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Blading Models for TURBAN and CSPAN Turbomachine Design Codes

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Blading Models for TURBAN and CSPAN Turbomachine Design Codes

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SUMMARY

This report presents blading models that were added to the turbine design code TURBAN and the compressor design code CSPAN. TURBAN is a meanline code based on a stage-average velocity diagram; CSPAN is a spanline code based on isentropic simple radial equilibrium. These blading models were all based on previously published correlations and analyses. Estimates of blade chord length, axial length, and number of blades for each blade row are now provided by each code.

Added to TURBAN were (1) calculation of axial solidity based on a cascade loading model and (2) calculation of blade stagger angle (i.e., blade chord angle) based on a blade geometry having a suction surface with circular-arc turning and straight transition sections at inlet and exit. A blade geometry model using a circular-arc camber line was added to CSPAN for calculating compressor blade stagger angle. Also added to CSPAN, because of their greater significance for compressors than for turbines, were calculations of incidence angle and deviation angle based on cascade correlations.

INTRODUCTION

Computer codes TURBAN (ref. 1) and CSPAN (ref. 2) were developed to perform preliminary sizing analyses for turbines and compressors, respectively. TURBAN is a meanline code based on a stage-average velocity diagram; CSPAN is a spanline (i.e., constant span-fraction sectors) code based on isentropic simple radial equilibrium. These codes provide the means for obtaining number of stages, flowpath inner and outer radii, flow velocities and angles, and efficiencies for these turbomachines. They utilize rapid approximate methodologies as is desired for conceptual design studies.

In order to be used for engine studies, component design programs must provide the information needed for computing engine dimensions and weight. Both TURBAN and CSPAN provided radial dimensions, but each had some shortcomings. Although TURBAN did include an axial length calculation, it did not provide blade number or blade chord. On the other hand, CSPAN had the capability to provide blade number and blade chord from the aspect ratio and solidity inputs, but it estimated the axial length by using the chord dimension. These shortcomings were remedied by adding a solidity computation to TURBAN and a blade geometry model to both codes. In addition, incidence and deviation were incorporated into the blade angle computation in CSPAN because of their significance in compressors.

This report presents the analytical methods used for the solidity model in TURBAN and for the geometry models in TURBAN and CSPAN. Typical modeling results are illustrated. These methods were not developed by the author but were already available in the literature.

SYMBOLS

a suction-surface, circular-arc radius in turbine blade model

b solidity exponent in deviation angle relation

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c blade chord length

i incidence angle

K_δ maximum thickness correction factor in deviation angle correlation

K_i maximum thickness correction factor in incidence angle correlation

m solidity coefficient in deviation angle correlation

n solidity coefficient in incidence angle correlation

s blade spacing

β flow angle or blade angle

γ blade chord angle

δ deviation angle

σ solidity

ϕ blade camber angle

ψ_z Zweifel loading coefficient

Subscripts:

ac annular cascade

opt optimum

x axial component

θ tangential component

0 zero camber

1 blade inlet

2 blade exit

2D two-dimensional cascade

10 blade maximum thickness-to-chord ratio of 10 percent

TURBAN MODELING

The computation of engine dimensions and weight requires knowledge of flowpath radii, axial length, blade chord length, and number of blades for each turbine and compressor blade row. The flowpath radii and axial length for turbines were already provided by TURBAN. In order to determine number of blades and blade chord length, a cascade loading model to compute axial solidity (ratio of blade chord axial projection to blade spacing) and a blade geometry model to compute stagger angle were added to the code. The derivations of the models will be referenced, and only the final expressions as used in the computer codes will be presented herein.

Axial Solidity

Zweifel (ref. 3) derived the following expression by equating the tangential force exerted by a fluid flowing through a two-dimensional cascade of blades to the tangential force due to the blade pressure loading:

$$\sigma_x = \frac{2 \cos \beta_2}{\psi_z \cos \beta_1} \sin \left(\beta_1 - \beta_2\right) \tag{1}$$

The derivation of this equation is also presented in reference 4. Equation (1) shows that axial solidity σ_x depends only on the blade inlet and exit flow angles and on the tangential loading coefficient ψ_z, which is the ratio of actual blade loading to Zweifel's ideal loading.

According to reference 3, minimum loss occurs when the Zweifel loading coefficient ψ_z is equal to 0.8. By using this value in equation (1), optimum axial solidity can be determined as a function of the blade inlet and exit flow angles, and this is plotted in figure 1, which is reproduced from reference 4. Turbines, especially at the mean section, will generally operate in the region below the curve for the impulse blade row.

Stagger Angle

In order to determine the blade chord length, as well as the optimum value of actual solidity (ratio of blade chord to blade spacing), it is necessary to calculate the stagger angle γ because

$$\cos \gamma = \frac{\sigma_x}{\sigma} = \frac{c_x}{c} \tag{2}$$

An analytical blade model was used in reference 5 to relate stagger angle to the flow angles and the axial solidity. This model, which is shown in figure 2, is based on the assumptions (1) that the leading and trailing edges have zero thickness, (2) that the suction-surface lengths from J to K and from L to M are straight and set at the inlet and exit flow angles, and (3) that the suction surface from K to L is a circular arc of radius *a*.

The equations used to compute stagger angle are

$$\tan \gamma = \frac{c_\theta}{\sigma_x} \tag{3}$$

$$c_\theta = \sin^2\beta_1 - a\left(\cos \beta_1 - \cos \beta_2\right) - \sin^2\beta_2 \tag{4}$$

$$a = \frac{\sigma_x - \sin \beta_1 \cos \beta_1 + \sin \beta_2 \cos \beta_2}{\sin \beta_1 - \sin \beta_2} \tag{5}$$

where the axial solidity σ_x is obtained from equation (1).

For optimum loading ($\psi_z = 0.8$) the stagger angle as a function of blade inlet and exit flow angles is presented in figure 3. The values computed by this model are generally within 5° to 15° of the stagger angles of real turbine blades having blunt leading edges and uncovered turning (i.e., suction surface curvature beyond the throat). The optimum actual solidity as a function of blade inlet and exit flow angles is presented in figure 4, which is reproduced from reference 4.

CSPAN MODELING

The CSPAN code already provides for calculating blade chord length and number of blades through the aspect ratio and solidity inputs for each blade row. However, the chord length determined from the aspect ratio is also used as the axial length of the blade. In order to provide realistic values for both chord length and axial length, a blade geometry model to compute stagger angle was added to CSPAN. Because incidence and deviation are more significant for compressors than for turbines, incidence angle and deviation angle correlations were also added to CSPAN.

Stagger Angle

The camber angle for compressors is much smaller than that for turbines, and for preliminary studies a circular arc is commonly used to model blade shape. For a circular-arc blade, equations (3) to (5) reduce simply to

$$\gamma = \frac{\beta_1 + \beta_2}{2} \tag{6}$$

Incidence and Deviation Angles

The incidence and deviation angles are defined as the flow angle minus the blade angle at the blade inlet and exit, respectively. The annular cascade correlations described in reference 6 were initially selected for incidence and deviation modeling. While testing these models against incidence and deviation angles published by engine manufacturers for NASA-program compressors, it was noted that the three-dimensional correction for incidence appeared to be excessive. A better match with published values of incidence angle was obtained by using the two-dimensional cascade correlation. Therefore, the incidence and deviation angle correlations used were

$$i_{2D} = K_i \left(i_0\right)_{10} + n\phi \tag{7}$$

$$\delta_{ac} = K_\delta \left(\delta_0\right)_{10} + \frac{m}{\sigma^b} \phi + \left(\delta_{ac} - \delta_{2D}\right) \tag{8}$$

The parameters for equations (7) and (8) (i.e., K_i, $(i_0)_{10}$, n, K_δ, $(\delta_0)_{10}$, m, b, and $\delta_{ac} - \delta_{2D}$) are plotted in reference 6 as functions of blade thickness, solidity, inlet angle, and inlet Mach number. These parameters are evaluated in CSPAN by using analytical functions from the code of reference 7. Incidence angles and deviation angles computed by CSPAN for the mean section of a 10-stage compressor are shown in figure 5 as an example of the levels encountered. Values for other compressors would vary somewhat depending on the velocity diagram and the blading geometry.

SUMMARY OF RESULTS

Computer codes TURBAN and CSPAN were developed to perform preliminary sizing analyses for turbines and compressors, respectively. These codes provide the means for obtaining number of stages, flowpath inner and outer radii, flow velocities and angles, and efficiencies for these turbomachines. To be used for engine studies, these programs must provide the information needed for computing engine dimensions and weight, including such additional information as blade axial length, blade chord length, and number of blades.

In order to provide both codes with the capabilities to compute all necessary information, additional modeling was required. Added to TURBAN were (1) calculation of axial solidity based on a cascade loading model and (2) calculation of blade stagger angle based on a blade geometry having a suction surface with circular-arc turning and straight transition sections at inlet and exit. A blade geometry model using a circular-arc camber line was added to CSPAN for the calculation of compressor blade stagger angle. Also added to CSPAN, because of their greater significance for compressors, were calculations of incidence angle and deviation angle based on cascade correlations. The models used for these computations are documented in this report. These models were not developed by the author but were all available in the literature.

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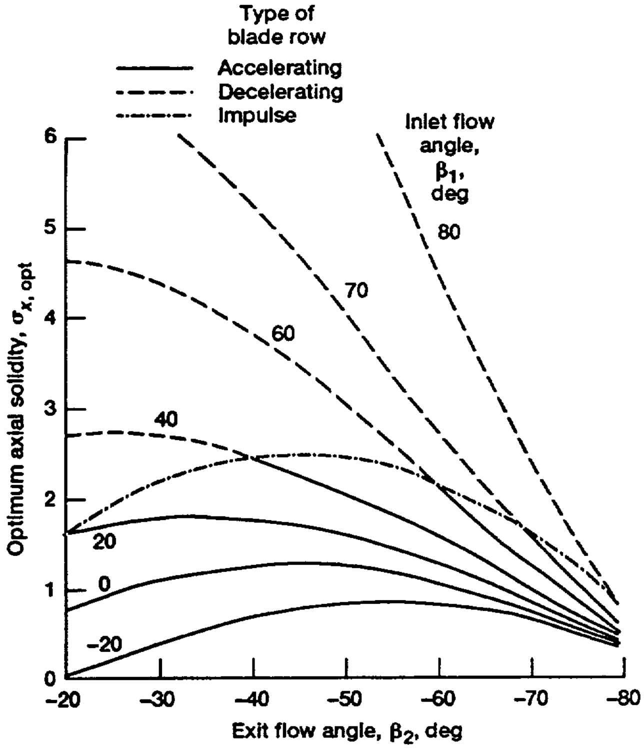

Figure 1.—Effect of inlet and exit angles on turbine optimum axial solidity. Zweifel loading coefficient, ψ_z, 0.8.

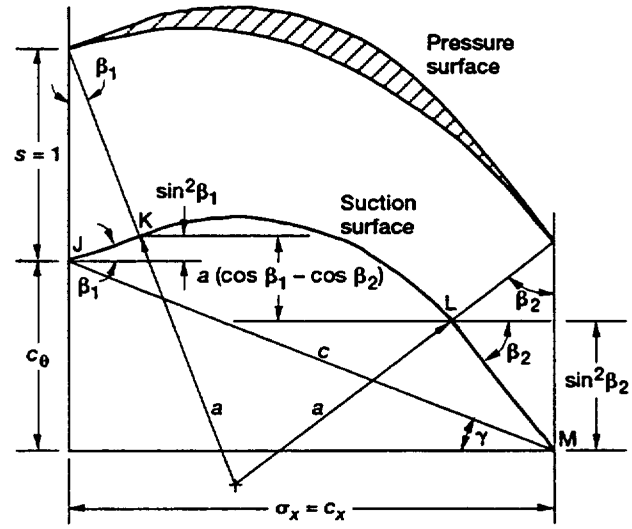

Figure 2.—Blade model used in determining stagger angle.

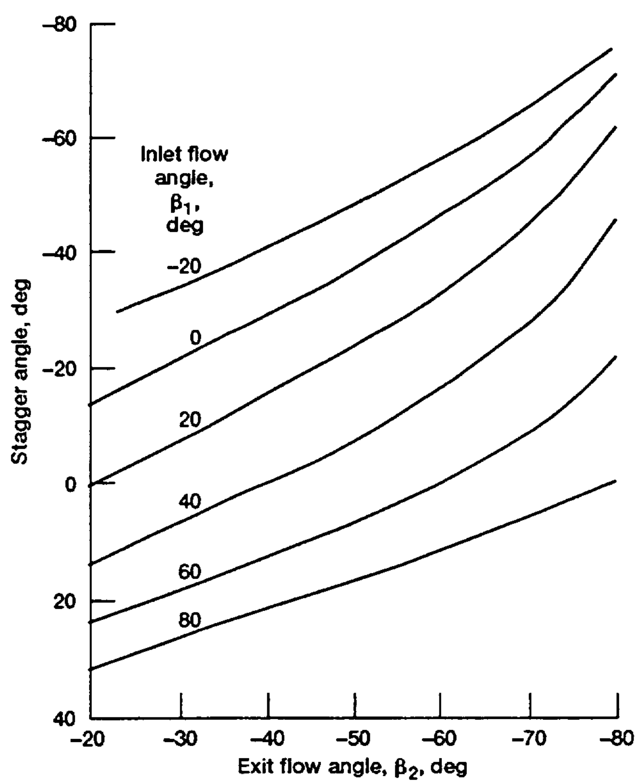

Figure 3.—Effect of inlet and exit flow angles on stagger angle. Zweifel loading coefficient, ψ_z, 0.8.

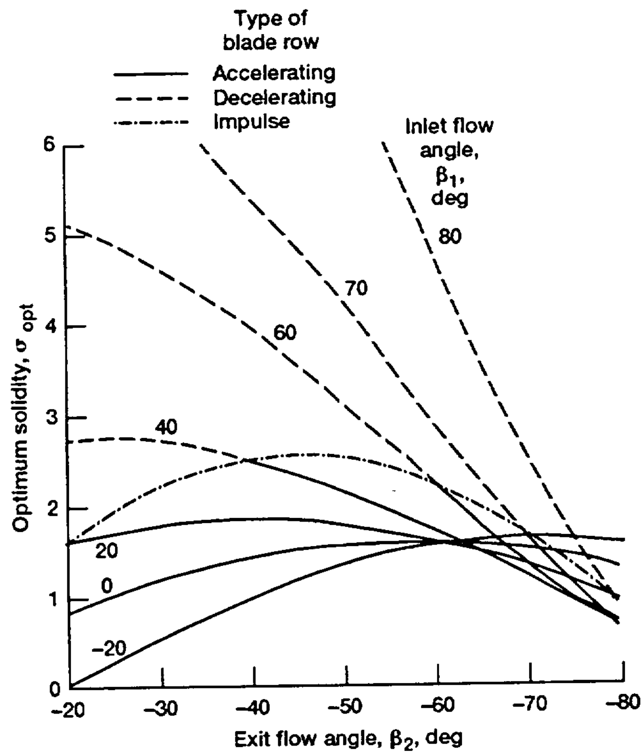

Figure 4.—Effect of inlet and exit angles on turbine optimum actual solidity. Zweifel loading coefficient, ψ_z, 0.8.

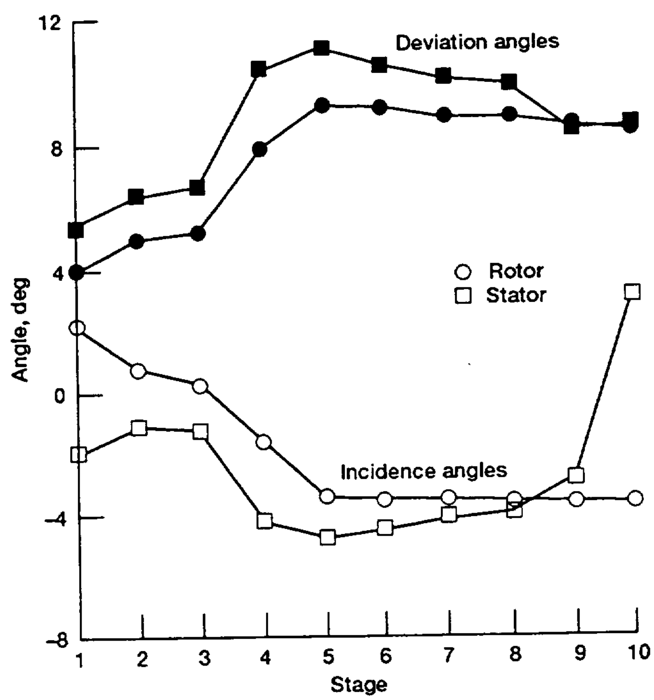

Figure 5.—Typical incidence and deviation angles for a 10-stage compressor.

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13. ABSTRACT *(Maximum 200 words)*

Blading models added to TURBAN, an axial turbine meanline design code, and CSPAN, an axial compressor spanline design code, are presented. Calculations of blade chord length, blade axial length, and number of blades for each blade row are now provided by each code. In order to accomplish this, computational models for axial solidity and stagger angle were added to TURBAN. For a compressor, where solidity and chord were already available from input, the modeling additions to CSPAN were for stagger angle and for the blade angles to include incidence and deviation. All added computations utilized models already available in the literature.

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