
<td>DRTK= 0.9187448025   CPR= 4.999482155 EFF= 0.8674436212</td>
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</tr>
<tr>
<td>STALL MARGIN= 27.04190826</td>
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### TABLE IV.—MAIN OUTPUT FOR SAMPLE CASE

**NACA 5 STAGE TRANSONIC COMPRESSOR**

LOSS MODEL: INTERNAL CORRELATION FOR TOTAL-PRESSURE LOSS COEFFICIENTS

#### *** INLET INPUT DATA ***

<table>
<thead>
<tr>
<th>NO. RAD. STATIONS</th>
<th>NUMBER STAGES</th>
<th>SP. HEAT (BTU/(LB-R))</th>
<th>MOL. WT. (MOLES)</th>
<th>RATIO OF IN. TOT. TEMPERATURE</th>
<th>IN. TOT. TEMP. (DEG. R)</th>
<th>IN. TOT. PR. (PSI)</th>
<th>MASS AVG. TOT. PR. RATIO</th>
<th>IGV DEL PRESSURE</th>
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<tbody>
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<td>3</td>
<td>5</td>
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<td>28.9700</td>
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<td>518.7000</td>
<td>14.7000</td>
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<td>0.000</td>
</tr>
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</table>

#### *** ROTOR INLET INPUT DATA ***

<table>
<thead>
<tr>
<th>TIP RADIUS (INCHES)</th>
<th>TIP WHEEL SPEED (FT/SEC)</th>
<th>HUB TO TIP RADIUS RATIO</th>
<th>MASS FLOW (LBS/SEC)</th>
<th>TIP BLOCKAGE FACTOR</th>
<th>HUB BLOCKAGE FACTOR</th>
<th>ROT. SPEED (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0000</td>
<td>1100.0000</td>
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<td>67.5000</td>
<td>0.9900</td>
<td>0.9900</td>
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**COEFFICIENTS IN TANGENTIAL VELOCITY EQUATION**

<table>
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<tr>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
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<tbody>
<tr>
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<td>0.000</td>
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*** STATOR HUB MACH NO. LIMIT VIOLATED ***

---

19
### TABLE IV—Continued.

#### STAGE DATA

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<th>MAX ANGLE</th>
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<th>TIP</th>
<th>HUB</th>
<th>MAX ANGLE</th>
<th>MAX ANGLE</th>
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<tbody>
<tr>
<td>RATIO</td>
<td>EFFICIENCY</td>
<td>AT TIP</td>
<td>ASPECT</td>
<td>BLOCKAGE</td>
<td>RATIO</td>
<td>FACTOR</td>
<td>(DEGREES)</td>
<td>(DEGREES)</td>
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#### STAGE OUTPUT DATA

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<th>OVERALL</th>
<th>RATIO</th>
<th>VELOCITY</th>
<th>EFFICIENCY</th>
<th>TEMPERATURE</th>
<th>EFFICIENCY</th>
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<th>NO.</th>
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#### ROTOR INLET OUTPUT DATA

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<tr>
<th>STA NO.</th>
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<th>WHL VELOCITY</th>
<th>TANGENT VELOCITY</th>
<th>ABS. VELOCITY</th>
<th>REL. VELOCITY</th>
<th>TOTAL VELOCITY</th>
<th>TEMP. PRESS.</th>
<th>AIR ANG.</th>
<th>AIR ANG.</th>
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<td>14.700</td>
<td>1.188</td>
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<td>7.538</td>
<td>657.038</td>
<td>659.252</td>
<td>659.252</td>
<td>1057.634</td>
<td>51.440</td>
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#### ROTOR EXIT OUTPUT DATA

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<th>REL. VELOCITY</th>
<th>TOTAL VELOCITY</th>
<th>TEMP. PRESS.</th>
<th>AIR ANG.</th>
<th>AIR ANG.</th>
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#### STATOR EXIT OUTPUT DATA

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<th>ABS. VELOCITY</th>
<th>REL. VELOCITY</th>
<th>TOTAL VELOCITY</th>
<th>TEMP. PRESS.</th>
<th>AIR ANG.</th>
<th>AIR ANG.</th>
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<td>662.081</td>
<td>662.081</td>
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<td>.042</td>
<td>.269</td>
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<tr>
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<td>8.186</td>
<td>662.081</td>
<td>662.081</td>
<td>662.081</td>
<td>15.917</td>
<td>21.005</td>
<td>.042</td>
<td>.320</td>
</tr>
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#### BLADING GEOMETRY OUTPUT

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<tr>
<th>NO. OF BLADES</th>
<th>CHORD LENGTH</th>
<th>AXIAL ACTUAL</th>
<th>INCID</th>
<th>DEVIDA</th>
<th>CABER</th>
<th>ELD IN</th>
<th>ELD EX</th>
<th>AXIAL ACTUAL</th>
</tr>
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<tr>
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### TABLE IV.—Concluded.

**STAGE DATA**

**STAGE NO. 5**

**ROTOR INPUT DATA**

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<th>(FT/SEC)</th>
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<th>DEG</th>
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<tbody>
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**STATOR INPUT DATA**

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<th>(FT/SEC)</th>
<th>(FT/SEC)</th>
<th>(FT/SEC)</th>
<th>(FT/SEC)</th>
<th>DEG</th>
<th>DEG</th>
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</thead>
<tbody>
<tr>
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<td>.7500</td>
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</table>

**STAGE OUTPUT DATA**

<table>
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<tr>
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<th>OVERALL</th>
<th>OVERALL</th>
<th>OVERALL</th>
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<th>OVERALL</th>
<th>OVERALL</th>
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<tbody>
<tr>
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<td>PRESS AVE.</td>
<td>TEMP. RATIO</td>
<td>BULK TEMP.</td>
<td>BULK TEMP.</td>
<td>BULK TEMP.</td>
<td>BULK TEMP.</td>
<td>BULK TEMP.</td>
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**ROTOR INLET OUTPUT DATA**

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<th>VEL.</th>
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<th>REL.</th>
<th>ABS.</th>
<th>REL.</th>
<th>AIR ANG.</th>
<th>REL.</th>
<th>TOTAL TEMP.</th>
<th>TEMPERATURE</th>
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<td>9.081</td>
<td>1000.018</td>
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<td>1097.183</td>
<td>532.724</td>
<td>367.810</td>
<td>647.363</td>
<td>903.205</td>
<td>34.622</td>
<td>53.858</td>
<td>867.801</td>
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<tr>
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<td>903.205</td>
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</table>

**STATOR EXIT OUTPUT DATA**

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<th>REL.</th>
<th>ABS.</th>
<th>REL.</th>
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**BLADING GEOMETRY OUTPUT**

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**OVERALL PRESSURE RATIO LIMIT HAS BEEN REACHED — GO TO NEW DATA**

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21
Figure 1.--Stage-exit endwall-area blockage calculation results
Enhanced Capabilities and Modified Users Manual for Axial-Flow Compressor Conceptual Design Code CSPAN

Arthur J. Glassman and Thomas M. Lavelle

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

Modifications made to the axial-flow compressor conceptual design code CSPAN are documented in this report. Endwall blockage and stall margin predictions were added. The loss-coefficient model was upgraded. Default correlations for rotor and stator solidity and aspect-ratio inputs and for stator-exit tangential velocity inputs were included in the code along with defaults for aerodynamic design limits. A complete description of input and output along with sample cases are included.