MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A
A TWO-DIMENSIONAL DESIGN METHOD FOR HIGHLY-LOADED BLADES IN TURBOMACHINES

by

Thong Quoc Dang
James E. McCune

GT & PDL Report No. 173
April 1983

GAS TURBINE & PLASMA DYNAMICS LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS
A TWO-DIMENSIONAL DESIGN METHOD FOR HIGHLY-LOADED BLADES IN TURBOMACHINES
by
Thong Quoc Dang
James E. McCune

GT & PDL Report No. 173
April 1983

This research was supported by the U.S. Air Force Office of Scientific Research, Contract Number F49620-82-K-0002, Dr. J. D. Wilson, Program Manager.

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFSC)
NOTICE OF TRANSMITTAL TO DTIC
This technical report has been reviewed and is approved for public release. DISTRIBUTION IS UNLIMITED.
MATTHEW J. KISPER
Chief, Technical Information Division
A practical design method for high-loaded blades in an isolated cascade is presented in this report. The flow is assumed to be incompressible and inviscid. The upstream flow condition is taken to be uniform. The present goals of this research are to develop a practical numerical code for the design problem, and a nonlinear theory can be easily expanded to three-dimensions. The theory is based in part on the computational fluid dynamics formulation. The blade profile is determined iteratively through the blade design conditions using a "smoothing" technique. The program gives very fast convergence with satisfactory accuracy for practical solidity range.
ABSTRACT

A practical design method for highly-loaded blades in an isolated cascade is presented in this thesis. The flow is assumed to be incompressible and inviscid. The upstream inlet flow condition is taken to be uniform. The present goals of this research are to provide a practical numerical code for the design problem, and a non-linear theory which can be easily expanded to three-dimensions. The theory is based in part on the Clebsch formulation. The blade profile is determined iteratively through the blade boundary conditions using a "smoothing" technique. A practical numerical code is presented for the design problem using "partial smoothing". The program gives very fast convergence solutions with satisfactory accuracy for practical solidity range.
Acknowledgements

I wish to extend my most sincere thanks to Professor J.E. McCune, my thesis supervisor, for his patient supervision at the beginning of this work, and his continuing guidance, support and encouragement.

I also wish to express my thanks to the following people for their support in preparing this thesis:

- Dr. C.S. Tan for his guidance in the numerical work and many other matters.

- Mr. E.R. McFarland of NASA Lewis Research Center for providing his direct method numerical code in great details.

- Professor W.R. Hawthorne for discussing the project.

Many thanks to my family for their supports during my staying at MIT.

This research was supported by the U.S. Air Force Office of Scientific Research, Contract Number F49620-82-K-0002, Dr. J.D. Wilson, Program Manager.

Figure 1 was copied from reference [4].
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>2</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>3</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>4</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>8</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>9</td>
</tr>
<tr>
<td>PARTIAL LIST OF SYMBOLS</td>
<td>10</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>12</td>
</tr>
<tr>
<td>2. THEORETICAL APPROACH</td>
<td>15</td>
</tr>
<tr>
<td>2.1 Cascade Geometry and Notations</td>
<td>15</td>
</tr>
<tr>
<td>2.2 Fluid Mechanics Background</td>
<td>17</td>
</tr>
<tr>
<td>3. THE &quot;ZERO-THICKNESS&quot; PROBLEM</td>
<td>20</td>
</tr>
</tbody>
</table>
3.1 Flow Regions 20

3.2 Solution of the Velocity Field 22

3.2.1 smoothing series 23

3.2.2 matching conditions 25

3.2.3 blade boundary conditions 27

3.3 Iteration Process for the Blade Camber Line 28

3.4 "Partial Smoothing" 30

3.5 Numerical Method 31

3.6 Numerical Results 33

4. THE "FINITE-THICKNESS" PROBLEM 35

4.1 Flow Regions 36

4.2 Solution of the Velocity Field 38

4.2.1 relation between the gap average velocity and the unknowns 39

4.2.2 satisfaction of the Poisson equation 41

4.2.3 matching conditions 43
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.4 blade boundary conditions</td>
<td>44</td>
</tr>
<tr>
<td>4.3 Iteration Process for the Blade Camber Line</td>
<td>49</td>
</tr>
<tr>
<td>4.4 Numerical Method</td>
<td>50</td>
</tr>
<tr>
<td>4.5 Design Choices</td>
<td>53</td>
</tr>
<tr>
<td>4.5.1 blockage distribution</td>
<td>53</td>
</tr>
<tr>
<td>4.5.2 loading distribution</td>
<td>54</td>
</tr>
<tr>
<td>4.6 Numerical Results</td>
<td>54</td>
</tr>
<tr>
<td>4.7 Design Procedure</td>
<td>59</td>
</tr>
<tr>
<td>5. CONCLUSION</td>
<td>61</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>62</td>
</tr>
<tr>
<td>TABLES</td>
<td>63</td>
</tr>
<tr>
<td>FIGURES</td>
<td>71</td>
</tr>
<tr>
<td>APPENDIX A: The Relationship between the swirl schedule and the pressure difference across the blade</td>
<td>88</td>
</tr>
</tbody>
</table>
APPENDIX B: The Bound Vorticity

APPENDIX C: The Periodic Generalized Functions

APPENDIX D: The "Physical" Interpretations of $\beta$ and $\delta$

APPENDIX E: Numerical Difficulties

APPENDIX F: Computer Code of "Zero-Thickness" problem

APPENDIX G: Computer Code of "Finite-Thickness" problem
List of Tables

1. Numerical Example of "Zero-Thickness" Problem
2. Comparison of "Smoothing" and "Exact" Results
3. Flow Chart for "Finite-Thickness" Problem
4. Numerical Example of "Finite-Thickness" Problem (without filter)
5. Numerical Example of "Finite-Thickness" Problem (with filter)
6. Results from Direct Method (inlet condition specified)
7. Results from Direct Method (circulation specified)
8. Comparison of "Zero-Thickness" and "Finite-Thickness" Results in the Zero Blockage Limit
List of Figures

1. 2D Cascade Notation
2. Blade Camber and Mean Streamline
3. Blade Shapes Obtained from "Smoothing" Technique
4. Pressure Coefficients Obtained from "Smoothing" Technique
5. Pressure Coefficients Obtained from Direct Method
6. Comparison of Cp's from Direct and Inverse Methods
7. Comparison of 'Zero-Thickness' and 'Finite-Thickness' Results in the Zero Blockage Limit
8. Effects of Spacing to Chord Ratio on Blade Cambers
9. Effects of Maximum Blockage on Cp's (BLOCK = 0.001)
10. Effects of Maximum Blockage on Cp's (BLOCK = 0.1)
11. Effects of Maximum Blockage on Cp's (BLOCK = 0.25)
12. Rounded Leading Edge Inlet Guide Vane
13. Effects of Loading Distribution on Cp's (Max. Loading at x = 1/3)
14. Effects of Loading Distribution on Cp's (Max. Loading at x = 1/2)
15. Effects of Loading Distribution on Cp's (Max. Loading at x = 2/3)
16. Compressor Blade
17. Impulse Blade
Partial List of Symbols

Δp - pressure coefficient
f - blade camber line ordinate
fo - mean streamline ordinate
G - negative of the y-component of the pitch average velocity
Gg - negative of the y-component of the gap average velocity
I - "smoothing" function (defined in Appendix C)
J - "smoothing" function (defined in Appendix C)
K - "smoothing" function (defined in Appendix C)
S - spacing to chord ratio
S - "sawtooth" function (defined in Appendix C)
T - blockage distribution
V - actual velocity
V - average velocity
ς - perturbed velocity
α - blade camber surfaces
αi - inlet angle
αo - outlet angle
δp - "periodic delta" function (defined in Appendix C)
- actual vorticity
- average vorticity
- perturbed vorticity
( )⁺ - pressure side
( )⁻ - suction side
( )ₓ - x-component of a vector
( )ᵧ - y-component of a vector

NOTATIONS

\[
\overline{ } \equiv \frac{1}{\lambda} \int_{f}^{f+\lambda} ( ) \, dy \\
\langle \rangle_{T} \equiv \frac{1}{\lambda - 2T} \int_{f+T}^{f+\lambda-T} ( ) \, dy \\
\langle ( ) \rangle \equiv \frac{1}{2} \left[ ( )^{T} + ( )^{-T} \right] \\
\langle ( ) \rangle_{T} \equiv \frac{1}{2} \left[ ( )^{T} + ( )^{-T} \right] \\
\Delta_{T}( ) = \frac{1}{2} \left[ ( )^{T} - ( )^{-T} \right]
\]
Chapter 1: Introduction

This thesis presents a technique for solving the design problem (the inverse problem) for highly loaded blades in an isolated cascade. In the present study, the flow is treated as if it were incompressible and inviscid, and the upstream inlet flow condition is assumed to be uniform.

Historically, there have been several approaches to the design problem. In one approach, for example, the velocity distributions on both surfaces of the blade are specified, and the resulting blade shape is calculated. The advantage of this technique is that the designer can prescribe surface pressure distributions which minimize the chance of flow separation. However, the resulting blade geometry is not guaranteed to have a realistic configuration: the blade may be wavy, or even have negative thickness.

In a second approach, the velocity distribution on one surface and the profile thickness distribution are specified, and the resulting blade shape is calculated. This formulation does not guarantee obtaining an acceptable pressure distribution on the second blade surface. Moreover, the resulting loading distribution may not be structurally favorable: for example, the loading may be maximum where the blade is thinnest.

In a third approach, the loading and thickness (or 'blockage') distributions are specified, and the resulting blade shape is calculated. This formulation does not guarantee giving acceptable pressure distributions on either of the blade surfaces, but the resulting blade shape can be guaranteed to be at least structurally sound.
In applying classical aerodynamics methods to these problems, the presence of the blades and their effects on the flow can be modeled by distributing singularities (vortices, sources and sinks) on the blade camber or blade surfaces. Lewis [1] carried out the design problem using the first two approaches mentioned above. His analysis is based on Martensen’s method [2]: vortices are distributed on each of the blade surfaces, and the induced flow field in the cascade plane is calculated using the Biot-Savart law.

Kashiwabara [3] carried out the design problem using the first of the above approaches by arranging vortices, sources and sinks along the blade camber. This theory also attempts to take into account some three-dimensional effects, and can be used for designing blades in axial, mixed and radial turbomachines.

These design theories, based in part on the Biot-Savart law, are simple for cascade calculation only. Until recently [4], only linearized theories have been developed to design three-dimensional blades [5], [6].

One goal of the present project is to provide a practical numerical code for the design problem which can give good accuracy and fast convergence solutions. An equally important goal is to provide a non-linear theory which can be practically expanded to three-dimensions. The present theory is based in part on the Clebsh formulation which has been successfully investigated by Tan, Wang, Hawthorne and McCune [4] in their study of a three-dimensional design method for highly-loaded but infinitely thin blades.

In the present study, the blade profile is determined iteratively through the blade boundary conditions using a "smoothing" technique: the velocity potential is expressed in a series of "smoothing" functions developed by
McCune [Appendix C]. The "smoothing" technique represents an asymptotic expansion (in the blade spacing) of the Green's function for blade rows, and can be applied in both 2D and 3D.

In the first example, the blades are assumed to be infinitely thin (the 'Zero-Thickness' problem) to show the power of the "smoothing" technique: the blade shape is solved iteratively through a set of algebraic equations. The results compare very well with the "exact" method [4]. Then, a similar approach is used to solve the inverse problem (in the third formulation, outlined above) for high swirl blades having prescribed finite thickness (the 'Finite-Thickness' problem). A set of numerical examples are presented, which in part use "partial smoothing", i.e. a practical truncation of the smoothing series. Blades shapes with prescribed thickness (or blockage) distributions are obtained for prescribed swirl schedules or loading distributions. To confirm the results a 'direct' method, developed by McFarland [10], is used to compute both the circulation and the pressure coefficients on the blade obtained from the indirect method. The results show that the blade does in fact produce the desired circulation and loading distribution. Moreover, the pressure distributions on each surface agree well, at least away from the leading and trailing edges.

Finally, a practical design procedure is presented which allows for rapid exploration of various blade loading and thickness distributions, so as to be able to select favorable individual-surface pressure distributions as well.
Chapter 2: Theoretical approach

2.1 Cascade geometry

The cascade geometry is shown in the above figure. The flow direction is from left to right. All lengths are non-dimensionalized to the axial chord length.

The blade camber lines are located at:
where \( n = 0, 1, 2, 3, \ldots \)

\( \delta \) = spacing between blade cambers

\( f \) = location of the camber line \( n = 0 \)

If we define \( \alpha \) as

\[
\alpha = y - f(x)
\]

then blade cambers lie on surfaces of \( \alpha = n \delta \), \( n = 0, \pm 1, \pm 2 \ldots \)

Consider the blade located at \( n = 0 \). The blockage distribution \( T(x) \) is defined such that:

- the blade upper surface is located at \( y = f(x) + T(x) \)
- the blade lower surface is located at \( y = f(x) - T(x) \)

Physically, \( 2T(x) \) can be interpreted as the axial blockage distribution. We note that \( T(x) \) is not the blade thickness as defined in classical aerodynamics, where the thickness is defined as the perpendicular distance from the blade camber to the blade surface.

The far upstream flow condition is assumed to be uniform. All velocities are non-dimensionalized to the upstream inlet \( x \)-component velocity. The inlet flow angle is denoted by \( \alpha_1 \). Likewise, the outlet flow angle is denoted by \( \alpha_2 \).
2.2 Fluid mechanics background

As mentioned in the introduction, we have chosen to model the presence of the blade shape by distributing singularities on the blade camber. In this section, we will derive the governing equation for the velocity field in the "Zero-Thickness" problem. In chapter 4, we will extend this theory to the "Finite-Thickness" problem.

In the case of infinitely thin blades, the presence of each blade is modeled by arranging vortices along the blade camber. In the design problem the swirl schedule \( \overline{\nabla y}(x) \) is given. It can be shown that the swirl schedule is proportional to the pressure difference (i.e. the loading) across the blade [Appendix A].

The velocity is divided into two parts: an average velocity \( \overline{\nabla y}(x) \), and a perturbed velocity \( \tilde{\nabla y}(x, y) \), i.e.

\[
\nabla y(x, y) \equiv \overline{\nabla y}(x) + \tilde{\nabla y}(x, y) \tag{2.2-1}
\]

where the average velocity is here taken to be the pitch average defined by:

\[
\overline{\nabla y}(x) \equiv \frac{1}{\Delta} \int_{f}^{f+\Delta} \nabla y(x, y) \, dy
\]

and thus, by the definition of equation (2.2-1), we must have

\[
\int_{f}^{f+\Delta} \tilde{\nabla y}(x, y) \, dy = 0
\]

The above equation suggests that if we are to represent \( \tilde{\nabla y} \) as a series of smooth functions, perhaps we should choose functions which possess this
zero pitch average property. In chapter 3, we will show that the "smoothing" functions used to represent $\tilde{\zeta}$ possess this property.

Consider the vorticity field. Given the assumption of incompressible, inviscid and uniform inlet condition, then by Kelvin's theorem, the vortices must lie on the blade camber, and the flow must be irrotational everywhere else.

It can be shown that the vorticity is related to the blade surface $\alpha$ and the $y$-component of the pitch average velocity $\tilde{V}(\alpha)$ by [Appendix B]:

$$\Omega(x, y) = \delta_p(\alpha) \left[ \nabla \alpha \times \nabla G \right]$$

(2.2-2)

where $\delta_p(\alpha)$ is the "periodic delta" function [Appendix B].

Further, $G(x) = -\tilde{V}_y(x)$

The pitch average vorticity $\Omega$ is defined as:

$$\Omega(x) \equiv \frac{1}{\delta} \int_f^{f+\delta} \Omega(x, y) \, dy$$

(2.2-3)

The vorticity $\Omega$ is defined as:

$$\Omega(x, y) \equiv \Omega(x) + \Omega(x, y)$$

and thus, the perturbed vorticity $\tilde{\Omega}$ is

$$\tilde{\Omega}(x, y) = \left[ \delta \delta_p(\alpha) - 1 \right] \nabla \alpha \times \nabla G$$

$$= \nabla S(\alpha) \times \nabla G$$

(2.2-4)

where $S(\alpha)$ is the "sawtooth" function [Appendix B].
We are now in the position to write down the governing equation for the velocity field $\vec{V}$. From equation (2.2-4), we can write

$$\nabla \times \vec{V} = \nabla S \times \nabla G$$  \hspace{1cm} (2.2-5)

The Clebsh formulation says that, to satisfy (2.2-5), write the perturbed velocity $\vec{\delta}$ as the sum of a potential part and a rotational part:

$$\vec{\delta}(x, y) = \nabla \vec{\phi}(x, y) + S(x) \nabla G(x)$$ \hspace{1cm} (2.2-6)

Note that the curl of $\vec{\delta}$ gives $\vec{\delta}$ back.

If the flow is incompressible, then $\nabla \cdot \vec{V} = 0 = \nabla \cdot \vec{\delta} = \nabla \cdot \vec{\delta}$. Thus, from equation (2.2-6),

$$\nabla^2 \vec{\phi}(x, y) = - \nabla \cdot (S \nabla G)$$

$$= - \nabla S \cdot \nabla G - S \nabla^2 G$$ \hspace{1cm} (2.2-7)

This gives a Poisson equation to be solved for $\vec{\phi}$ with appropriate boundary conditions (e.g. on the blades).

Finally, the velocity field in the cascade region is of the form:

$$\vec{V}(x, y) = \vec{V}(x) + \left[ \nabla \vec{\phi}(x, y) + S(x) \nabla G(x) \right]$$ \hspace{1cm} (2.2-8)

In the design problem, $\vec{V}$ is given and we seek the solution for $\vec{V}$ which satisfies all necessary boundary conditions. In chapter 3, we present a design method for infinitely thin blades using the above theory. In chapter 4, we present a design method for blades having finite thickness based in part on the above approach. In this case, the gap average velocity is given instead of the pitch average velocity, and the above theory needs to be modified.
Chapter 3: The 'Zero-Thickness' problem

The "Zero-Thickness" problem refers to the design problem of infinitely thin blades. The blades are represented by a distributed bound vorticity which is related to the y-component of the pitch average velocity by equation (2.2-2). We seek the velocity field which must satisfy equation (2.2-8) in the cascade region and appropriate boundary conditions. The blade camber lines are solved iteratively using the blade boundary conditions. The flow is assumed to be incompressible and inviscid. The upstream flow condition is assumed to be uniform.

3.1 Flow regions

The flow field is divided into three regions (figure 1).

(1) Region 1

Region 1 is defined in the interval $-\infty < X < 0$. In this region, the flow is irrotational everywhere. We may write

$$\nabla_4 (x, y) = \vec{v}(-\infty) + \tilde{\omega}_4 (x, y)$$

$$\tilde{\omega}_4 (x, y) = \nabla \Phi_h (x, y)$$

(3.1-1)

where $\vec{v}(-\infty)$ is the inlet flow condition.

The boundary conditions in this region are:
- far upstream, \( \nabla h_1 = 0 \)
- at the leading edge, \( \overrightarrow{V}_4 = \overrightarrow{V}_2 \)

(2) Region 2

Region 2 is defined in the interval \( 0 < \chi < 1 \). In this region, the flow is rotational and must satisfy equation (2.2-8), i.e.

\[
\overrightarrow{V}_2 (\chi, \gamma) = \overrightarrow{V} (\chi) + \overrightarrow{\zeta}_2 (\chi, \gamma)
\]

\[
\overrightarrow{\zeta}_2 (\chi, \gamma) = \nabla \Phi (\chi, \gamma) + S (\chi) \nabla \Phi (\chi)
\]

where \( \overrightarrow{V} (\chi) \) is the prescribed pitch average velocity.

The boundary conditions in this region are:

- matching conditions at the leading and trailing edges
- no flow-through conditions at the blade surfaces

(3) Region 3

Region 3 is defined in the interval \( 1 < \chi < +\infty \). In this region, the flow is irrotational. We may write

\[
\overrightarrow{V}_3 (\chi, \gamma) = \overrightarrow{V} (+\infty) + \overrightarrow{\zeta}_3 (\chi, \gamma)
\]

\[
\overrightarrow{\zeta}_3 (\chi, \gamma) = \nabla \Phi_h (\chi, \gamma)
\]

where \( \overrightarrow{V} (+\infty) \) is the outlet flow condition.

The boundary conditions in this region are:
- far downstream, \( \nabla \Phi = 0 \)
- at the trailing edge, \( \nu_2 = \nu_3 \)

3.2 Solution of the velocity field

In this section, we present our method of solving the velocity fields in the three regions. At the same time, we try to give reasons for our choice of such a method.

The solution for the perturbed velocities \( \tilde{\nu}_n \) are assumed to be of the form of series of smooth functions: Fourier series and "smoothing" series [Appendix C]. In choosing these series solutions, we note that by our definitions of \( \tilde{\nu} \), equation (2.2-1), we must satisfy the condition of zero pitch average for \( \tilde{\nu} \). One way of satisfying this condition is to choose functions in the series having zero pitch average. This is one of the property of "smoothing" functions. In addition, these "smoothing" functions have other properties which are ideal for our applications, i.e.

1. they are periodic in the y-direction. Thus, they can be used to represent the periodicity of the velocity field in the cascade.

2. they are derivatives and integrals of one another. This is a useful property for analysis purpose.

3. they are proportional to \( \tilde{\nu}^n \), where \( n = 1,2,3,... \). This property is desired in the case of highly-loaded blade where the solidity is high (or \( A \) is less than 1).

4. they have amplitudes which decrease very fast with increasing order "smoothing" functions. Because of this property, very few terms in the smoothing series are needed to represent a smooth function while high accuracy can still be achieved.
In the case of infinitely thin blades, we expand part of the velocity potential \( \Phi \) in region 2 as a series of these "smoothing" functions. This is the "smoothing" technique. It turns out that by using this technique, the expressions for the velocity fields are very simple to compute.

Refer to equation (3.1-2), we assume the velocity potential \( \Phi \) in region 2 of the form

\[
\tilde{\Phi}(x, y) = \Phi_\delta(x, y) + \Phi_{h2}(x, y) \tag{3.2-1}
\]

where \( \Phi_\delta(x, y) = A(x) I(\kappa) + B(x) J(\kappa) + C(x) K(\kappa) + \ldots \)

The coefficients \( A(x) \), \( B(x) \), \( C(x) \), ... are chosen such that the blade boundary conditions are satisfied. This form gives \( \Phi_\delta \) to have zero pitch average and curl free.

The "homogeneous part" of the velocity potential \( \Phi_{h2} \) is chosen so as to satisfy \( \nabla^2 \Phi_{h2} = 0 \), to have zero pitch average, and to match the velocities at the leading and trailing edges with those in regions 1 and 3.

The velocity field in the cascade region can then be written as

\[
\vec{V}_2(x, y) = \vec{V}(x) + [S(x) \nabla \psi(x) + \nabla \tilde{\Phi}_\delta(x, y) + \nabla \phi_{h2}(x, y)] \tag{3.2-2}
\]

### 3.2.1 Smoothing series

For incompressible, continuity requires

\[
\nabla \cdot \vec{V} = 0 \tag{3.2-3}
\]
but \( \vec{\nabla}_x = 1 \) (by continuity of the pitch average flow), and equation (3.2-3) implies

\[ \nabla \cdot \tilde{\omega} = 0 \quad \tag{3.2-4} \]

or

\[ \nabla \cdot \tilde{\varphi}^s = - \nabla \cdot (S \nabla \varphi) \]

Now, from equation (3.2-1), we can write

\[ \nabla^2 \tilde{\varphi}^s = -A |\nabla \alpha|^2 + s(\alpha) \left[ A \nabla^2 \alpha + 2 \nabla A \cdot \nabla \alpha + B |\nabla \alpha|^2 \right] \]

\[ + \ I(\alpha) \left[ \nabla^2 A + B \nabla \alpha + 2 \nabla B \cdot \nabla \alpha + C |\nabla \alpha|^2 \right] \]

\[ + \ J(\alpha) \left[ \nabla^2 B + C \nabla^2 \alpha + 2 \nabla C \cdot \nabla \alpha + D |\nabla \alpha|^2 \right] \]

\[ \vdots \]

To satisfy (3.2-4), we choose

\[ A |\nabla \alpha|^2 = - \nabla \alpha \cdot \nabla \varphi \]

\[ B |\nabla \alpha|^2 = - (\nabla^2 \varphi + 2 \nabla A \cdot \nabla \alpha + A |\nabla \alpha|^2) \]

\[ C |\nabla \alpha|^2 = - (\nabla^2 A + 2 \nabla B \cdot \nabla \alpha + B |\nabla \alpha|^2) \]

\[ \vdots \]

(3.2-5)

and the pattern for all the coefficients is apparent.
3.2.2 Matching conditions

As mentioned earlier, the velocity potentials \( \Phi_h \)'s are used solely to satisfy the far upstream and far downstream flow conditions, and the matching conditions of the velocities at the leading and trailing edges. We have chosen \( \Phi_h \)'s to satisfy Laplace equation; therefore

we assume \( \Phi_h \)'s of the forms:

\[
\Phi_{h1}(x, y) = \sum_{n=1}^{\infty} A_n e^{-\lambda_n |x|} e^{i\lambda_n y}
\]

\[
\Phi_{h2}(x, y) = \sum_{n=1}^{\infty} \left( B_n^+ e^{-\lambda_n |x|} + B_n^- e^{-\lambda_n |x-1|} \right) e^{i\lambda_n y}
\]

\[
\Phi_{h3}(x, y) = \sum_{n=1}^{\infty} C_n e^{-\lambda_n |x-1|} e^{i\lambda_n y}
\]

These assumed forms for \( \Phi_h \)'s satisfy

- Laplace equation
- The far upstream and far downstream flow conditions
- The periodicity condition in the \( y \)-direction of the flow field

The unknowns coefficients, \( A_n \), \( B_n^+ \), \( B_n^- \) and \( C_n \), are determined using the matching conditions of the velocities at the leading and trailing edges:
Now, the velocities in the three regions are the following.

For region 1,
\[
V_{1x} (x=0, y) = V_{2x} (x=0, y)
\]
\[
V_{1y} (x=0, y) = V_{2y} (x=0, y)
\]
\[
V_{2x} (x=1, y) = V_{3x} (x=1, y)
\]
\[
V_{2y} (x=1, y) = V_{3y} (x=1, y)
\]
(3.2-6)

For region 2,
\[
\bar{V}_{2} = \bar{V} (x) + \nabla \phi_{h2}
\]
\[
+ \mathcal{S}(\alpha) (\nabla G + A \nabla \alpha)
\]
\[
+ \mathcal{I}(\alpha) (\nabla A + B \nabla \alpha)
\]
\[
+ \mathcal{J}(\alpha) (\nabla B + C \nabla \alpha)
\]
\[
\vdots
\]
(3.2-7)

For region 3,
\[
\bar{V}_{3} = \bar{V} (+ \infty) + \nabla \phi_{h3}
\]

The "sawtooth" function \( \mathcal{S}(\alpha) \) has a finite jump across any constant \( \alpha \) lines. At the leading and trailing edges, we assume that the flow comes and leaves smoothly (zero-incidence and Kutta conditions respectively). Thus, from (3.2-7), we require at \( X = 0 \) and \( X = 1 \),
\[(\nabla G + A \nabla \kappa) = 0\]

or

\[A(X = 0, 1) = 0\]  \hspace{1cm} (3.2-8)

\[G'(X = 0, 1) = 0\]

From equation (3.2-5), by choosing a loading distribution with the condition 
\[G'(X = 0, 1) = 0,\] we automatically satisfy the condition

\[A(X = 0, 1) = 0.\]

Substituting equation (3.2-7) into equation (3.2-6) using equation (3.2-8), we can show that, in region 2

\[
\mathcal{Y}_{h_2}(x, \gamma) = \sum_{t=0}^{1} \sum_{n=1}^{\infty} \frac{e^{-\frac{\lambda_n t}{x-\gamma}}}{\lambda_n^3} \left\{ \right. \\
\left. + \left( B(t) \sin \lambda_n [y-f(t)] - (-1)^k [A'(t) - B(t) f(t)] \cos \lambda_n [y-f(t)] \right) \right. \\
- \frac{1}{\lambda_n^3} \left( C(t) \cos \lambda_n [y-f(t)] - (-1)^k [B'(t) - C(t) f(t)] \sin \lambda_n [y-f(t)] \right) \\
\cdots \right\} 
\]  \hspace{1cm} (3.2-9)

where

\[\lambda_n = \frac{2\pi n}{\delta}\]

3.2.3 Blade boundary conditions

The blade boundary conditions are used to generate the blade camber.

By adding the blade boundary conditions together, we obtain
Define

\[ f' = \frac{-V_y}{V_x} \]

Then, \( f_0 \) represents the mean streamline.

If we define the blade camber line as

\[ f \equiv f_0 + \Delta f \]

then, we can show that equation (3.2-10) is a perfect derivative in \( \Delta f \) and reduces to

\[
\Delta f(x) = -I(\phi)(\mathbf{G} - A \mathbf{f}') - K(\phi)(\mathbf{B} - C \mathbf{f}') - \ldots \\
- \sum_{\tau=0}^{\infty} \sum_{n=1}^{\infty} \frac{\frac{\lambda}{\lambda_n} |X - \tau|}{\lambda_n^3} \left\{ \\
\left[ (-1)^\tau B(t) - \frac{1}{\lambda_n} [B(t) - C(t) f'(t)] \ldots \right] \cos \lambda_n [f(x) - f(t)] \\
+ \left[ [\Lambda(t) - B(t)] f'(t) + \frac{(-1)^t}{\lambda_n} C(t) \ldots \right] \sin \lambda_n [f(x) - f(t)] \right\}
\]

(3.2-11)

3.3 Iteration process for the blade camber line

We are now in the position to compute the blade shape using equation (3.2-11). We call this equation the "camber generator". The beauty of the
"smoothing" technique is that the blade shape and the velocity field can be obtained by solving a set of algebraic equations, i.e. equations (3.2-5) and (3.2-11):

\[
\begin{align*}
A(x) &= \frac{f'G'}{(1 + f''^2)} \\
B(x) &= \frac{-G'' + 2A'f' + Af''}{(1 + f''^2)} \\
C(x) &= \frac{-A'' + 2B'f' + Bf''}{(1 + f''^2)} \\
\vdots
\end{align*}
\tag{3.3-1}
\]

\[
f(x) = f_0(x) + \Delta f(x)
\tag{3.3-2}
\]

Thus, we have (n+1) equations and (n+1) unknowns. The (n+1) unknowns are: n coefficients in the smoothing series: \( A(x), B(x), C(x), \ldots \), plus the blade camber line \( f(x) \).

We choose to solve the blade camber line by an iteration process. We expect that the blade camber line \( f \) is not very different from the mean streamline \( f_0 \), especially in the case where the spacing \( \delta \) is small. Thus we can use \( f_0 \) as the initial guess for \( f \) and go through the following iteration process:

1. Compute \( A, B, C, \ldots \) (with the guessing value of \( f \) as \( f_0 \) at the first iteration) using equations (3.3-1)
2. Update $f$ by solving equation (3.3-2)

3. Go back to step 1 to update $A$, $B$, $C$, ...
   with the new value of $f$ computed in step 2.
   Continue this process until convergence in $f$ is achieved.

The whole flow field and the pressure coefficients at the blade surfaces can be computed using equations (3.2-7) and Bernoulli's equations.

3.4 "Partial smoothing"

The proposed iteration process for the camber line in section 3.3 shows that we can get infinite accuracy for $f$ by keeping an infinite number of terms in the smoothing series. From the engineering point of view, however, we want to take the least number of terms in the smoothing series for a given required accuracy criteria. "Partial smoothing" refers to the truncation of the smoothing series.

In the inverse problem, we are most interested in three quantities: the blade camber line and the pressure coefficients at the blade upper and lower surfaces. Since $f' \sim V$, we see that $f$ has the same order of accuracy as $\phi$. Similarly, since $C_p \sim V^2$, we see that $C_p$ also has the same order of accuracy as $\phi$. We now construct a table showing the truncation errors in $f$ and $C_p$ as a function of the number of terms used in the smoothing series $\phi$. 
<table>
<thead>
<tr>
<th>Number of terms kept in the smoothing series</th>
<th>Truncation errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$K(\alpha)$</td>
</tr>
<tr>
<td>4</td>
<td>$J(\alpha)$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

### 3.5 Numerical method

As an example of the design problem, we write a program to compute the blade camber line by keeping two terms in the smoothing series. In this case, the smoothing series $\tilde{\varphi}$ is of the form:

$$\tilde{\varphi}(x,y) = A(x)I(\alpha) + B(x)J(\alpha)$$

Let's investigate the order of magnitude of the truncation error in $f$ when the above "partial smoothing" form is used. From equation (3.2-11), we see that the truncation error in $f$ is of the order of $K(\alpha)$, or [Appendix C]:

$$\text{error in } f(x) \sim \frac{8^4}{720}$$

Therefore, for the above example, the truncation error in $f$ is about three orders of magnitude less than $8^4$. By keeping only two terms in the smoothing series, we can still maintain very high accuracy (accurate to $0.0014 \cdot 8^4$). Moreover, the numerical calculation is very simple. Given the loading distribution $\bar{V}_y'(\alpha)$ as an analytical form, the blade camber can be calculated through a set of algebraic equation. No numerical technique is needed to compute derivatives or integrals.
The iteration process for $f$ involves calculating the following parameters:

1. Guess $f$ and its derivatives as:

   \[ f(x) = f_0(x) + \frac{\lambda}{12} (G' - A f_0') \]

   \[ f'(x) = f'_0(x) \]

   \[ f''(x) = f''_0(x) \]

   For simplicity, we set $f''(x) = f''_0(x)$ throughout the iteration process.

2. Compute

   \[ A(x) = \frac{f'G'}{(1 + f'^2)} \]

   \[ A'(x) = \frac{(1 + f'^4)(f'G'' + f''G') - 2f'f''G'}{(1 + f'^2)^2} \]

   \[ B(x) = \frac{-G'' + 2f'A' + Af''}{(1 + f'^2)} \]

3. Update

   \[ f'(x) = f'_0(x) + \frac{\lambda}{12} (G'' - A'f' - Af'') - \frac{d}{dx} (\text{FSUM}) \]
\[ f(x) = f_0(x) + \frac{A'}{l^2} (G' - Af') = F_{SUM} \]

where

\[
F_{SUM} = \sum_{t=0}^{1} \sum_{n=1}^{\infty} \frac{-\lambda_n |x-t|}{\lambda_n^3} \left\{ (-1)^t B(t) \cos \lambda_n [f(x) - f(t)] + [A'(t) - B(t)f'(t)] \sin \lambda_n [f(x) - f(t)] \right\}
\]

4. Go back to step 2 and repeat the calculations until convergence in \( f \) is achieved.

The convergence criteria used in the calculation is, at each location \( X_i \),

\[ f^{n+1}(X_i) - f^n(X_i) \leq \text{ERROR} \]

i.e. if the difference between the present value of \( f \) and the previous value of \( f \) at all locations \( X_i \) is less than ERROR (the convergence criteria), then convergence in \( f \) is achieved.

3.4 Numerical results

Numerical results shows that convergence in \( f \) can be achieved fast, depending on the spacing to chord ratio \( \lambda \). In this section, we present a numerical example. The results are compared with the "exact" solution (using the Biot-Savart law) [4].
We have taken the case of an inlet guide vane with the following inputs:

- spacing to chord ratio \( \delta = 0.75 \)
- inlet angle \( \alpha_1 = 0^\circ \)
- outlet angle \( \alpha_2 = 45^\circ \)
- loading distribution \( \Delta P \sim x(1-x) \)

Calculations are made at 21 points and the convergence criteria \( \text{ERROR} \) is \( 10^{-5} \).

17 iterations are required for \( \int \) to converge. The computer program output is shown in table 1. Figure 2 show the plots of the blade camber line and the mean streamline. Note that there is reverse curvature of the blade near the trailing edge. This observation is also found in the results performed by Tan, Wang, Hawthorne and McCune [4]. The computational time for this example is around 7 seconds CPU time on the Digital VAX-11 computer.

Table 2 shows a comparison of the blade camber obtained from the "smoothing" technique and the "exact" method. The results compare well.

This preliminary study of the "smoothing" technique shows that it is indeed a very powerful engineering tool for the design problem in terms of computational time and accuracy (if desired).
Chapter 4: The "Finite-Thickness" Problem

In this chapter, we will present a method to solve the inverse problem for blades having finite thickness. The method will be similar to the one presented in the "Zero-Thickness" problem, except that we now have to differentiate the average flow quantities. In the case of blades having finite thickness, we can define two average quantities:

1. The pitch average velocity which is defined as:

$$\overline{V}(x) = \frac{1}{\delta} \int_{f}^{f+\delta} V(x, y) \, dy$$

The pitch average velocity has no physical representation of the flow since there is no flow in the blade. However, if we are to model the presence of the blades by distributing singularities on the blade camber lines, then $\overline{V}$ does exist in this sense.

2. The gap average velocity which is defined as:

$$\overline{V_T}(x) = \frac{1}{\delta - 2T(x)} \int_{f+T}^{f+\delta - T} V(x, y) \, dy$$

Obviously, the gap average velocity does represent the average of the actual flow.

In the design problem of blades having finite thickness, as mentioned in the introduction, we choose to model the presence of the blades by distributing vortices, sources and sinks on the blade camber lines. In our method, the two main given quantities are: the loading distribution $\overline{V_T'}$, and the blockage distribution $T$.

Given these two quantities, the gap average velocity is known. It is defined by:
\[
\overline{V_T}(x) = \overline{V_{Tx}}(x) \hat{e}_x + \overline{V_{Ty}}(x) \hat{e}_y
\]

where \( \overline{V_{Tx}}(x) \) is found using continuity, i.e.

\[
\overline{V_{Tx}}(x) = \frac{\Lambda}{\Lambda - 2T(x)}
\]

4.1 Flow regions

Using the same general approach as in the "Zero-Thickness" problem, we again divide the flow field into three regions. The velocity potentials \( \phi_h \) and \( \phi_s \) are used to satisfy the far upstream and far downstream flow conditions, and the matching conditions of the velocities at the leading and trailing edges. We again make use of the "smoothing" functions to satisfy the blade boundary conditions.

The three flow regions are:

1. Region 1

Region 1 is defined in the interval \(-\infty < x < 0\). In this region, the flow is irrotational everywhere. We may write
\[
\mathbf{V}_2 (x, y) = \mathbf{V}(-\infty) + \mathbf{\tilde{V}}_2 (x, y)
\]
\[
\mathbf{\tilde{V}}_2 (x, y) = \nabla \mathbf{h}_2 (x, y)
\]

where \( \mathbf{V}(-\infty) \) is the inlet flow condition. The boundary conditions are:

- far upstream \( \nabla \mathbf{h}_2 = 0 \)
- at the leading edge \( \mathbf{V}_1 = \mathbf{V}_2 \)

(2) Region 2

Region 2 is defined in the interval \( 0 < x < 1 \). We choose to analyze the flow in a region between the blade camber lines. The flow in this region is divergence free and curl free. We may write

\[
\mathbf{V}_2 (x, y) = \nabla \phi (x, y)
\]
\[
\nabla^2 \phi = 0
\]

The boundary conditions in this region are:

- matching conditions at the leading and trailing edges
- no flow-through condition at the blade surfaces

(3) Region 3

Region 3 is defined in the interval \( 1 < x < +\infty \). In this region, the flow is irrotational. We may write

\[
\mathbf{V}_3 (x, y) = \mathbf{V}(+\infty) + \mathbf{\tilde{V}}_3 (x, y)
\]
\[
\mathbf{\tilde{V}}_3 (x, y) = \nabla \mathbf{h}_3 (x, y)
\]

where \( \mathbf{V}(+\infty) \) is the outlet flow condition. The boundary conditions in this region are:
- far downstream $\nabla^2 p = 0$
- at the trailing edge $\nabla \phi = \nabla \phi_3$

4.2 Solution of the velocity field

Consider the flow between the two camber lines (excluding these camber lines) located at $y = f^+$ and $y = f^- + \delta$. In this region, we can write $\nabla \phi$ as a velocity potential satisfying Laplace equation:

$$\nabla \phi = \nabla \phi_3$$

Let's assume $\phi$ to be of the form

$$\phi(x, y) = S(x) G_T(x) + \bar{\phi}(x) + \phi_{T5}(x, y) + \phi_{h2}(x, y)$$

where the smoothing series $\phi_{T5}$ is assumed to be of the form

$$\phi_{T5}(x, y) = \bar{\phi}_{T5}(x) + \delta(x) S(x)$$

$$+ A_T(x) I(x) + B_T J(x) + ...$$

and thus, $\phi$ can be written as

$$\phi(x, y) = \left[ G_T + \delta \right] S(x) + \bar{\phi} + \phi_{T5} + \phi_{h2}$$

$$A_T I(x) + B_T J(x) + ...$$

Combining equation (4.2-1), (4.2-2) along with the choice $\nabla^2 \phi_{h2} = 0$, we obtain

$$\nabla^2 \phi_{T5} = - \nabla^2 \phi - S \nabla G_T + 2 \nabla G_T \nabla \delta - G_T \nabla^2 S$$
Based on the experience from the "Zero-Thickness" problem, there are a few motivations in choosing $\phi$ of the above form:

- $\delta$ in the smoothing series $\phi_\tau$ is the additional amount of vorticity needed to represent the total amount of vorticity distributed on the blade camber lines.

- $\overline{\phi}$ and $\overline{\phi}_\tau$ represent some average in the potential velocity which we have the freedom to choose at our convenience.

- $\phi_{nz}$ is chosen to satisfy the matching conditions at the leading and trailing edges.

- $A_\tau, B_\tau, C_\tau, \ldots$ are chosen to satisfy the blade boundary conditions.

We are now in the position to solve for the velocity field in region 2. Our tasks are to:

1. relate some of the unknowns in the assumed form of $\phi$ to the given gap average velocity $\overline{\nu}_\tau$

2. satisfy the Poisson equation (4.2-5)

3. satisfy the blade boundary conditions

$$\overline{\nu}_\perp \cdot \nabla (\kappa - \tau) = 0 \quad (4.2-6)$$

$$\overline{\nu}_\parallel \cdot \nabla (\kappa + \tau) = 0 \quad (4.2-7)$$

4.2.1 Relation between the gap average velocity and the unknowns

In this subsection, we relate some of the unknowns in the velocity potential $\phi$ defined in equation (4.2-4) to the gap average velocity.

By definition of the gap average velocity,
\[
\int_{f+T}^{f+\Delta -T} \nabla \phi \, dy = (\Delta - 2T) \overline{\nabla}_T \\
= 2 \, S(T) \overline{\nabla}_T
\]

Evaluating the above integral using equation (4.2-4), we obtain

\[
(\overline{\Phi} + f'(G_T) \hat{e}_x + (-G_T) \hat{e}_y + (\nabla \phi_{TS} + \nabla \phi_{h2})_T = \overline{\nabla}_T
\]

We now choose the coefficients in \( \phi \) such that

\[
(\overline{\Phi} + f'(G_T) \hat{e}_x + (-G_T) \hat{e}_y = \overline{\nabla}_T
\]

Therefore, we require

\[
(\overline{\Phi} + f'(G_T) = \overline{\nabla}_T \hat{x}
\]

and

\[
(\nabla \phi_{TS} + \nabla \phi_{h2})_T = 0
\]

Equation (4.2-8) requires

\[
\overline{\Phi}' = \overline{\nabla}_T \hat{x} - f'(G_T)
\]

Equation (4.2-9), a vector quantity, can be satisfied by choosing

\[
\delta = - \frac{J(T)}{S(T)} B_T - \frac{L(T)}{S(T)} D_T - \ldots
\]

and

\[
\overline{\Phi}_{TS} = \frac{S(T)}{S(T)} (A'_T - B_T f') + \frac{L(T)}{S(T)} (C'_T - D_T f') \ldots
\]

\[
- \delta f' - (\frac{\partial \phi_{h2}}{\partial x}) T
\]
Define

$$\beta = \frac{\mathcal{I}(\tau)}{S(\tau)} (A'_T - B_T f') + \frac{L(\tau)}{S(\tau)} (C'_T - J_T f') + \cdots \quad (4.2-13)$$

We will show later that $\beta$ relates to the source/sink strength.

4.2.2 Satisfaction of the Poisson equation

We now choose the coefficients in the smoothing series so that the Poisson equation (4.2-5) can be satisfied.

From the assumed form of the smoothing series $\phi_{TS}$, equation (4.2-3), we can write

$$\nabla^2 \phi_{TS} = (\nabla^2 \phi_{TS} - \delta \nabla \phi - \phi \nabla \nabla \phi - A_T |\phi|^2)$$

$$+ S(\phi) (\nabla^2 \phi + A_T \nabla \phi + 2 \nabla A_T \cdot \nabla \phi + B_T |\phi|^2)$$

$$+ I(\phi) (\nabla^2 A_T + B_T \nabla \phi + 2 \nabla B_T \cdot \nabla \phi + C_T |\phi|^2)$$

$$+ J(\phi) (\nabla^2 B_T + C_T \nabla \phi + 2 \nabla C_T \cdot \nabla \phi + D_T |\phi|^2)$$

$$+ \cdots$$

Substituting the above equation into equation (4.2-5) using equations (4.2-10) through (4.2-12), we obtain, in scalar form
The above equation is of the form

$$a_0(x) = g_1(x,y) a_1(x) + g_2(x,y) a_2(x) + \ldots$$

One way to satisfy the above equation is to choose

$$a_0(x) = 0$$
$$a_1(x) = 0$$
$$a_2(x) = 0$$
$$\vdots$$

Using the choices suggested above, we obtain

$$A_T |\nabla \kappa|^2 = f'(G_T' + \delta') + (\overline{V}_{T\kappa} + \beta')$$
\[ B_T |\nabla \alpha |^2 = - \left( \mathcal{G}_T'' + \delta'' \right) + A_T f'' + 2 A_T' f' \]
\[ C_T |\nabla \alpha |^2 = - A'' + B_T f'' + 2 B_T' f' \]
\[ D_T |\nabla \alpha |^2 = - B'' + C_T f'' + 2 C_T' f' \]

\[ \vdots \]

(4.2-14)

By choosing \( A_T, B_T, C_T, \ldots \) of the above forms, it turns out that one of the blade boundary conditions is satisfied. This fact will be discussed in section (4.2.4).

4.2.3 Matching conditions

As in the infinitely thin blade case, the velocity potential \( \varphi_{h \eta}, \lambda \) are used to satisfy the matching conditions of the velocities at the leading and trailing edges, and the far upstream and far downstream flow conditions. Again, \( \varphi_{h \eta}, \lambda \) are chosen to satisfy Laplace equation. A similar analysis for \( \varphi_{h z} \) as in the "Zero-Thickness" problem gives:

\[
\varphi_{h z} (x, y) = \sum_{t=0}^{1} \sum_{n=1}^{\infty} \frac{e^{-\lambda_n |x-t|}}{\lambda_n^2} \left\{ \begin{array}{l}
+ \left( B_T(t) \sin \lambda_n [y-f(t)] - (1)^t [A_T'(t) - B_T(t) f'(t)] \cos \lambda_n [y-f(t)] \right) \\
- \frac{1}{\lambda_n} \left( C_T(t) \cos \lambda_n [y-f(t)] - (1)^t [B_T'(t) - C_T(t) f'(t)] \sin \lambda_n [y-f(t)] \right) \\
+ \cdots \end{array} \right. 
\]

(4.2-15)
where \( \lambda_n = \frac{2\pi n}{\beta} \)

With the analysis done so far, we can now write down the velocity in region 2:

\[
V_2(x, y) = \bar{V}_2(x) + \left[ \beta(x) \hat{e}_x - \delta(x) \hat{e}_y \right] + \nabla \phi_{z2}(x, y) \\
+ S(\alpha) \left[ \nabla \left( \xi_2(x) + \delta(x) \right) + A_2(x) \nabla \alpha \right] \\
+ I(\alpha) \left[ \nabla B_2(x) + C_2(x) \nabla \beta \right] \\
+ J(\alpha) \left[ \nabla A_2(x) + B_2(x) \nabla \alpha \right] + \ldots 
\]

(4.2-16)

Again, we require

\[
\begin{align*}
A_T &= 0 \\
\mathcal{G}' + \delta' &= 0
\end{align*}
\]

at \( X = 0,1 \)

for the flow to come and leave smoothly leading and trailing edges (the zero-incidence and the Kutta conditions respectively). Using the definition of \( A_T \) in equation (4.2-14), the above conditions become:

\[
\begin{align*}
\mathcal{G}' + \delta' &= 0 \\
\mathcal{V}'_{xT} + \beta' &= 0
\end{align*}
\]

at \( X = 0,1 \) (4.2-17)

4.2.4 Blade boundary conditions

So far, we have chosen all the coefficients in the expression for \( \phi \). We must now satisfy the two blade boundary conditions, i.e. equations (4.2-6) and (4.2-7). It turns out that one boundary condition is automatically satisfied
through the choices of $A_T$, $B_T$, $C_T$, ... in equation (4.2-14) while the other blade boundary condition is used to generate the blade camber line.

By adding and subtracting equations (4.2-6) and (4.2-7), the blade boundary conditions become:

$$< \nabla \phi >_T \cdot \nabla \alpha - \Delta_T (\nabla \phi) \cdot \nabla T = 0$$

$$\Delta_T (\nabla \phi) \cdot \nabla \alpha - < \nabla \phi >_T \cdot \nabla T = 0$$

Evaluating $\nabla \phi$ at the upper and lower surfaces of the blade and substituting them into the above equations, we obtain:

$$- (G_T + \delta) + (\nabla \phi + \nabla \phi_T) \cdot \nabla \alpha + < \nabla \phi >_{h_T} \cdot \nabla \alpha$$

$$+ I(\tau) \left[ \nabla A_T \cdot \nabla \alpha + B_T |\nabla \alpha|^2 \right]$$

$$+ K(\tau) \left[ \nabla C_T \cdot \nabla \alpha + D_T |\nabla \alpha|^2 \right] + ...$$

$$= \Delta_T (\nabla \phi_{h_T}) \cdot \nabla T$$

$$+ S(\tau) \left[ \nabla (G_T + \delta) \cdot \nabla T + A_T \nabla \alpha \cdot \nabla T \right]$$

$$+ J(\tau) \left[ \nabla B_T \cdot \nabla T + C_T \nabla \alpha \cdot \nabla T \right] + ...$$

(4.2-18)

and
\[ \Delta_T (\nabla \psi_{h_2}) \cdot \nabla \alpha \]
\[ + S(\tau) \left[ \nabla (G_T + \delta) \cdot \nabla \alpha + A_T |\nabla \alpha|^2 \right] \]
\[ + J(\tau) \left[ \nabla B_T \cdot \nabla \alpha + C_T |\nabla \alpha|^2 \right] + \ldots \]
\[ = - (G_T + \delta) \nabla \alpha \cdot \nabla T + (\nabla \phi + \nabla \phi_T) \cdot \nabla T \]
\[ + < \nabla \phi_{h_2} >_T \cdot \nabla T \]
\[ + I(\tau) \left[ \nabla A_T \cdot \nabla T + B_T \nabla \alpha \cdot \nabla T \right] \]
\[ + K(\tau) \left[ \nabla C_T \cdot \nabla T + D_T \nabla \alpha \cdot \nabla T \right] + \ldots \]

By substituting the choices of \( A_T, B_T, C_T \ldots \) in equations (4.2-14) into equation (4.2-19) and along with the identity

\[ \frac{d}{d\chi} \left[ S(\tau) \left( \frac{\nabla \psi_{h_2}}{\nabla \alpha} \right)_T \right] = \Delta_T (\nabla \psi_{h_2}) \cdot \nabla \alpha \]
\[ - < \nabla \psi_{h_2} >_T \cdot \nabla T \]

we can show that the blade boundary condition (4.2-19) is automatically satisfied.

Finally, the other blade boundary condition, equation (4.2-18), is satisfied by choosing the blade camber line \( \ell \) appropriately. We will call equation (4.2-18) the "camber generator".

Substituting the choices of the coefficients \( A_T, B_T, C_T, \ldots \) into the blade boundary conditions (4.2-18), we obtain
\[ S(\tau) \nabla_T \cdot \nabla \alpha = S(\tau) \left( \nabla h_z \right)_T \cdot \nabla \alpha \]
\[ + S(\tau) \left\{ \Delta_T \left( \nabla h_z \right) \cdot \nabla T - \left< \nabla h_z \right>_T \cdot \nabla \alpha \right\} \]
\[ + \left[ J(\tau) \frac{d}{dx} + s(\tau) \frac{d}{dx} I(\tau) \right] \left\{ (\underline{\varepsilon} \tau + \delta') - A_T \Phi' \right\} \]
\[ + \left[ L(\tau) \frac{d}{dx} + s(\tau) \frac{d}{dx} K(\tau) \right] \left\{ B_T - C_T \Phi' \right\} \]
\[ + \ldots \]  

(4.2-20)

This is a differential equation relating \( \Phi \) and the coefficients \( A_T, B_T, C_T, \ldots \). As in the "Zero-Thickness" problem, we can reduce the above equation into an algebraic equation for \( \Phi \) (in the iterative sense).

Again, define

\[ \Phi' (x) \equiv \frac{V_{TY}}{V_{TX}} \]

Then \( \Phi' \) represents the mean streamline.

Also, define

\[ \Phi (x) = \Phi_0 (x) + \Delta \Phi (x) \]

Then, referring to equation (4.2-20), it can be shown that

\[ S(\tau) \nabla_T \cdot \nabla \alpha = -\frac{1}{2} \frac{d}{dx} (\Delta \Phi) \]
\[
\begin{align*}
\left[ J(T) \frac{d}{dx} + S(T) \frac{d}{dx} \right] \left\{ (G'_T + \delta'_T) - A_T f' \right\} \\
= \frac{d}{dx} \left[ \left[ J(T) + S(T) \right] I(T) \right] \left\{ (G'_T + \delta'_T) - A_T f' \right\}
\end{align*}
\]
\[
\begin{align*}
\left[ L(T) \frac{d}{dx} + S(T) \frac{d}{dx} K(T) \right] \left\{ B'_T - C_T f' \right\} \\
= \frac{d}{dx} \left[ \left[ L(T) + S(T) K(T) \right] [ B'_T - C_T f' ] \right]
\end{align*}
\]
and finally
\[
\begin{align*}
S(T) \left\{ \Delta_T (\nabla \varphi_{h_2}) \cdot \nabla T - \langle \nabla \varphi_{h_2} \rangle \cdot \nabla \alpha \right\} \\
+ S(T) \left( \overline{\nabla \varphi_{h_2}} \right) \cdot \nabla T = \frac{d}{dx} (FSUM)
\end{align*}
\]
where
\[
FSUM = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{e^{-\lambda_n l x - t}}{\lambda_n^2} \left( \frac{\sin \Lambda_n T}{\Lambda_n} + S(T) \cos \Lambda_n T \right) \left\{ \begin{array}{c} \\
\left[ (-i)^{t} B_T (t) - \frac{1}{\lambda_n} \left[ B'_T (t) - C_T (t) f' (t) \right] \\
- \frac{(-1)^t}{\lambda_n^2} D_T (t) + \ldots \right] \cos \Lambda_n \left[ f (x) - f (t) \right] \\
\left[ \left[ A'_T (t) - B_T (t) f' (t) \right] \right. \\
+ \frac{(-1)^t}{\lambda_n} C_T (t) \\
\left. - \frac{1}{\lambda_n} \left[ C'_T (t) - D_T (t) f' (t) \right] - \ldots \right] \sin \Lambda_n \left[ f (x) - f (t) \right] \end{array} \right. \}
\]
Combining these equations together, the "camber generator" becomes
\[ \Delta f(x) = -\frac{2}{\lambda} \left[ J(\tau) + S(\tau) I(\tau) \right] (G + \delta_A + A_T f') \\
- \frac{2}{\lambda} \left[ L(\tau) + S(\tau) K(\tau) \right] (B_T C_T f') - \cdots \\
- \frac{2}{\lambda} (F_{SUM}) \] (4.2-21)

4.3 Iteration process for the blade camber line

We choose a very similar iteration scheme used in the "Zero-Thickness" problem. The iteration process consists of calculating the coefficients \( A_T \), \( B_T \), \( C_T \), ... using equations (4.2-14). Then, update \( S' \) and \( \beta' \) using equations (4.2-11) and (4.2-13). Finally, update \( f \) using equation (4.2-21).

In quantitative forms,

1. Compute

\[
A_T(x) = \frac{f' \left( G_T' + \delta' \right) + \left( \bar{V}_T'' + \beta' \right)}{\left( 1 + f'' \right)} \\
B_T(x) = \frac{-(G_T'' + \delta'') + A_T f'' + 2 A_T f'}{\left( 1 + f'' \right)} \\
C_T(x) = \frac{-A_T'' + B_T f'' + 2 B_T f'}{\left( 1 + f'' \right)}
\] (4.3-1)
\[ D(x) = \frac{-B'' + Cf'' + 2C'f'}{(1 + f')^2} \]

2. Update

\[
\beta' = \frac{d}{dX}\left[ \frac{j(x)}{s(x)} \left( A' - Bf' \right) + \frac{L(x)}{s(x)} \left( C' - Df' \right) + \cdots + \left( \frac{\partial^2 y}{\partial x^2} \right) \right]
\]

\[
\delta' = \frac{d}{dX}\left[ \left( \frac{j(x)}{s(x)} \right) B - \frac{j(x)}{s(x)} D - \cdots \left( \frac{\partial^2 y}{\partial x^2} \right) \right] \tag{4.3-2}
\]

\[
f(x) = f_0(x) + \Delta f(x)
\]

In order to start the above iteration process, we need to know not only an initial guess for \( f \), but also for \( \beta' \) and \( \delta' \). A discussion of the "physical" representations of \( \beta \) and \( \delta \) is given in Appendix D.

4.4 Numerical method

A computer program is written to solve the inverse problem using "partial smoothing" (refer to section 3.4). As mentioned in section 4.3, the iteration process for \( f \) consists of, in "partial smoothing" forms:

1. Guess \( \beta', \delta', f \) as:
\[ \beta' = \bar{V}_{T_x} (\sin 2\pi x - 1) \]
\[ \delta' = 0 \]
\[ f = f_0(x) + \frac{\gamma}{\beta} \left[ J(T) + S(T) I(T) \right] (G'_T + \delta' - A_T f') \]

2. Compute
\[ A_T(x) = \frac{f' (G'_T + \delta') + (\bar{V}_{T_x} + \beta')}{{(1 + f'/2)}^2} \]
\[ B_T(x) = \frac{(G''_T + \delta'') + A_T f'' + 2 A_T f'}{{(1 + f'/2)}^2} \]

3. Update
\[ f(x) = -\frac{\gamma}{\beta} \left[ J(T) + S(T) I(T) \right] (G'_T + \delta' - A_T f') \]
\[ -\frac{\gamma}{\beta} (F_{SUM}) \]

4. Check for convergence. If not, go back to step 2 to recompute \( A_T, B_T \) with the updated values of \( \beta', \delta' \) and \( f' \) and continue this process until convergence in \( f \) is achieved.

As in the "Zero-Thickness" problem, the convergence criteria for \( f \) used during the iteration process is, at every location \( x_i \), we require
\[ f^{n+1}(x_i) - f^n(x_i) \leq \text{ERROR} \]

for convergence to succeed.

After convergence has been achieved, we proceed to calculate the pressure coefficients on the blade surfaces defined by:
\[ C_p = 1 - \left( \frac{V}{V_{onset}} \right)^2 \]

where \( V \) is defined in equation (4.2-16), and \( V_{onset} \) is defined as

\[ V_{onset} = \sqrt{1 + \frac{1}{4} \left( \tan \alpha_1 + \tan \alpha_2 \right)^2} \]

Finally, in order to accelerate convergence, we pre-calculate all leading and trailing edges variables needed in the iteration process. The flow chart for the computer program is shown in table 4.

The above iteration process requires computing derivatives. Two methods of computing derivatives were investigated: the Spectral method (Chebyshev collocation) [7], [8], and the finite difference method (central difference). The finite difference method was chosen over the Spectral method because it is numerically more stable.

Numerical problems were encountered in the iteration process for \( f \). Due to "partial smoothing", this method is not able to resolve the singular point in the source/sink distribution at the leading edge. It was found that when approximately 11 points (depending on the value of the spacing \( \delta \) ) are used in the calculation, convergence in \( f \) is achieved in about 10 iterations. When more than 11 points are used in the calculation, the iteration process fails to converge. We propose to use a filter to resolve this problem. Studies of this numerical problem and the filtering method are discussed in Appendix E.
4.5 Design choices

In our method, there are two main input parameters available to the designer: The blockage distribution \( T(x) \) and the loading distribution \( V_{xy}(x) \). As an example, we use analytical forms for both \( T(x) \) and \( V_{xy}(x) \) as inputs to our numerical code.

4.5.1 Blockage distribution

In our numerical example, the blockage distribution \( T(x) \) is chosen to be of the form

\[
T(x) \sim x^a (1-x)^b
\]

We define the maximum blockage parameter BLOCK as

\[
\text{BLOCK} \equiv \frac{2T_{\text{max}}}{\delta}
\]

We restrict ourselves to the case where \( T' = 0 \) at the trailing edge. If \( T'(1) \neq 0 \), then a stagnation point must exist at the trailing edge. We do not think that this is a good model of the real flow. In the actual low speed flow situation, the potential flow outside the boundary layer is pushed away from the trailing edge by the presence of the wake. Therefore, we think that the condition \( T'(1) = 0 \) is a better model for the real flow giving more realistic pressure coefficients at the trailing edge. This condition require \( a > 1 \). We note that this is not the restriction of our method. \( b \) can be any real number.
4.5.2 Loading distribution

In our numerical example, the loading distribution is taken to be of the form

\[ V_{\tau y}' \sim \Delta P \sim X^c (1 - X)^d \]

where \( c \) and \( d \) can be any real numbers.

With these design choices, we will be able to study some effects of the blockage and loading distributions on the pressure coefficients at the blade surfaces. A more practical way would be to read in the thickness and loading distributions at discrete points and use a numerical method to compute their derivatives and integrals.

4.6 Numerical results

In this section, we will first discuss the limitations of our current numerical code. Then, we will attempt to close the loop for our method using a direct method. Finally, some results are presented.

Limitations of the current numerical code

Our current numerical code (using the iteration scheme of section 4.4) is limited to the following cases:

1. when the axial chord is divided into 10 intervals or less (< 11 points), \( f \) converges without using the filter. Otherwise, the filter is needed for convergence in \( f \) to succeed.
2. when the spacing to chord ratio $\delta$ is of the order of 1 and greater, $f$ converges slow and fails to converge when the convergence criteria $\text{ERROR}$ is less than $10^{-4}$.

These problems can be resolved if many more terms in the smoothing series (equation(4.2-3)) are kept so that the singular point at the leading edge can be resolved. However, we decide not to do so because the idea of the "smoothing" technique is to be able to achieve high accuracy using very few terms in the smoothing series.

Closing the loop

Our design method is supposed to find the blade shape which is supposed to do two specified jobs: a certain amount of circulation, and a certain loading distribution. Given these two parameters and the blockage distribution, our numerical code computes the corresponding blade shape and pressure coefficients at the blade surfaces.

Does this blade profile actually do the specified jobs? In an attempt to answer this question, we use a direct method to compute the circulation and the pressure coefficients of the blade shape obtained from our indirect method. If there are agreements in these results between the two methods, then we succeed to close the loop for our design method.

We choose the direct method developed by McFarland [10]. It makes use of the panel method. The numerical code has many options, some of which are what we need to perform the comparison.

In general, results of the comparison show that:

- for the individual pressure coefficients, there are good agreements between the two methods (\(\sim 5\%\)) away from the leading and
trailing edges \((.1 < X < .9)\). Near the edges, the two results differ substantially (see example discussed below).

- for the loading (or pressure difference across the blade) distribution, the two results agree within 5%.

- for the circulation (or comparing the outlet angle), the two results agree well within 5%.

An example of closing the loop for our design problem is now presented. We have taken the case where:

- inlet angle \(\alpha_1 = 0^\circ\)
- outlet angle \(\alpha_2 = 45^\circ\)
- BLOCK = .1
- spacing \(A = .5\)
- \(T \sim X (1 - X)^2\)
- \(\Delta p \sim X^{0.5} (1 - X)\)

Table 4 and 5 show the numerical results of our indirect method using 11 points and 41 points respectively. Note that the two results agree well within the error of the numerical scheme used to compute derivatives. Figures 3 and 4 show the corresponding blade shapes and pressure coefficients.

The pressure coefficients for the above blade shape (obtained from our indirect method) are calculated using the direct method. Two options in the direct method program are used:

1. Option 1 - the inlet flow condition is specified, and the program uses the Kutta condition to determine the outlet flow condition.

2. Option 2 - both the inlet and outlet flow conditions are specified (or the circulation is specified).
Table 6 shows the results obtained using option 1. The results show that:

- the exit flow angle is 45.42°, compared to the specified outlet angle of 45°.
- the loading distribution is of the specified shape (figure 5).

Table 7 shows the results obtained using option 2. The results are very similar to those obtained using option 1.

Figure 6 shows a comparison of the pressure coefficients obtained from the direct and indirect methods. It shows that the two results agree well away from the leading and trailing edges. Near these edges, the pressure coefficients obtained from the direct method show oscillations. At the trailing edge, because our blade shape is thin, the direct method fails to fit a curve through the control points giving negative thickness. Consequently, the Kutta condition at the trailing edge is not satisfied, and the results near the edges are not to be trusted.

We conclude that the blade shape obtained from our design method succeed to do the two specified jobs. We were unable to close the loop completely, but the individual pressure coefficients obtained from the two methods do have the same general shape.

Comparison of the "Zero-Thickness" and "Finite-Thickness" results in the zero blockage limit

It is found that, in the limit of $T(x)$ going to zero, the blade camber lines obtained from the two theories are not the same. Although the two theories themselves are the same in this limit, the results are not the same
because the "Zero-Thickness" problem does not predict the presence of a stagnation point at the leading edge while the "Finite-Thickness" problem does.

Table 8 shows an example of how the camber lines obtained from the two theories compare. Plots of these two blade camber lines are shown in figure 7.

**Effects of the spacing to chord ratio on the blade camber**

Figure 8 shows the effects of the spacing to chord ratio \( \lambda \) on the blade camber line. As \( \lambda \) increases, a smaller number of blades are available to do the same job resulting in highly cambered blades.

**Effects of the maximum blockage on the pressure coefficients**

Figure 9, 10, 11 show the effects of increasing the parameter BLOCK (the maximum blockage) on the pressure coefficients. We have taken the case where:

- inlet angle = \( 0^\circ \)
- outlet angle = \( 45^\circ \)
- spacing to chord \( \lambda = 0.5 \)
- \( T \sim X(1-X)^2 \)
- \( \Delta p \sim X(1-X) \)

As the parameter BLOCK increases, the flow near the maximum thickness location (in this example \( X^* = .33333 \)) accelerates due to the Venturi effect. This effect can result in highly unfavorable pressure gradients at both the upper and lower surfaces if the loading distribution is not chosen
properly. Figure 11 shows such a situation. A better loading distribution should be sought for this example to give more acceptable pressure coefficients.

**Rounded leading edge example**

Figure 12 shows an example of an inlet guide vane having a rounded leading edge. Compare with figure 10 (this is a fair comparison since all inputs in the two cases are the same except for the blockage distribution), we see that the effect of the rounded leading edge is to further overexpand the fluid near the leading edge. However, we do not think the current numerical code can resolve the rounded leading edge case accurately because of the limitations on the size of the computational intervals.

**4.7 Design procedure**

The numerical code outlined in section 4.5 can be used to explore the effects of blade loading and blockage distributions on the behavior of the pressure coefficients at the blade surfaces. Given some design requirements, the designer can use the above program to find the "best" blade shape using a trial and error method.

In this section, we present an example of a design procedure using our numerical code. Suppose that we wish to design inlet guide vanes which can do the following jobs:

- the flow is to be turned from $\alpha_1 = 0^\circ$ to $\alpha_2 = 45^\circ$, with a spacing to chord ratio $\Delta = .5$. 
- the blockage distribution is to have an analytical shape of the form

\[ X \left( 1 - X \right)^2 \]

with the maximum blockage parameter \( BLOCK = 0.1 \).

We seek a loading distribution which gives "good" pressure coefficients at
the blade surfaces (in terms of minimizing flow separation). We start the trial
and error process by choosing the loading distributions which is

1. highly loaded near the leading edge (maximum at \( X = .33333 \)).

   Figure 13 shows the corresponding blade shape and pressure
   coefficients.

2. highly loaded at midchord. Figure 14 shows the corresponding
   blade shape and pressure coefficients.

3. highly loaded near the trailing edge (maximum at \( X = .66666 \)).

   Figure 15 shows the corresponding blade shape and pressure
   coefficients.

Comparing the results, we conclude that, for the above example, case 1
gives the "best" pressure coefficients. In general, results show that by loading
high near the leading edge, the corresponding pressure coefficients are "good".
Figure 16 shows an example of a compressor blade after going through the
above trial and error process. Figure 17 shows an example of an impulse
blade going after going through the same process.
Chapter 5: Conclusion

A two-dimensional design method for highly-loaded blades was presented in this thesis. Singularities are distributed on the blade camber lines to model the presence of the blades. The non-linear theory is based in part on the Clebsch formulation. A "smoothing" technique was used to solve for the blade boundary conditions. Numerical examples was presented using a "partial smoothing" form of the iteration scheme for the blade camber lines.

It was found that when the blades are assumed to be infinitely thin, the blade camber lines can be solved through an iteration process of a set of algebraic equations. The iteration process converges very fast (~7 seconds CPU time on the Digital VAX-11 computer) for the typical solidity range found in turbomachines. The results compare very well with those obtained from an "exact" method.

When the blades are assumed to have finite thickness, the "partial smoothing" form of the iteration scheme for the blade camber lines fails to resolve the singular point at the blade leading edge accurately. In order to get high accuracy, an infinite number of terms in the smoothing series would have to be kept, making the "smoothing" technique less attractive compared to other techniques. A practical numerical code based on a "partial smoothing" form of the iteration scheme for the blade camber lines was presented giving very fast convergence solutions (~10 seconds CPU time on the Digital VAX-11 computer) with satisfactory accuracy.
References


8. Tan, C.S., Private Communication


INPUT

SPACING S = 0.75
INLET ANGLE = 0.000
OUTLET ANGLE = 45.000
NUMBER OF POINTS = 21
PARABOLIC LOADING INPUT PROPORTIONAL TO x(1-x)

CONVERGENCE HISTORY OF F(X)

<table>
<thead>
<tr>
<th>ITER</th>
<th>ERRMAX = 0</th>
<th>AT X = 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01466</td>
<td>90000</td>
</tr>
<tr>
<td>2</td>
<td>0.00336</td>
<td>50000</td>
</tr>
<tr>
<td>3</td>
<td>0.00127</td>
<td>45000</td>
</tr>
<tr>
<td>4</td>
<td>0.00039</td>
<td>55000</td>
</tr>
<tr>
<td>5</td>
<td>0.00027</td>
<td>45000</td>
</tr>
<tr>
<td>6</td>
<td>0.00013</td>
<td>40000</td>
</tr>
<tr>
<td>7</td>
<td>0.00011</td>
<td>45000</td>
</tr>
<tr>
<td>8</td>
<td>0.00007</td>
<td>50000</td>
</tr>
<tr>
<td>9</td>
<td>0.00006</td>
<td>45000</td>
</tr>
<tr>
<td>10</td>
<td>0.00004</td>
<td>50000</td>
</tr>
<tr>
<td>11</td>
<td>0.00003</td>
<td>45000</td>
</tr>
<tr>
<td>12</td>
<td>0.00003</td>
<td>50000</td>
</tr>
<tr>
<td>13</td>
<td>0.00002</td>
<td>45000</td>
</tr>
<tr>
<td>14</td>
<td>0.00002</td>
<td>50000</td>
</tr>
<tr>
<td>15</td>
<td>0.00001</td>
<td>45000</td>
</tr>
<tr>
<td>16</td>
<td>0.00001</td>
<td>50000</td>
</tr>
<tr>
<td>17</td>
<td>0.00001</td>
<td>55000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>X</th>
<th>FM(X)</th>
<th>FLOW ANGLE</th>
<th>F(X)</th>
<th>BLADE ANGLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0000</td>
<td>0 0000</td>
<td>0 00000</td>
<td>0 00000</td>
<td>-9 10520</td>
</tr>
<tr>
<td>0 0500</td>
<td>0 0012</td>
<td>0 41538</td>
<td>-0 00809</td>
<td>-9 27549</td>
</tr>
<tr>
<td>0 1000</td>
<td>0 0095</td>
<td>1 60386</td>
<td>-0 01633</td>
<td>-8 61382</td>
</tr>
<tr>
<td>0 1500</td>
<td>0 0312</td>
<td>3 47844</td>
<td>-0 23244</td>
<td>-6 47547</td>
</tr>
<tr>
<td>0 2000</td>
<td>0 0720</td>
<td>5 93741</td>
<td>-0 27668</td>
<td>-2 95814</td>
</tr>
<tr>
<td>0 2500</td>
<td>0 1567</td>
<td>8 88085</td>
<td>-0 28410</td>
<td>2 22342</td>
</tr>
<tr>
<td>0 3000</td>
<td>0 2295</td>
<td>12 68862</td>
<td>-0 23800</td>
<td>8 79763</td>
</tr>
<tr>
<td>0 3500</td>
<td>0 3537</td>
<td>15 73617</td>
<td>-0 12930</td>
<td>15 43566</td>
</tr>
<tr>
<td>0 4000</td>
<td>0 5120</td>
<td>19 39320</td>
<td>0 03820</td>
<td>21 19807</td>
</tr>
<tr>
<td>0 4500</td>
<td>0 7062</td>
<td>23 03781</td>
<td>0 25883</td>
<td>26 04913</td>
</tr>
<tr>
<td>0 5000</td>
<td>0 8375</td>
<td>26 56504</td>
<td>0 52898</td>
<td>30 19280</td>
</tr>
<tr>
<td>0 5500</td>
<td>0 1208</td>
<td>29 08813</td>
<td>0 84603</td>
<td>33 76094</td>
</tr>
<tr>
<td>0 6000</td>
<td>0 1512</td>
<td>32 94323</td>
<td>0 11954</td>
<td>36 63603</td>
</tr>
<tr>
<td>0 6500</td>
<td>0 1853</td>
<td>35 68779</td>
<td>0 15883</td>
<td>39 48203</td>
</tr>
<tr>
<td>0 7000</td>
<td>0 2229</td>
<td>38 09645</td>
<td>0 20192</td>
<td>41 75705</td>
</tr>
<tr>
<td>0 7500</td>
<td>0 2637</td>
<td>40 15600</td>
<td>0 24621</td>
<td>43 86834</td>
</tr>
<tr>
<td>0 8000</td>
<td>0 3072</td>
<td>41 86034</td>
<td>0 29744</td>
<td>45 27878</td>
</tr>
<tr>
<td>0 8500</td>
<td>0 3531</td>
<td>43 20571</td>
<td>0 34918</td>
<td>46 50853</td>
</tr>
<tr>
<td>0 9000</td>
<td>0 4009</td>
<td>44 18653</td>
<td>0 40285</td>
<td>47 31881</td>
</tr>
<tr>
<td>0 9500</td>
<td>0 4501</td>
<td>44 79155</td>
<td>0 45763</td>
<td>47 54620</td>
</tr>
<tr>
<td>1 0000</td>
<td>0 5000</td>
<td>45 00000</td>
<td>0 51216</td>
<td>47 42213</td>
</tr>
</tbody>
</table>

Table I Numerical example of 'Zero-Thickness' problem
INPUT

SPACING S = 0.75
INLET ANGLE = 0.000
OUTLET ANGLE = 45.000
PARABOLIC LOADING INPUT PROPORTIONAL TO x(1-x)

<table>
<thead>
<tr>
<th>X</th>
<th>EXACT F</th>
<th>SMOOTH F</th>
<th>EXACT BLADE ANGLE</th>
<th>SMOOTH BLADE ANGLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>-6.36362</td>
<td>-9.10520</td>
</tr>
<tr>
<td>0.0500</td>
<td>-0.00733</td>
<td>-0.00809</td>
<td>-6.77228</td>
<td>-9.27549</td>
</tr>
<tr>
<td>0.1000</td>
<td>-0.01498</td>
<td>-0.01633</td>
<td>-7.83866</td>
<td>-8.61382</td>
</tr>
<tr>
<td>0.1500</td>
<td>-0.02102</td>
<td>-0.02224</td>
<td>-5.31557</td>
<td>-6.47547</td>
</tr>
<tr>
<td>0.2000</td>
<td>-0.02428</td>
<td>-0.02768</td>
<td>-1.64080</td>
<td>-2.95814</td>
</tr>
<tr>
<td>0.2500</td>
<td>-0.02390</td>
<td>-0.02641</td>
<td>2.90811</td>
<td>2.22304</td>
</tr>
<tr>
<td>0.3000</td>
<td>-0.01923</td>
<td>-0.02380</td>
<td>6.06028</td>
<td>0.79703</td>
</tr>
<tr>
<td>0.3500</td>
<td>-0.00979</td>
<td>-0.01293</td>
<td>13.51490</td>
<td>15.43656</td>
</tr>
<tr>
<td>0.4000</td>
<td>0.00475</td>
<td>0.00382</td>
<td>18.96298</td>
<td>21.19087</td>
</tr>
<tr>
<td>0.4500</td>
<td>0.02460</td>
<td>0.02583</td>
<td>24.13298</td>
<td>26.04913</td>
</tr>
<tr>
<td>0.5000</td>
<td>0.04947</td>
<td>0.05269</td>
<td>28.83133</td>
<td>30.19280</td>
</tr>
<tr>
<td>0.5500</td>
<td>0.07947</td>
<td>0.08403</td>
<td>32.95549</td>
<td>33.76094</td>
</tr>
<tr>
<td>0.6000</td>
<td>0.11423</td>
<td>0.11954</td>
<td>36.48344</td>
<td>36.83503</td>
</tr>
<tr>
<td>0.6500</td>
<td>0.15338</td>
<td>0.15693</td>
<td>39.44676</td>
<td>39.48202</td>
</tr>
<tr>
<td>0.7000</td>
<td>0.19850</td>
<td>0.20192</td>
<td>41.90393</td>
<td>41.75795</td>
</tr>
<tr>
<td>0.7500</td>
<td>0.24316</td>
<td>0.24521</td>
<td>43.91742</td>
<td>43.68334</td>
</tr>
<tr>
<td>0.8000</td>
<td>0.29286</td>
<td>0.29744</td>
<td>45.53462</td>
<td>45.27875</td>
</tr>
<tr>
<td>0.8500</td>
<td>0.34517</td>
<td>0.34918</td>
<td>46.77274</td>
<td>46.50683</td>
</tr>
<tr>
<td>0.9000</td>
<td>0.39940</td>
<td>0.40285</td>
<td>47.59450</td>
<td>47.31881</td>
</tr>
<tr>
<td>0.9500</td>
<td>0.45473</td>
<td>0.45763</td>
<td>47.84251</td>
<td>47.54620</td>
</tr>
<tr>
<td>1.0000</td>
<td>0.50954</td>
<td>0.51216</td>
<td>46.88512</td>
<td>47.42213</td>
</tr>
</tbody>
</table>

Table 2: Comparison of 'smoothing' and 'exact' results
Inputs

Compute Edge Variables

Guess $f, \delta', \beta'$

Compute $A_T, B_T$

Update $\delta'', \beta'', f$

$f$ converges?

Yes

Compute $C_p$

STOP

No

Table 3: Flow chart for the 'Finite-Thickness' problem
INPUT PARAMETERS

\[
\begin{align*}
\text{MAX BLOCKAGE} &= 0.10\,000 \\
\text{SPACING} &= 0.50\,000 \\
\text{INLET ANGLE} &= 0.00\,000 \\
\text{OUTLET ANGLE} &= 45.00\,000
\end{align*}
\]

\[
\text{NUMBER OF POINTS I/X} = 11 \\
\text{MAX NUMBER OF ITERATIONS ALLOWED} = 20 \\
\text{MAX ERROR IN F(X) ALLOWED} \quad \text{ERRMAX} = 0.000001
\]

FILTERING OPTION = 0

BLOCKAGE AND LOADING PARAMETERS

\begin{align*}
A &= 1.00 \\
B &= 2.00 \\
C &= 0.50 \\
D &= 1.00
\end{align*}

\begin{align*}
\text{ITERATION} \# 1 & \quad \text{ERRMAX} = 0.00376 \quad \text{AT} \quad X = 0.10000 \\
\text{ITERATION} \# 2 & \quad \text{ERRMAX} = 0.00046 \quad \text{AT} \quad X = 0.10000 \\
\text{ITERATION} \# 3 & \quad \text{ERRMAX} = 0.00013 \quad \text{AT} \quad X = 0.10000 \\
\text{ITERATION} \# 4 & \quad \text{ERRMAX} = 0.00002 \quad \text{AT} \quad X = 0.10000 \\
\text{ITERATION} \# 5 & \quad \text{ERRMAX} = 0.00000 \quad \text{AT} \quad X = 0.10000
\end{align*}

\[
\begin{array}{cccccc}
X & \text{LOAD(X)} & T(X) & \text{FM(X)} & F(X) & \text{Cp+} & \text{Cp-} \\
0.0000 & 0.0000 & 0 & 0 & 0 & 0 & 0 \\
0.1000 & 1.0974 & 0.01367 & 0.00259 & -0.01371 & 0.21609 & -0.00000 \\
0.2000 & 1.3795 & 0.02160 & 0.01335 & -0.00982 & 0.32123 & 1.00000 \\
0.3000 & 1.7839 & 0.02461 & 0.03600 & 0.01488 & 0.35421 & -0.91697 \\
0.4000 & 1.4323 & 0.02430 & 0.07164 & 0.05381 & 0.30674 & -0.85721 \\
0.5000 & 1.3622 & 0.02109 & 0.12073 & 0.10615 & 0.21504 & 0.85185 \\
0.6000 & 1.1947 & 0.01620 & 0.18316 & 0.17181 & 0.09234 & 0.83185 \\
0.7000 & 0.9673 & 0.01663 & 0.25817 & 0.24985 & -0.05235 & 0.80053 \\
0.8000 & 0.8977 & 0.00540 & 0.34412 & 0.33873 & -0.21089 & 0.74507 \\
0.9000 & 0.3658 & 0.00152 & 0.43835 & 0.43595 & -0.37577 & 0.66237 \\
1.0000 & 0.0000 & 0 & 0 & 0 & 0 & 0
\end{array}
\]

Table 4 Numerical example of 'Finite-Thickness' problem (without filter)
**INPUT PARAMETERS**

- **MAX. BLOCKAGE**: 0.10000
- **SPACING**: 0.50000
- **INLET ANGLE**: 0.00000
- **OUTLET ANGLE**: 45.00000

**NUMBER OF POINTS | IX = 41**

**MAX. NUMBER OF ITERATIONS ALLOWED | IT = 10**

**MAX. ERROR IN F(X) ALLOWED | ERRMAX = 0.000100**

**FILTERING OPTION**: 1

**BLOCKAGE AND LOADING PARAMETERS**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>2.00</td>
<td>0.50</td>
<td>1.00</td>
</tr>
</tbody>
</table>

**ITERATION # 1**

<table>
<thead>
<tr>
<th>ERRMAX</th>
<th>AT X = 0.02500</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00100</td>
<td></td>
</tr>
</tbody>
</table>

**ITERATION # 2**

<table>
<thead>
<tr>
<th>ERRMAX</th>
<th>AT X = 0.02500</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00097</td>
<td></td>
</tr>
</tbody>
</table>

**ITERATION # 3**

<table>
<thead>
<tr>
<th>ERRMAX</th>
<th>AT X = 0.02500</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00094</td>
<td></td>
</tr>
</tbody>
</table>

**ITERATION # 4**

<table>
<thead>
<tr>
<th>ERRMAX</th>
<th>AT X = 0.02500</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00091</td>
<td></td>
</tr>
</tbody>
</table>

**ITERATION # 5**

<table>
<thead>
<tr>
<th>ERRMAX</th>
<th>AT X = 0.02500</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00087</td>
<td></td>
</tr>
</tbody>
</table>

**ITERATION # 6**

<table>
<thead>
<tr>
<th>ERRMAX</th>
<th>AT X = 0.02500</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00084</td>
<td></td>
</tr>
</tbody>
</table>

**ITERATION # 7**

<table>
<thead>
<tr>
<th>ERRMAX</th>
<th>AT X = 0.02500</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00080</td>
<td></td>
</tr>
</tbody>
</table>

**ITERATION # 8**

<table>
<thead>
<tr>
<th>ERRMAX</th>
<th>AT X = 0.02500</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00076</td>
<td></td>
</tr>
</tbody>
</table>

**ITERATION # 9**

<table>
<thead>
<tr>
<th>ERRMAX</th>
<th>AT X = 0.02500</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00073</td>
<td></td>
</tr>
</tbody>
</table>

**ITERATION # 10**

<table>
<thead>
<tr>
<th>ERRMAX</th>
<th>AT X = 0.02500</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00069</td>
<td></td>
</tr>
</tbody>
</table>

**Table 5**

**Numerical example of 'Finite-Thickness' problem**

(with filter)
<table>
<thead>
<tr>
<th>CONTROL POINT</th>
<th>X</th>
<th>Y</th>
<th>NORMAL VELOCITY</th>
<th>TANGENTIAL VELOCITY</th>
<th>PRESSURE COEFFICIENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.387487</td>
<td>0.531408</td>
<td>-0.327205</td>
<td>0.00008</td>
<td>-0.000351</td>
</tr>
<tr>
<td>2</td>
<td>0.389872</td>
<td>0.5053759</td>
<td>-0.379390</td>
<td>0.00033</td>
<td>-0.006031</td>
</tr>
<tr>
<td>3</td>
<td>0.337506</td>
<td>0.79227</td>
<td>-0.327877</td>
<td>0.00008</td>
<td>-0.17961</td>
</tr>
<tr>
<td>4</td>
<td>0.312111</td>
<td>0.53769</td>
<td>-0.322337</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>5</td>
<td>0.062159</td>
<td>0.422795</td>
<td>-0.31736</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>6</td>
<td>0.087520</td>
<td>0.278796</td>
<td>-0.310993</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>7</td>
<td>0.081253</td>
<td>0.352270</td>
<td>-0.303829</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>8</td>
<td>0.072538</td>
<td>0.278373</td>
<td>-0.295577</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>9</td>
<td>0.076253</td>
<td>0.303137</td>
<td>-0.286542</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>10</td>
<td>0.072538</td>
<td>0.278373</td>
<td>-0.277600</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>11</td>
<td>0.061253</td>
<td>0.257399</td>
<td>-0.264155</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>12</td>
<td>0.068739</td>
<td>0.229864</td>
<td>-0.251015</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>13</td>
<td>0.065242</td>
<td>0.213323</td>
<td>-0.236844</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>14</td>
<td>0.062744</td>
<td>0.192158</td>
<td>-0.220878</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>15</td>
<td>0.051253</td>
<td>0.177883</td>
<td>-0.113432</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>16</td>
<td>0.037459</td>
<td>0.153274</td>
<td>-0.08656</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>17</td>
<td>0.026536</td>
<td>0.133273</td>
<td>-0.06110</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>18</td>
<td>0.023208</td>
<td>0.116933</td>
<td>-0.03672</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>19</td>
<td>0.021523</td>
<td>0.096444</td>
<td>-0.01207</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>20</td>
<td>0.021254</td>
<td>0.002949</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>21</td>
<td>0.016502</td>
<td>0.036524</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>22</td>
<td>0.012749</td>
<td>0.022992</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>23</td>
<td>0.006765</td>
<td>0.002395</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>24</td>
<td>0.004611</td>
<td>0.011764</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>25</td>
<td>0.003747</td>
<td>0.000000</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>26</td>
<td>0.001523</td>
<td>0.001029</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>27</td>
<td>0.001410</td>
<td>0.000000</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>28</td>
<td>0.000650</td>
<td>0.000000</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>29</td>
<td>0.000274</td>
<td>-0.001913</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>30</td>
<td>0.000123</td>
<td>0.004353</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>31</td>
<td>0.000052</td>
<td>0.000896</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>32</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>33</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>34</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>35</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
<tr>
<td>36</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.00000</td>
<td>0.00008</td>
<td>-0.377364</td>
</tr>
</tbody>
</table>

UNIFORM ERROR (EPS) = -0.74787546-03

CL = -0.297096
CD = 0.26666348-02
CIRCULATION = -0.4525191

POTENTIAL FLOW VELOCITY DIAGRAM
UPSTREAM VELOCITY = 1.00000 AT 90.00004 DEGREES
ONSET VELOCITY = 1.00000 AT 28.98546 DEGREES
DOWNSTREAM VELOCITY = 1.00000 AT 43.42916 DEGREES

*** NOTE: ALL VELOCITY QUANTITIES ARE SCALED BY THE ONSET VELOCITY ***

Table 6: Results from direct method (inlet condition specified)
Table 8: Comparison of 'Zero-Thickness' and 'Finite-Thickness' results in the zero blockage limit.
Figure 1  2D cascade notation
Figure 2: Blade camber and mean streamline

- Mean streamline
- Blade camber

Variables:
- $s = 0.75$
- $\alpha_1 = 0^\circ$
- $\alpha_2 = 45^\circ$
- $\Delta p \sim x(1-x)$
Figure 3: Blade shapes obtained from 'Smoothing' technique
Figure 4: Pressure coefficients obtained from 'Smoothing' technique
Figure 5: Pressure coefficients obtained from direct method
Figure 6: Comparison of $C_p$'s from direct and inverse methods

$S = 0.5$

$\Delta P \sim \sqrt{X(1 - X)}$

$T \sim X(1 - X)^2$

$\text{BLOCK} = 0.1$
Figure 7: Comparison of 'Zero-Thickness' and 'Finite-Thickness' results in the zero blockage limit.
Figure 8. Effects of spacing to chord ratio on the blade cambers.
Figure 9: Effects of maximum blockage on Cp's
(BLOCK = 0.001)
Figure 10: Effects of maximum blockage on Cp's (BLOCK = 0.1)
Figure 11: Effects of maximum blockage on Cp's
(BLOCK = 0.25)
Figure 12: Rounded leading edge inlet guide vane
Figure 13: Effects of loading distribution on $C_p$'s (maximum loading at $x = 1/3$)

$\Delta p \sim x^{0.5(1-x)}$
Figure 14: Effects of loading distribution on Cp's (maximum loading at $x = 1/2$)
Figure 15: Effects of loading distribution on $C_p$'s  
(maximum loading at $x = 2/3$)

\[ \Delta p \sim x(1-x)^{0.5} \]
Figure 16: Compressor blade

- $s = 0.5$
- BLOCK = 0.1
- $\alpha_1 = 45^\circ$
- $\alpha_2 = 0^\circ$
- $T \sim x(1-x)^2$
- $\Delta p \sim x^{0.3}(1-x)$
Figure 17: Impulse blade
Appendix A: The Relationship between the Swirl Schedule and the Pressure Difference across the Blade

Consider the cascade geometry shown below

![Cascade Geometry Diagram]

Under the assumption of incompressible, inviscid and uniform inlet flow condition, Bernoulli's equation is valid everywhere. We can write:

\[ P^+ + \frac{1}{2} \rho (V^+)^2 = P^- + \frac{1}{2} \rho (V^-)^2 \]

Therefore

\[ \Delta P = P^+ - P^- \propto (V^- - V^+) \left( \frac{V^- + V^+}{2} \right) \]  \hspace{1cm} (A-1)

We can do the following approximation:

\[ (V^- + V^+) \sim 2 \bar{V}_T \]
To estimate \((V^- - V^+)\), we consider the circulation along the closed path \(\odot\) - \(\odot\) - \(\odot\) - \(\odot\) shown in the figure. From Kelvin's theorem, we can write

\[ \Gamma_c = \Gamma_1 + \Gamma_2 + \Gamma_3 + \Gamma_4 = 0 \]  

(A-2)

Now,

\[ \Gamma_1 = \int_{f+\Delta\tau}^{f+\Delta\tau} V_y(x+\Delta x, y) \, dy = (A-2\tau) \bar{V}_y(x+\Delta x) \]

\[ \Gamma_2 = -\gamma^- \cdot d\ell^- \approx -V^- \Delta x \]

\[ \Gamma_3 = -\int_{f+\Delta\tau}^{f+\Delta\tau} V_y(x, y) \, dy = -(A-2\tau) \bar{V}_y(x) \]

\[ \Gamma_4 = \gamma^+ \cdot d\ell^+ \approx V^+ \Delta x \]

where

\[ |d\ell^-| = \Delta x \sqrt{1 + (\gamma' \pm \tau')^2} \approx \Delta x \]

Substitute the above relations into (A-2), we obtain

\[ (V^- - V^+) \Delta x \approx (A-2\tau)[\bar{V}_y(x+\Delta x) - \bar{V}_y(x)] \]

and thus, in the limit of \(\Delta x \to 0\)

\[ (V^- - V^+) \approx \bar{V}_y' \]

Therefore, equation (A-1) reduces to

\[ \Delta p \propto \bar{V}_T (\bar{V}_y') \]

and we conclude that the pressure difference across the blade is directly proportional to the swirl schedule \(\bar{V}_y'\). We will call \(\bar{V}_y'\) the swirl schedule or the loading distribution.
Appendix B: The Bound Vorticity

In this appendix, we will show the relationship between the bound vorticity (vortices distributed on the blade camber lines to model their presence) and the swirl schedule (or the gradient of the pitch average velocity defined in chapter 2).

The flow is assumed to be incompressible and inviscid, and the far upstream flow is assumed to be uniform. The flow is thus irrotational and the vorticity must lie on the blade camber lines (see figure above). Therefore, we require:

\[ \mathbf{\Omega} \cdot \nabla \kappa = 0 \]  \hspace{1cm} (B-1)

Moreover, by vector identity
\[ \nabla \cdot \nabla = 0 \quad \text{(B-2)} \]

To satisfy both equations (B-1) and (B-2) and the condition that the vorticity direction must be normal to the x-y plane (2D assumption), we can write the vorticity field as

\[ \nabla = \delta_{\rho}(\alpha) \left( \nabla \alpha \times \nabla \theta \right) \quad \text{(B-3)} \]

where \( \delta_{\rho}(\alpha) \) is the "periodic delta" function defined in Appendix C.

To find out what \( \theta \) is, consider the circulation around path C shown in the figure. We may write, by Stokes theorem,

\[ \oint_{C} \nabla \cdot d\ell = \iint_{A} \nabla \cdot dA \quad \text{(B-4)} \]

Note that the line integrals along path \( \ell \) and \( \delta \) cancel out each other exactly, and by substituting equation (B-3) into the right hand side of equation (B-4), along with the definition of the pitch average velocity, we can show that

\[ \int_{f}^{f+\Delta} V_y(x+\Delta x, y) \, dy - \int_{f}^{f+\Delta} V_y(x, y) \, dy \]

\[ = \Delta X \int_{f}^{f+\Delta} \delta_{\rho}(\alpha) \left( - \frac{d\theta}{d\alpha} \right) \, dy \]

and finally, by taking the limit as \( \Delta X \to 0 \), \( \theta \) in equation (B-3) is defined as

\[ \theta = - \nabla y \]
Appendix C: The Periodic Generalized Functions

The "periodic delta" function, the "sawtooth" function and the "smoothing" functions are constructed in this appendix.

1. The "periodic delta" function

The "periodic delta" function may be expressed in a Fourier series of the form

\[ \delta_p(\alpha) = \frac{1}{\lambda} \sum_{n = -\infty}^{\infty} e^{i\left(\frac{2\pi n}{\lambda}\right)\alpha} \]

where \( \lambda \) is the spacing between blade camber lines, and \( \alpha \) represents the blade camber's surfaces.

The plot of \( \delta_p(\alpha) \) vs \( \alpha \) looks like

\[ \delta_p(\alpha) \]

\[ \ldots \]

\[ -2\lambda \quad -\lambda \quad 0 \quad \lambda \quad 2\lambda \quad 3\lambda \quad \alpha \]

It has the property

\[ \int_{(n-1)\lambda}^{n\lambda} \delta_p(\alpha) \, d\alpha = 1.0 \]

for any integer \( n \).
2. The "sawtooth" function

The "sawtooth" function may be expressed in a Fourier series of the form

$$S(\alpha) = \sum_{n \neq 0} \frac{e^{i \left( \frac{2\pi n}{\lambda} \right) \alpha}}{i \left( \frac{2\pi n}{\lambda} \right)}$$

The plot of $S$ vs $\alpha$ looks like

![Plot of the sawtooth function](image)

Its properties are:

- It has first derivative related to the "periodic delta" function by
  $$S'(\alpha) = \left[ \lambda \delta_p(\alpha) - 1 \right]$$

- It has zero average between $\alpha$ lines
  $$\int_{(n-1)\lambda}^{n\lambda} S(\alpha) \, d\alpha = 0$$

- It has a jump in magnitude of $\lambda$ everytime an $\alpha$ surface is crossed

- It reduces to a polynomial form when $(n-1)\lambda < \alpha < n\lambda$ for any integer $n$. Its polynomial form being
  $$S(\alpha) = \frac{\lambda}{2} - \alpha$$
3. The "smoothing" functions

The "smoothing" functions $I_k(\alpha)$ are defined as

$$I_k(\alpha) = \sum_{n \neq 0} \frac{e^{i\lambda_n \alpha}}{(i\lambda_n)^{k+1}} \quad k = 1, 2, 3, \ldots$$

where

$$\lambda_n = \frac{2\pi n}{\delta}$$

Their properties are:

- they have derivatives of the forms

$$\nabla I_k(\alpha) = I_{k-1}(\alpha) \nabla \alpha$$

- they have zero average between $\alpha$ lines

$$\int_{\alpha}^{\alpha + \Delta \alpha} I_k(\alpha) \, d\alpha = 0$$

- they have polynomial forms in the intervals $(n-1)\delta < \alpha < n\delta$ for any integer $n$.

$$I_1(\alpha) \equiv I(\alpha) = -\frac{\Delta^4}{12} + \frac{\Delta \alpha}{2} - \frac{\alpha^2}{2}$$

$$I_2(\alpha) \equiv J(\alpha) = -\frac{\Delta^6}{12} + \frac{\Delta \alpha}{4} - \frac{\alpha^3}{6}$$

$$I_3(\alpha) \equiv K(\alpha) = -\frac{\Delta^8}{720} - \frac{\Delta^4 \alpha^2}{24} + \frac{\Delta \alpha^3}{12} - \frac{\alpha^4}{24}$$

$\vdots$
A TWO-DIMENSIONAL DESIGN METHOD FOR HIGHLY-LOADED BLADES IN TURBOMACHINES. (U) MASSACHUSETTS INST OF TECH CAMBRIDGE GAS TURBINE AND PLASMA D. T Q DANG ET AL.

UNCLASSIFIED APR 83 GT/PDL-173 AFOSR-TR-85-0066 F/G 20/4
Appendix D: The "Physical" Representations of $\mathbf{A}$ and $\mathbf{B}$

In this appendix, we will show the "physical" representations of $\mathbf{A}$ and $\mathbf{B}$. We will also find the strength of the vortices, sources and sinks which model the presence of the blades.

Consider the pitch average velocity $\mathbf{\vec{V}}$ of the 'Finite-Thickness' problem. By definition

$$\mathbf{\vec{V}}(x) = \frac{1}{A} \int_{f}^{f+\delta} \mathbf{\vec{V}_z}(x, y) \, dy$$

using equation (4.2-16) for $\mathbf{\vec{V}_z}$, $\mathbf{\vec{V}}$ can be shown to be

$$\mathbf{\vec{V}} = \left( \frac{\mathbf{V}_{Tx}}{\mathbf{V}_{Ty}} + \gamma \right) \hat{x} + \left( \frac{\mathbf{V}_{Ty}}{\mathbf{V}_{Tx}} - \delta \right) \hat{y} \quad (D-1)$$

Since $\mathbf{V}_{Tx}$ and $\mathbf{V}_{Ty}$ are the gap average velocity components, $\gamma$ and $-\delta$ represent the $x$-component and $y$-component of the "imaginary" flow in the "blade" region respectively. We expect these variables to be proportional to the blockage distribution.

Consider the curl of $\mathbf{\vec{V}}$

$$\nabla \times \mathbf{\vec{V}} = \left( \mathbf{V}_{Ty}' - \delta' \right) \quad (D-2)$$

In chapter 2, we have shown that if the vorticity is distributed along the blade camber, then its strength is related to the gradient of the $y$-component of the pitch average velocity. Equation (D-2) is indeed the case.

Consider the divergence of

$$\nabla \cdot \mathbf{\vec{V}} = \left( \frac{\mathbf{V}_{Tx}'}{\mathbf{V}_{Ty}'} + \beta' \right) \quad (D-3)$$

Since the flow is incompressible, $\left( \frac{\mathbf{V}_{Tx}'}{\mathbf{V}_{Ty}'} + \beta' \right)$ represents the source/sink distribution. Note that the boundary conditions $\left( \frac{\mathbf{V}_{Tx}'}{\mathbf{V}_{Ty}'} + \beta' \right) = 0$ (equation(4.2-17)) at $X = 0$ and $X = 1$ are the conditions required for the blade profile to close there.
Appendix E : Numerical Difficulties

In this appendix, we will attempt to understand the convergence problem encountered in the iteration process for the blade camber line \( f \) when "partial smoothing" is used. We study the mathematical behavior of \( \beta \) and \( \delta \).

By combining \( A_T, B_T, \beta \) and \( \delta \) in the "partial smoothing" forms of equations (4.3-1) and (4.3-2), we arrive at the following boundary value problems:

\[
F(x)(f'' - 1) X'' + F(x)f'f''(3 - f''') X' + X = V_{TX} - \left( \frac{\partial Y_T}{\partial x} \right)_T + F(x)\left[ 2f'\left(1 + f'^{1/2}\right) Y'' + f''(3 - f''') Y' \right] \tag{E-1}
\]

with boundary conditions

\[
X'(0) = 0 \\
X'(1) = 0
\]

and

\[
F(x)(f'' - 1) Y'' + F(x)f'f''(3 - f''') Y' + Y = -V_{TY} + \left( \frac{\partial Y_T}{\partial y} \right)_T + F(x)\left[ -2f'\left(1 + f'^{1/2}\right) X'' + f''(3 - f''') X' \right] \tag{E-2}
\]

with boundary conditions

\[
Y'(0) = 0 \\
Y'(1) = 0
\]

where

\[
X \equiv V_{TX} + \beta
\]
\[ Y \equiv -\bar{V}_T + \xi \]

\[ F(\zeta) \equiv \frac{J(\tau)}{S(\tau)} \left( \frac{1}{1 + f' \bar{\tau}} \right)^3 \]

Since \( f \) itself is a function of \( \beta \) and \( \xi \), we have a boundary value problem consisting of two coupled non-linear second order ordinary differential equations. In solving them iteratively, we expect that certain difficulties can arise.

The strut problem

We study the mathematical behavior of \( \beta \) and \( \xi \) by first consider the case where \( f \) is identically zero everywhere, but \( T \) is finite. This is the case of a symmetric blade (or a strut). In this case, \( Y \) is also identically zero everywhere, and the above boundary value problem reduces to

\[ - \frac{J(\tau)}{S(\tau)} \beta'' + \beta = \frac{J(\tau)}{S(\tau)} \bar{V}_{\tau x}'' - \left( \frac{\partial^2 \bar{\tau}}{\partial X} \right)_T \]

with boundary conditions

\[ \beta'(0) = - \bar{V}_{\tau x}'(0) \]
\[ \beta'(1) = - \bar{V}_{\tau x}'(1) \]

Consider the homogeneous solution of the above differential equation by assuming \( \beta \) to be of the form

\[ \beta = e^{i \kappa(x)} \]

Substituting it into equation (E-3), we obtain

\[ - \frac{J(\tau)}{S(\tau)} \left( i \kappa'' - \kappa' \kappa' \right) + 1 = 0 \]

Assume \( \kappa'' << \kappa' \). Then
\[ E(x) = \pm \int \sqrt{-\frac{S(r)}{J(r)}} \, dx \]

Consider the case where \( T/A << 1 \). Then, by definition

\[ S(T) \sim \theta(A) \]
\[ J(T) \sim \theta(-A^2 T) \]

and thus

\[ \frac{-J(T)}{S(T)} \sim \theta \left( \frac{1}{AT} \right) \]

It can be shown that under the assumption of \( T/A << 1 \), we can say that \( \varepsilon'' / \varepsilon' \sim \theta(T) \) and the assumption \( \varepsilon'' \ll \varepsilon' \) is justifiable, except perhaps near \( x = 0 \) or 1.

Finally, we can write

\[ \beta \sim e^{\pm i \int \sqrt{\frac{1}{AT}} \, dx} \]

As an example, let

\[ T(x) = 2 A (\text{BLOCK}) x(1-x) \]

where \( \text{BLOCK} \) is defined in subsection 4.5.1. Then, it can be shown that

\[ \beta \sim e^{\pm i \sqrt{\frac{2}{A^2 \text{BLOCK}}} (\sin^{-1} \sqrt{x})} \]

With the assumption that \( T/A << 1 \), we conclude that \( \beta \) can be a highly oscillating function, having a "natural frequency" of the order of \( \theta \left( \sqrt{\frac{2}{A^2 \text{BLOCK}}} \right) \).
Finally, we look at the amplitude of $\beta$. By definition, i.e. equation (4.2.13) in "partial smoothing" form

$$\beta = \frac{\mathcal{J}(\tau)}{\mathcal{S}(\tau)} \left( A_T^' - B_T f^' \right) - \left( \frac{\partial \mathcal{V}_{n \tau}}{\partial x} \right)^T$$

Therefore, the above analysis shows that $\beta$ behaves like

$$\beta \sim \Theta(\Delta T)$$

and thus, the source/sink distribution ($\mathcal{V}'_{Tx} + \beta^'$) oscillates.

A computer program was written to solve the differential equation (E-3) using the Chebyshev collocation technique [7], [8]. Numerical results show that $\beta$ oscillates with a natural frequency in agreement with the above analysis.

In classical aerodynamics we know that, for a smooth blade with finite thickness, the source/sink distribution used to model its presence should exhibit like a "sine" wave with a singular point at the leading edge. Numerically, in order to resolve this singular point, we would need an infinite number of terms in the smoothing series. We conclude that in the case of "partial smoothing" (by using only two terms in the smoothing series), we are unable to represent the usual source/sink distribution. However, such a representation is also not necessary.

Accordingly, we will call ($\mathcal{V}'_{Tx} + \beta^'$) the "modified" source/sink distribution, and show that it can be used to produce corresponding blade shapes satisfactorily. Thus we seek a practical method for the design problem, using "partial smoothing", without necessarily having to go into more extensive mathematical development.
The loaded blade problem

From the above discussion of the strut problem, we expect both $\beta$ and $S$ to have oscillating behaviors when the blades are loaded. Two iteration schemes for $f$ were investigated using "partial smoothing".

We note that equations (E-1) and (E-2) have certain symmetry. Rewrite them in operator forms:

\[
\begin{align*}
\mathcal{L}_1 \{ \chi \} - \mathcal{L}_2 \{ \gamma \} &= \mathcal{S}_1 \\
\mathcal{L}_1 \{ \gamma \} + \mathcal{L}_2 \{ \chi \} &= \mathcal{S}_2
\end{align*}
\]  

(E-4)

where

\[
\begin{align*}
\mathcal{L}_1 \{ \chi \} &= \left[ F(x) \left( f'' + 1 \right) \frac{d^2}{dx^2} + F(x) f' \left( \beta - f' \right) \frac{d}{dx} + 1 \right] \{ \chi \} \\
\mathcal{L}_2 \{ \gamma \} &= \left[ 2 f' \left( f' + \tau \right) \frac{d}{dx} + f'' \left( 1 + \beta f' \right) \frac{d}{dx} \right] \{ \gamma \} \\
\mathcal{S}_1 &= \bar{V}_{T_T} - \left( \frac{\partial \nu}{\partial x} \right)_T \\
\mathcal{S}_2 &= - \bar{V}_{T_T} \gamma + \left( \frac{\partial \nu}{\partial y} \right)_T
\end{align*}
\]

The boundary conditions remain the same as in equations (E-1) and (E-2).

Method 1

In this method, we attempt to solve equations (E-4) simultaneously for $\beta$ and $S$ using the Chebyshev collocation technique.

We express $\beta$ and $S$ as Chebyshev series and convert equations (E-4) into matrix forms:
\[
\begin{bmatrix}
[A] \\ [B]
\end{bmatrix}
\begin{bmatrix}
\{x\} \\
\{y\}
\end{bmatrix}
=
\begin{bmatrix}
\{s, 1\} \\
\{s, 2\}
\end{bmatrix}
\]

which can be arranged in the form

\[
\begin{bmatrix}
[A] & -[B] \\
[B] & [A]
\end{bmatrix}
\begin{bmatrix}
\{x\} \\
\{y\}
\end{bmatrix}
=
\begin{bmatrix}
\{s, 1\} \\
\{s, 2\}
\end{bmatrix}
\]

\(x\) and \(y\) are solved by inverting the above matrix using an IMSL subroutine [9].

Results show that when more than approximately 11 collocation points are used in the calculation, convergence in \(f\) cannot be achieved. \(\phi\) and \(\delta\) are found to oscillate and their Chebyshev coefficients fail to converge. When around 51 points or more collocation points are used in the calculation, the iteration process diverges rapidly. Two conclusions can be made from the results of this method:

1. \(\phi\) and \(\delta\) process oscillating behavior as predicted by the analysis of the strut problem. By using more than 51 collocation points, the numerical calculation tries to resolve the Gibbs phenomenon at the leading edge, but fails to do so because of "partial smoothing".

2. The iteration process can diverge rapidly because of the very nature of the iteration process. We note that even though we are solving \(x\) and \(y\) simultaneously, we are in effect solving equation (E-4) iteratively because \(f\) and its derivatives are
updated at every iteration. We can therefore look at the iteration process of method 1 as if we were attempting to solve for $X$ and $Y$ in the following manner:

a. First update

$$\mathcal{L}_1 \{X^{n+1}\} = \mathcal{L}_2 \{Y^n\} + S^n_1$$

b. Then update

$$\mathcal{L}_2 \{Y^{n+1}\} = -\mathcal{L}_2 \{X^n\} + S^n_2$$

where $n$ is the iteration level in the iteration process for $f$.

Since operators $\mathcal{L}_1$ and $\mathcal{L}_2$ are both expected to have normal mode solutions of oscillating behavior, we conclude that there is a chance for a driven resonance to occur during the iteration process for $f$, which can lead to divergence of the iteration scheme itself. We think that this is indeed the case. When too many terms are kept in the Chebyshev series, higher modes are present resulting in a greater chance for resonance to occur. When fewer terms (around 10) are kept in the Chebyshev series, we are staying away from the natural frequency of the operators $\mathcal{L}_1$ and $\mathcal{L}_2$ resulting in a stable iteration process.

**Method 2**

In this method, we use the iteration process described in section 4.3. Derivatives are computed numerically using two methods: Chebyshev collocation method, and finite difference method. Numerical results show that similar problems as in method 1 were encountered here. This should be expected, as observed above, because iterations are being used.

We decided to use method 2 for our design method because of two reasons.
1. method 2 is much more efficient than method 1 (faster, cheaper and simpler). In method 1, we are required to invert a matrix at each iteration of \( f \). In method 2, we are required to compute derivatives instead.

2. method 2 can easily be modified if we wish to keep more terms in the smoothing series. Equations (E-1) and (E-2) are only valid when the first two terms in the smoothing series are kept.

Finally, the finite difference scheme (central difference) is used to compute derivatives because it is numerically more stable than the Chebyshev collocation method.

A computer program was written using the above method. It is found that when around 11 points are used in the calculations, convergence in \( f \) is achieved in about 10 iterations. When more than around 20 points are used in the calculation, \( f \) fails to converge. In order to resolve this problem, we propose to use a filter. The calculation procedure is:

1. when more than 11 points are used in the calculation, iterate for \( f \) using a "filter".
2. when 11 points or less are used in the calculation, iterate for \( f \) without using the "filter".

Filtering method

Two different "filters" are developed for the above iteration scheme:

1. \( f \) is filtered using a least-squares chord-wise fitting method [10]. The combination \((c^r + s' - A_r f')\) in equation (4.2-22) is filtered using a fourth order polynomial. The motivation for using a polynomial curve fitting method is that we expect \( f \) itself be represented by a polynomial of low order.

2. the pressure coefficients are filtered by taking the average of the maximum and minimum envelopes of the \( C_p \) curves. The
$C_p$ curves are filtered only near the leading edge region ($0 < \alpha < .4$). The envelopes are constructed by straight lines going through the maximum and minimum points of the $C_p$ curves. This procedure has been chosen to date for its simplicity, it clearly admits improvement possibilities near the leading edge. But, till now at least, this approach has compared adequately with known results (see Text).
Appendix F: Computer Code of "Zero-Thickness" problem

```
C ******************************************************************************
C *  PROGRAM NAME THIN FOR C
C *  MAIN PROGRAM FOR INVERSE DESIGN OF COMPRESSOR BLADES C
C *  2-D INCOMPRESSIBLE, INVISCID, INFINITELY THIN THE C
C *  LOADING DISTRIBUTION IS OF PARABOLIC FORM C
C *
C *  INPUTS  S  -  SPACING C
C *  ALPI  -  INLET ANGLE (DEGREE) C
C *  ALP2  -  OUTLET ANGLE (DEGREE) C
C *  IJK  -  NUMBER OF POINTS C
C *  ITER  -  MAXIMUM NUMBER OF ITERATIONS ALLOWED C
C *  ERR  -  CONVERGENCE CRITERIA 'ERROR' C
C *
C ******************************************************************************
REAL X(101),VXY(101),DVXY(101),DVXYZ(101),FM(101),AM(101)
1,DA(101),FNEW(101),F(101),DF(101),DFD(101),PLOT(3,101)
COMMON/S,AO,ALPI,ALP2,IJK,ITER,ERR,COR
C
C READ STATEMENT
C
READ(1,*)S,ALPI,ALP2,IJK,ITER,ERR
WRITE(2,50)S,ALPI,ALP2
50 FORMAT(S,'SPACING S = ',F6.3,S,'INLET ANGLE ALPI = ',F7.3/
15X,'OUTLET ANGLE ALP2 = ',F7.3,S,'NUMBER OF POINTS IJK = ',
1.13//)
C
C INITIALIZE VARIABLES FOR CALCULATION PURPOSE
C
NMAX=20
PI=3.141592654
RAD=57.29577951
TAN1=TAN(0.17453294*ALPI)
TAN2=TAN(0.17453294*ALP2)
X(IJK)=IJK-1
DX=X/IJK
XX=1+DX
SUN=0
DO 5 N=1,IJK
   XX=X
   SUN=SUN+(1/(XX*XX))
5 CONTINUE
COR=1.6449341/SUN
C
C COMPUTE COMPUTATIONAL LOCATIONS
C
DO 10 I=1,IJK
   J=IJK+1-I
   XX=XX-DX
   X(I)=XX
   PLOT(3,J)=X(I)
10 CONTINUE
C
C COMPUTE INPUT FOR PARABOLIC LOADING CASE
C
DO 15 I=1,IJK
   J=IJK+1-I
   XX=X(I)
   CONST=6*(TAN2-TAN1)
   VXY(I)=CONST*(S+XX*XX+XX*XX/3)+TAN1
```
DVLY(I) = CONST*XX*(1 - XX)
DVLY(I) = CONST*(1 - XX)
FV(I) = CONST*(XX**3/6 - XX**4/12) + TANH*XX
PLAT(I) = FV(I)
DF(I) = DYVY(I)
DDF(I) = DDDVY(I)
DEN = -DF(I)*DF(I)
F(I) = FV(I) + 08333333*S*S + DVY(I)*(-1 + DF(I)*DF(I)/DEN)
15 CONTINUE
FNEX(IJK) = 0
F(IJK) = 0
C C START ITERATION PROCESS FOR CAMBER LINE
C C
OLDERR = 100
DO 1 MIT = 1, ITER

C C COMPUTE A AND ITS DERIVATIVE
C
DO 100 I=1, IJK-1
DEN = -DF(I)*DF(I)
A(I) = -DF(I)*DVY(I)/DEN
TERM1 = -DEN *(DDF(I) + DDFY(I) + DF(I) + DDFY(I))
TERM2 = 2 *DF(I)*DF(I)*DDF(I)*DVMY(I)
DA(I) = (TERM1*TERM2)/DEN
100 CONTINUE

C C COMPUTE EDGE VALUES
C
DEN0 = -DF(IJK)**2
DEN1 = -DF(IJK)**2
BO = DDDVY(IJK)*(1 - 2*DF(IJK)*DF(IJK)/DEN0)/DEN0
B1 = DDDVY(IJK)*(1 - 2*DF(IJK)*DF(IJK)/DEN1)/DEN1
AO = -2 *DF(IJK)*DVY(IJK)*(1 - DF(IJK)*DF(IJK)/DEN0)/DEN0
A1 = -2 *DF(IJK)*DVY(IJK)*(1 - DF(IJK)*DF(IJK)/DEN1)/DEN1
C C UPDATE CAMBER LINE F(X)
C
XWORK = -2 *FSUM(IJK,F)/S
ERRVAX = 0
SUXERR = 0
XLOC = 1
DO 101 I=1, IJK
DF(I) = VY(I) + 08333333*S*S*(-DDVY(I) - A(I) + DDF(I) - DA(I))
1-2 -DFSUM(I,F)/S
1*XWORK
ERROR = ABS(FNEX(I) - F(I))
SUXERR = SUXERR + ERROR
IF (ERROR > ERRMAX) XLOC = X(I)
IF (ERROR > ERRMAX) ERRMAX = ERROR
101 CONTINUE

C C CHECK FOR CONVERGENCE IN F(X)
C
WRITE(2,55)MIT, ERRMAX, XLOC
55 FORMAT(10X', 'ITER ', 12, ' ----- ERRMAX = ',F7.5
1.' AT X = ',F8.5)
AVGERR=SUMERR/XJXK
IF(ERRMAX GT (1+OLDERR))WRITE(2,54)AVGERR
54 FORMAT(/2X,6X, iteration scheme diverges !!!!!!/)
IF(ERRMAX LE ERR)G0 TO 998
IF(ERRMAX GT (1+OLDERR))GO TO 998

C UPDATE VALUES FOR NEXT ITERATION
C
DO 103 I=1,IJK-1
F(I)=FNEW(I)
103 CONTINUE
OLDERR=ERRMAX
C
C CONTINUE
C
998 CONTINUE
C
C OUTPUT
C
WRITE(2,60)
60 FORMAT(/2X,'X',25,'FM',37,'Flow angle',155,'F',T67
1,'Blade angle'/)
DO 501 I=1,IJK
PLOT(2,I)=FKEY(I)
Angular=RAD*ATAN(V1*T(I))
Angular=RAD*ATAN(DP(I))
WRITE(2,61)(PLOT(I),FNEW(I),Angular)
501 CONTINUE
C
C CALL JCF PLOTTING SUBROUTINE
C
CALL QPICTR(PLOT,1,3,DATA(1,2),DATA(3,4),LABEL(4)
1,QLAB('Blade [#2] - Mean Streamline [#1]')
1,QLAB('Axial Location X'))
C
STOP
END
C
C COMPUTE FUNCTION FSUN1
C
FUNCTION FSUN1(I,F)
REAL F(101),X(101)
COMMON/S,AO,A1,30,31,PI,IJK,XNAX,COR
REAL LANDM
SUM=0
DO 100 MMIN1AJ
LANDM=2*PI*XU/S
DELFIN=(F(I)-F(IJK))/LANDM
TER=EXP(-LANDV*X(1))/LANDM**3
TER1=EXP(-LANDV*(1-X(1)))/LANDM**3
TER2=AO*COS(DELFIN)*AO*SIN(DELFIN)
TERU=AL+COS(DELFIN)*AL*SIN(DELFIN)
SUM=SUM+TER0+TER1+TERU
100 CONTINUE
RETURN
END
FUNCTION DFSUM(1, F, DF)
REAL F(101), DF(101), X(101)
COMMON/S, A0, A1, B0, B1, PI, IJK, X, NMAX, COR
REAL LAMEW
SUN=0
DO 100 M=1, NMAX
M=M
LAMEW = 2 * PI * X(I)/S
DELFO = (F(I) - F(IJK)) * LAMEW
DELFI = (F(I) - F(I))/LAMEW
COSO = COS(DELFO)
COSI = COS(DELFI)
SINO = SIN(DELFO)
SINI = SIN(DELFI)
EXP0 = EXP(-LAMEW * X(I))/LAMEW**2
EXP1 = EXP(-LAMEW * (1 - X(I)))/LAMEW**2
TERM00 = EXP0 * (B0 * COSO + A0 * SINO)
TERM01 = DF(I) * EXP0 * (-B0 * SINO + A0 * COSO)
TERM10 = EXP1 * (-B1 * COSI + A1 * SINI)
TERM11 = DF(I) * EXP1 * (B1 * SINI + A1 * COSI)
SUN = SUN + TERM00 + TERM01 + TERM10 + TERM11
100 CONTINUE
DFSUM = 5 * S * COR * SUN
RETURN
END

C ******************************************************************************
Appendix G : Computer Code of "Finite-Thickness" problem

C ***************************************************************
C = PROGRAM NAME THICK FOR
C = MAIN PROGRAM FOR INVERSE DESIGN OF COMPRESSOR BLADES
C = 2-D INCOMPRESSIBLE, INVISCID WITH FINITE THICKNESS
C = USING THE CENTRAL DIFFERENCE METHOD TO COMPUTE
C = DERIVATIVES
C =***************************************************************
C
REAL X(IO1),T(IO1),DT(IO1),RI(IO1),RJ(IO1)
1. VX(IO1),DVX(IO1),DVNVT(IO1),VTT(IO1),DVXV(IO1)
1. DAVX(IO1),FMO(IO1),F(IO1),DF(IO1),DDF(IO1)
1. BETA(IO1),DBETA(IO1),DDBETA(IO1),DELT(IO1),DDDELDT(IO1)
1. DDELDT(IO1),PHIHX(IO1),PHIHY(IO1),PHINX(IO1),PHINY(IO1)
1. XLOAD(IO1),XLOAD(IO1),CPT(IO1),CPB(IO1)
1. T(IO1),VXT(IO1),VCT(IO1),VTB(IO1),PLOT(6,IO1)
1. AAA1(10,10),OSCC(IO1),SMOSC(IO1),SMCF(IO1),PLOT(101)
1. A(IO1),DA(IO1),DA(101),D(101),D(101)

REAL LAXDM

COMMON/COMMA/TS,AL PAC,130,11,PI
COMMON/COMM2/T,DT,DT,RI,RI,DVX,DVNVT,DVXV,DVXV,FM
READ(5,*)BLOCK,S,ALP1,ALP2,13K,NMAX,ITER,CA,CB,CC,CD,MOPT
I. IPOIER,BLADET,DADEB,PRESST,PRESSB
WRITE(1,1)BLOCK,S,ALP1,ALP2,13K,ITER,ERR,MOPT,CA,CB,CC,CD
C
C INITIALIZE VARIABLES FOR COMPUTATION
C
PI= 3.141592654
RALP1= 017453293*ALP1
RALP2= 017453293*ALP2
RAD= 57.29577951
TAN= TAN(RALP1)
TAN= TAN(RALP2)

VTB= (1+TAN+TAN)/2**5


A= VTB**2*2+((CA/(CA+CB))+CA)*((CB/(CA+CB))+CB)
XIJK= IJK+I
DX1 = XIJK
X= 1
DO 666 N=1,NMAX

SUM= SUM+(1/IN+EN)
666 CONTINUE
COR= 1+44934068/SUM
C
C COMPUTE LOCATION
C
DO 20 IM=1,IJK
XX=XX-DX
X(I)=XX
CONTINUE
IF(NOPT EQ 1)CALL SHA1(IJK,IPower,X,AAA)
C
COMPUTE THICKNESS INPUT
C
T(IJK)=0
T(I)=0
DO 21 I=2,IJK-1
XX=X(I)
T(I)=ASPT*(XX**CA)+(1-XX)**CB
21 CONTINUE
CALL DERIV(IJK,DX,T,DT)
DT(1)=0
CALL DERIV(IJK,DX,DT,DDT)
C
COMPUTE INPUT LOADING
C
XLOAD(IJK)=0
XLOAD(I)=0
DO 22 I=2,IJK-1
XX=X(I)
XLOAD(I)=(XX**CC)*((1-XX)**CD)
22 CONTINUE
C
GENERATE Y-COMPONENT GAP-AVERAGE VELOCITY
C
XLOAD0=0
CALL XINT(IJK,DX,XLOAD0,XLOAD,XLOAD)
AMPV=TAN2-TAN1/XLOAD(I)
DO 23 I=1,IJK
VLY(I)=AMPV*XLOAD(I)+TAN1
DVY(I)=AMPV*XLOAD(I)
23 CONTINUE
CALL DERIV(IJK,DX,DVY,D2VY)
C
COMPUTE FUNCTIONS
C
DO 2 I=1,IJK
XX=X(I)
RS(I)=5*S-T(I)
R1(I)=-(S+S/12)-(5*ST(I))-(5*T(I)**2)
RJ(I)=-(S+S*T(I)/12)-(25*S*T(I)**2)-(T(I)**3/6)
VFX(I)=S*S/RS(I)
D2VFX(I)=(S*S+DT(I))/(RS(I)**2)
DDVFX(I)=(S*S+DT(I)/RS(I)**2)+(S+DT(I)**2/RS(I)**3)
DF(I)=DY(I)/VFX(I)
DDF(I)=(VFX(I)*D2VFX(I)-VLY(I)*DY(I))/VFX(I)**2
2 CONTINUE
FZ0=0
CALL XINT(IJK,DX,FZ0,DF,F)
C
CALL SUBROUTINE TO COMPUTE EDGE VALUES
C
DDTH=2*DOT(I)/S
R0=R1(I)
VXY1=VLY(I)
DDVXY1=DDVY(I)
DDVFXY1=DDVFX(I)
FX1=FM(I)
DF1=VLY(I)/VFX(I)
CALL ECE(ER, NW, S, TN1, TN2, DDT, RIO, WVT1, DDPWXT, DDPVT)
1. F01, F0, DF0, DF1, A0, A1, B0, B1, COR)
FOLD(IJK)=F0
FOLD(I)=F1
DF(IJK)=DF0
DF(I)=DF1
F(IJK)=F0
F(I)=F1
C
C GUESS F FOR ITERATION PURPOSE
C
DELFO=-2*FSU(IJK,FOLD,RS.X,WMAX,COR)/S
DO 130 I=2, IJK-1
TERM1=RJ(I)-RI(I)
TERM2=(-DVT(I)-DF(I)+DVXT(I))/((1+DF(I))**2)
DELF=-2*(TERM1+TERM2)*FSU(I,FOLD,RS.X,WMAX,COR))/S
FOLD(I)=F(I)+DELF
CONTINUE
C
CALL DERIV(IJK,DX,FOLD,DF)
DF(IJK)=DF0
DF(I)=DF1
C
C CALL GUESSING SUBROUTINE FOR DBETA AND DDELT
C
CALL GUESS(IJK, X, T, DVX, DVXT, DBETA, DDBETA, DDELT, DDDELT)
C
WRITE(2,10)
10 FORMAT(5X,'GUESS INPUTS'/T10,'X',T25,'F',T40,'T55','DEL'
1.770,'BETA',T55,'DDELT'
1.770,'BETA',T55,'DDELT'
DO 11 I=1,1JK
11 CONTINUE
C
C ITERATION PROCESS FOR CAMBER LINE
C
NRR=0
OLDNRR=100
OLDD=100
DBETA(IJK)=DVX(IJK)
DBETA(I)=DVX(I)
DDELT(IJK)=DVXT(IJK)
DDELT(I)=DVXT(I)
DO 999 NIR=1, ITER
NIR=NIR-1
CALL HOMOB(WMAX, IJK, FOLD, RS, X, PHIX, PHIXT, COR)
CALL DERIV(IJK, DX, PHIX, PHIXT)
CALL DERIV(IJK, DX, PHIX, PHIXT)
C
DO 110 I=1, IJK
DEN=1+DF(I)**2
A(I)=(DF(I)*(DVXT(I)+DDELT(I)))/DEN
CONTINUE
C
CALL DERIV(IJK, DX, A, DA)
CALL DERIV(IJK, DX, A, DA)
DO 111 I=1, IJK
DEN=1 +DF(I)**2
B(I)=(CVMY(I)-DDDEL(I)*A(I)*ODF(I)+2 +DA(I)*DF(I))/DEN
111 CONTINUE
CALL DERIV(IJK, DX, DB, DB)

C
DO 112 I=2, IJK-1
TERM=DT(I)+(RS(I)+RI(I)+RJ(I))/RS(I)**2
DBETA(I)=RJ(I)*(DDA(DB(I)-DF(I))/R(I)+DDF(I))/RS(I)
TERM=(DA(I)+B(I)+DF(I))-(DBMIX(I)
DDEL(I)=RJ(I)*DB(I)/RS(I)*TERM+B(I)*DPHIMY(I)
112 CONTINUE
CALL DERIV(IJK, DX, DBETA, DBET)
CALL DERIV(IJK, DX, DDEL, DDEL)

C
COMPUTES CAMBER LINE
C
DO 155 I=1, IJK
OSC(I)=(-DPVX(I)-DDEL(I)-DF(I)+(DVMX(I)+DBETA(I)))/(1 +DF(I)**2)
OPT(I)=OSC(I)
155 CONTINUE
IF(NOPT EQ 1)CALL SMOOTH(IJK, IPower, X, AAAI, OSC, SMOSC)
C
ERRMAX=0
SUNERR=0
XLOC=-1
DO 160 I=2, IJK-1
TERM=RJ(I)-RS(I)*RI(I)
IF(NOPT EQ 1)OPT(I)=SMOSC(I)
DELF=2*(TERM+OPT(I)+FSUN(I,FOLD,T.RS.X.WMAX.COR))/S
F(I)=FM(I)+DFLDF
ERROR=ABS(F(I)-FOLD(I))
SUNERR=SUNERR+ERROR
IF(ERROR GT ERRMAX) ERRMAX=ERROR
160 CONTINUE
CALL DERIV(IJK, DX, F, DF)
DF(IJK)=DF0
DF(I)=DF1
C
WRITE CONVERGENCE
C
IF(NOPT EQ 1)GO TO 165
WRITE(1,162)ERRMAX, XLOC
162 FORMAT(15X, 'ITERATION #',13,'---', 'ENMAX = ',F7.5
1 AT X = ',F8.5)
IF(ERRMAX GT (I+3*OLDERR))WRITE(1,163)AVGERR
163 FORMAT(15X, 'AVGERR', 'ITERATION SCHEME DIVERGES',F6.3)
1 2X. AVERAGE ERROR = ', F9.5)
IF(ERRMAX GT (I+3*OLDERR))GO TO 998
IF(ERRMAX LE ERR)GO TO 998
GO TO 169
C
ERRAVG=SUNERR/XIJK
WRITE(1,166)ERRAVG
166 FORMAT(15X, 'ERRAVG = ',F7.5)
IF(ERRAVG GT ERR)GO TO 998
C
C UPDATE VALUES
169  DO 170 I=2, IJK-1
     FOLD(I)=F(I)
170  CONTINUE
     OLDER=ERRMAX
     OLDER=ERRAVG
C
999  CONTINUE
C
999  CONTINUE
C
C WRITE
C
WRITE(1,60)
60  FORMAT(/T10. 'X', T24. 'LOAD(X)', T40. 'T(X)', T55. 'FWM(X)', T70. 'F(X)/')
DO 501 I=1, IJK
   J=IJK+1-I
   PLOT(1.1)=X(J)
   PLOT(2.1)=F(J)
   PLOT(3.1)=F(J)+T(J)
   PLOT(4.1)=F(J)-T(J)
   PLOT(5.1)=BLADE
   PLOT(6.1)=BLADEB
   TERM=AXPV+XLOAD(J)
WRITE(1, 61)X(J), TERM, T(J), F(J), F(J)
501  CONTINUE
C
CALL QPICTR(PLOT.6, IJK, QY(2,3,4,5,6), QX(1), QXLAB(14)
   1, QYLAB( 'BLADE SHAPE' ), QXLAB( 'AXIAL LOCATION X' ))

C
WRITE(2,70)
70  FORMAT(/SF5X, F10.5))
501  CONTINUE
C
CALL VEL(IJK, NMAX, COR, X, Y, F, DF, DS, R, R, PHI, PHIB, PHNT
   1, VMX, DVMX, DDMX, VNY, DVNY, DDMY, DBETA, DDBETA, DDDEL, DDDEL
   1, VEX, VTY)
DO 801 I=1, IJK
   T(I)=F(I)-T(I)
800  CONTINUE
   CALL VEL(IJK, NMAX, COR, X, Y, F, DF, DS, R, R, PHI, PHIB, PHNT
   1, VMX, DVMX, DDMX, VNY, DVNY, DDMY, DBETA, DDBETA, DDDEL, DDDEL
   1, VEX, VTY)
WRITE(1,799)
799  FORMAT(/T10. 'X', T25. 'Cp-', T40. 'Cp-', T55. '(delta)F/')
DO 802 I=1, IJK
VT=(VXT(I)**2+VYT(I)**2)**.5
VB=(VXR(I)**2+VYR(I)**2)**.5
CPT(I)=1-(VT/VORSET)**2
CPB(I)=1-(VB/VORSET)**2

802 CONTINUE

810 DO 804 I=1,1,1
   J=1JX+1-1
   DIFF=ABS(CPT(J)-CPB(J))
   PLOT(2,1)=CPT(J)
   PLOT(3,1)=CPB(J)
   PLOT(4,1)=PRESS(J)
   WRITE(3,*)X(J),CPT(J),CPB(J),DIFF
   WRITE(1,805)(X(I),CPT(I),CPB(I),DIFF)
805 FORMAT(4(E15.6))
804 CONTINUE

CALL QPICTR(PLOT.6.IX.YQ.2.3.4.5).QX(I).QLABEL(14)
1,QLAND('PRESSURE COEFFICIENT Cp'),QLAB('AXIAL LOCATION X'))

C WRITE BLADE SHAPE TO A FILE FOR USE IN THE NASA DIRECT METHOD
C
C DO 900 I=1,1,1
   WRITE(6,*)X(I)
900 CONTINUE

DO 901 I=2,1,1
   J=1JX+1-1
   WRITE(6,*)X(J)
901 CONTINUE

DO 902 I=1,1,1
   JSURF=P(I)-T(I)
   WRITE(6,*)JSURF
902 CONTINUE

DO 903 I=2,1,1
   J=1JX+1-1
   TSURF=P(J)+T(J)
   WRITE(6,*)TSURF
903 CONTINUE

C STOP

C **************************************************************
C
C THIS FUNCTION COMPUTE FSUM(I)
C
C FUNCTION FSUM(I,FOLD,T.RS.X.RMAX,CON)
REAL FOLD(101),T(101),RS(101),X(101)
COMMON/CMDN/5,AO,A1,B0,B1,P1
REAL LAWDW
SIM=0
DO 100 I=1,RMAX
   X=U
   LAWD=0.*PI*X/S
   DELF=(FOLD(I)-FOLD(JK))/LAWDW
   DELF=(FOLD(I)-FOLD(I))/LAWDW
   TTT=1+TN((LAWDW+RS(I))*COS(LAWDW+T(I)))-EXP(-LAWDW*X(I))
   TO=TTT+EXP(-LAWDW+X(I))/LAWDW**3
   T1=TTT+EXP(-LAWDW+X(I))/LAWDW**3
   TEM=0.0+COS(DELFO)+AO+sin(DELFO)
C SUBROUTINE DE1UIV(IJX.DX.F.DF)
REAL F(101).DF(101)
DF(IJK)= 5*(-F(IJK-2)+4 *F(IJK-1)-3 *F(IJK))/DX
DF(1)= 5*(-F(1)+4 *F(2)+F(3))/DX
DO 1 I=2,1JK-1
DF(I)= 5*(F(I-1)-F(I+1))/DX
1 CONTINUE
RETURN
END
C C *****************************************************
C SUBROUTINE DERIV(IJK.DX.F.DF)
REAL F(101).DF(101)
DF(IJK)= 5*(-F(IJK-2)+4 *F(IJK-1)+F(IJK))/DX
DF(1)= 5*(-F(1)+4 *F(2)+F(3))/DX
DO 1 I=2,1JK-1
DF(I)= 5*(F(I-1)+F(I+1))/DX
1 CONTINUE
RETURN
END
C C *****************************************************
C SUBROUTINE XINT(IJK.DX.XINTP0.F.XINTF)
REAL F(101).XINTF(101)
SUM=XINT0
XINTF(IJK)=SUM
DO 1 I=2,1JK-1
J=1JK+1-I
SUM=SUM+ 5*(F(J)+F(J+1))*DX
XINTF(J)=SUM
1 CONTINUE
RETURN
END
C C *****************************************************
C SUBROUTINE EDGE
C THIS SUBROUTINE CALCULATE EXACT LE AND TE VALUES
C IN ORDER TO ACCELERATE CONVERGENCE IN F(X)
C
SUBROUTINE EDGE(ERR, NMAX, S, TAN, TAN2, DOTH, RIO, VMX1
1, DMX1, DVMX1, FMX1, 0, P1, DF0, DF1, A0, A1, B0, B1, COR)
REAL LANDM
PI=3 141592654
F0=0
DFO=TAN1
IC=0
100 SUN01=0
SUN11=0
SUN20=0
SUN22=0
SUN30=0
SUN33=0
SUN00=0
SUN#=
DO 101 N=1, NMAX
XM=X
LANM#=2 *PI*XM/S
DELF=LANM#*(F0-F1)
CC=EXP(-LANM#)/LANM#**2
SUMCI1=CC+SIN(DELF)
SUMCOS=CC+COS(DELF)
SUN01=SUN01*COR+SUMCOS
SUN11=SUN11*COR+SUMCOS/SUN01
SUN20=SUN20*COR+SUMCOS/SUN11
SUN22=SUN22*COR+SUMCOS/SUN01
SUN30=SUN30*COR+SUMCOS/SUN11
SUN33=SUN33*COR+SUMCOS/SUN01
SUN00=SUN00*COR/LANDM**3
SUN#2+SUN#+COR/LANDM101 CONTINUE
Z1=RIO*DOTH-(1-DF1#)*Z2
Z2Z=-(2/RIO)*S(SUN01**2-SUN11**2)
Z2=-(5*RIO*Z2Z)*DOTH
Z3=-(4/RIO)*SUM01+SUM11*DOTH
SA1=(2*DOTH+(SUN11+TAN1+SUM01))/RIO-DMX1
SA2=(-2*DOTH+(SUN01+TAN1+SUM1))/RIO-DMX11
SA3=Z1-Z2
SA4#2 *DF1+Z3
SA22=Z1-Z22
DEN=SA3+SA22*SA4+SA4
A1=(SA3+SA2+SA4+SA4)/DEN
B1=(SA2+SA3+SA4)/DEN
A0=2 -(A1+SUN11-B1+SUN01-1 )/RIO
B0=2 +(A1+SUN1-B1+SUN11-TAN1)/RIO
XM02=B0+SUN00-A1+SUN02-B1+SUN22
FK1+FX1-B0+SUN22*A0+SUN02-B1+SUN00-XNORM
DPHINT+SN+B0+SUN33+B1+SUN3+B1+SUN03+A1
DPHIHX+SN+A0-SUN03+B1-SUN33+A1
RATIO=(2 *DPHIH* S+A0)/S(2+25*S*A0)
DFLE=5*DPHIH*RATIO
XNORM+VF1 -75+B1-RIO+B0+SUN11-A0-SUN01
DENTE=1 -75+A1+RIO+B0+SUN01+A0+SUN11
DFTE=XNORM/DENTE
ER1=ABS(FTE-F1)
ER2=ABS(DFTE-DF1)
ER3=ABS(DFLE-DF0)
F1=FTE
DF0=DFLE
DF1=DFTE
IC=IC+1
IF(ER1 GT ERR OR ER2 GT ERR OR ER3 GT ERR) GO TO 100
RETURN
END
SUBROUTINE NAME GUESS FOR
THIS SUBROUTINE INITIALIZE BETA AND DELTA
TO START THE ITERATION PROCESS OF F(X)

SUBROUTINE GUESS(IJK, X, T, DVVMX, DVMX, DBETA, DDBETA, DDELT, DDDDEL)
REAL DBETA(101), DDBETA(101), DDELT(101), DDDDEL(101), DVVMX(101), DVMX(101)
1. DVMX(101), DVMX(101), X(101), T(101)

PI=3 141592654
DO 1 I=1, IJK
X= X(I)
TCOS = COS (2 * PI * X(I))
TSIN = SIN (2 * PI * X(I))
DBETA(I) = -DVVMX(I) + TCOS
DDBETA(I) = -DVVMX(I) + TCOS
DDELT(I) = 0
DDDEL(I) = 0
1 CONTINUE

RETURN
END
SUBROUTINE NAME: HOMOB FOR

THIS SUBROUTINE CALCULATES THE HOMOGENEOUS

TERM PHIHXD AND PHIHYD

SUBROUTINE HOMOB(NMAX, IJK, F, T, RS, PHIHXD, PHIHYD, COR)

REAL F(I01), X(I01), T(I01), RS(I01), PHIHXD(I01), PHIHYD(I01)

C0 = MON/C0HIML/S.A0, A1, B0, B1, PI

REAL LAMDU

DO 200 I=1, IJK

SUZX=0

SUZX=O

DO 100 M=1, NMAX

X=V

LAMDU=2 *PI*XMS

DELFX=(F(I)-F(IJK))+LAMDU

DELFX=(F(I)-F(IJK))+LAMDU

XSIN=SIN(LAMDWH+T(I))

EXP0=EXP(-LAMDWH*X(I))

EXP1=EXP(-LAMDWH*(1-X(I)))

SINO=SIN(DELFX)

SIM=SIN(DELFX)

COSO=COS(DELFX)

COSI=COS(DELFX)

TO=XSIN*EXP0/LAMDWH3

T1=XSIN*EXP1/LAMDWH3

SUZX=SUZX + T0*(BO+SINO-AO*COSO) + T1*(B1+SINO+A1*COSO)

SUZT=SUZT + T0*(-BO+COSO-AO*SINO) + T1*(-B1+COSO+A1*SINO)

100 CONTINUE

PHIHXD(I)=COR*SUZX/RS(I)

PHIHYD(I)=COR*SUZT/RS(I)

200 CONTINUE

RETURN

END
C SUBROUTINE NAME VEL FOR
C THIS SUBROUTINE COMPUTES THE VELOCITY FIELD
C IN THE CASCADE REGION (REGION 2)
C
SUBROUTINE VEL(I,JX,MAX,IX,Y,F,DF,DDF,RJ,PHIHX,PHIHY)
  REAL X(101), Y(101), F(101), DF(101), DDF(101), RJ(101), PHIHX(101), PHIHY(101)
  CALL HOMO(MAX, IJX, F, X, Y, PHIHX, PHIHY)
  DO 200 I = 2, IJX - 1
  DEN = (1.0*DF(I)**2)**3
  X1 = 2.0*DF(I)**3
  X2 = -DF(I)**3
  X3 = 0.0
  X4 = 0.0
  DXX = DDF(I)**3
  DYY = DDF(I)**3
  AX(I) = (X1*X3 + X1 + X2 + X4) / DEN
  BX(I) = (X1*X2 - X1 + X3 + X4) / DEN
  VX(I) = (AX(I) + BX(I)) / RJ(I)
  VY(I) = (AX(I) + BX(I)) / RJ(I)
  CONTINUE
END

C CALL HOMO(MAX, IJX, F, X, Y, PHIHX, PHIHY, COR)
C
AX(IJX) = AO
AX(1) = A1
BX(IJX) = B0
BX(1) = B1
DO 200 I = 2, IJX - 1
DEN = (1.0*DF(I)**2)**3
X1 = 2.0*DF(I)**3
X2 = -DF(I)**3
X3 = 0.0
X4 = 0.0
DXX = DDF(I)**3
DYY = DDF(I)**3
AX(I) = (X1*X3 + X1 + X2 + X4) / DEN
BX(I) = (X1*X2 - X1 + X3 + X4) / DEN
VX(I) = (AX(I) + BX(I)) / RJ(I)
VY(I) = (AX(I) + BX(I)) / RJ(I)
CONTINUE
C
DO 100 I = 1, IJX
ALPHA = Y(I) - F(I)
RST = 5.0 + ALPHA
RIT = (5.0 + ALPHA) - (5.0 + ALPHA)**2
CCC = R(I) / R(S(I))
TERX = RX*TVX(I) + CCC*RIT)*AX(I)
TERY = RX*TVY(I) + CCC*RIT)*BX(I)
VX(I) = VX(I) + PHIHX(I) - PHIHY(I) + TERX
VY(I) = VY(I) + PHIHY(I) - PHIHX(I) + TERY
CONTINUE
C
RETURN
END
SUBROUTINE NAME HOMO FOR

THIS SUBROUTINE CALCULATES THE HOMOGENEOUS TERMS PHIHX AND PHIHY

SUBROUTINE HOMO(NMAX, IJK, X, Y, PHIHX, PHIHY, COR)
REAL F(IO1),X(IO1),Y(IO1),PHIHX(IO1),PHIHY(IO1)
COMMON/CUM1/S, AO, AI, BO, BI, PI
REAL LAMDX
DO 200 I=1, IJK
SUMX=0
SUMY=0
DO 100 M=1, NMAX
XM=M
LAMDX=M *PI* XM/S
DELF0=(Y(I)-F(I,K))*LAMDX
DELF1=(Y(I)-F(I))*LAMDX
EXP0=EXP(-LAMDX*X(I))
EXP1=EXP(-LAMDX*(1 -X(I)))
SINO=SIN(DELF0)
COSO=COS(DELF0)
SINI=SIN(DELF1)
COSI=COS(DELF1)
TO=EXP0/LAMDX**2
TI=EXP1/LAMDX**2
SUMX=SUMX+TO*(-BO*SINO+AI+COSO)-TI*(BI+SINI+AI+COSI)
SUMY=SUMY+TO*(BO+COSO+AI+SINO)+TI*(BI+COS1-AI+SIN1)
100 CONTINUE
PHIHX(I)=COR+SUMX
PHIHY(I)=COR+SUMY
200 CONTINUE
RETURN
END
SUBROUTINE SMOOTH(XJX, IORDER, X, AI, F, SMF)
REAL X(101), F(101), SMF(101), AI(10, 10), B(10), SMCF(10)

DO 400 J=1, IORDER-1
SUM=0
DO 500 I=1, IJK
SUM=SUM+(F(I)-F(JK))*(X(I)**J)
CONTINUE
500 CONTINUE
B(J)=SUM
400 CONTINUE
B(IORDER)=F(I)-F(JK)

DO 100 I=1, IORDER
SUM=0
DO 200 J=1, IORDER
SUM=SUM+AI(I,J)*B(J)
200 CONTINUE
SMCF(I)=SUM
100 CONTINUE

DO 600 I=1, IJK
SUM=F(I)
DO 700 J=1, IORDER
SUM=SUM+SMCF(J)*(X(I)**J)
700 CONTINUE
SMF(I)=SUM
600 CONTINUE

RETURN
END
C SUBROUTINE NAME SMAI FOR
C SUBROUTINE USED TO GENERATE MATRIX [ AI ]
C USED IN THE LEAST-SQUARE FITTING FILTER
C
C SUBROUTINE SMAI(IJK, IORDER, X, AI)
REAL A1(10,10), B(10), WKAREA(20), X(101), XM(19)
C
DO 100 I=2,2+IORDER
SU=0
DO 200 J=1,1,IJK
SU=SU+X(J)**2
200 CONTINUE
XM(I-1)=SU
100 CONTINUE
C
K=0
DO 10 I=1,1,IORDER
DO 20 J=1,1,IORDER
AI(I, J)=XM(K+J)
20 CONTINUE
K=K+1
10 CONTINUE
DO 300 J=1,1,IORDER
AI(IORDER, J)=1
300 CONTINUE
C
D1=1
CALL LINV3F(A1, B, IORDER, 10, D1, D2, WKAREA, IER)
C
RETURN
END
SUBROUTINE NAME FILTER FOR
THIS SUBROUTINE FILTER
THE PRESSURE
COEFFICIENTS

SUBROUTINE FILTER3(IJK.X.FFFILT)
REAL X(101),F(101),FT(101),FB(101),XB(101),FFILT(101)
X=J+1
PI=3.1415926534
DX=1/X=J
I=1(J+1)/2

NB=0
MT=0
I=I+1
100 IF(I GT (I-1)) GO TO 999
IF(F(I+1) GT F(I)) GO TO 100
IF(I EQ 1) GO TO 20
MT=MT+1
FT(NT)=F(I)
XT(NT)=X(I)
200 I=I+1
IF(I GT (I-1)) GO TO 999
IF(F(I+1) LE F(I)) GO TO 200
NB=NB+1
FB(NB)=F(I)
XB(NB)=X(I)
GO TO 100
999 CONTINUE

FT(NT)=F(I)
FB(NB)=F(I)
XB(NB)=X(I)

XP=NT*1
CALL FIT(IJK.DX.NP.X.XT.F.FT)
NP=NP+1
CALL FIT(IJK.DX.NP.X.XB.F.FB)
DO 700 I=1.IJK
FFILT(I)= 5*(FB(I)+FT(I))
700 CONTINUE

RETURN
END

SUBROUTINE FIT(IJK.DX.NP.X.XT.F.FT)
REAL X(101),XTB(101).F(101),FTB(101),FFIT(101)
X=FIT(101),FIT1(101),FIT2(101),X(101)

XTB=XTB(I)/DX
HST=IJK-11FIX(XST)
HST1=HST
DO 10 I=2.HP
XH=FTB(I)-FTB(I-1)/XTB(I)-XTB(I-1)
X=FTB(I)-XH*XTB(I)
X=XTB(I)/DX
10 I=IJK-11FIX(XI)
DO 20 N=NST+1
FFIT(N)=XW*X(N)*XB
20 CONTINUE
NST=JJ
10 CONTINUE
C
DO 30 I=1,NST
FTB(I)=F(I)
30 CONTINUE
DO 31 I=NST+1,JK
FTB(I)=FFIT(I)
31 CONTINUE
C
N=0
DO 100 I=NST+1,JK-2
N=N+1
XFILT(N)=X(I)
FILT(N)=FTB(I)
100 CONTINUE
CALL SMAI(N,4,XFILT,AAAI)
CALL SMOOTH(N,4,XFILT,AAAI,FILT1,FILT2)
N=0
DO 101 I=NST+1,JK-2
N=N+1
FTB(I)=FILT2(N)
101 CONTINUE
C
DO 200 I=NST+1,JK-3
FTB(I)=3333*(FTB(I+1)*FTB(I)+FTB(I-1))
200 CONTINUE
DO 201 I=NST+1,JK-5
FTB(I)=3333*(FTB(I+2)*FTB(I)+FTB(I-2))
201 CONTINUE
C
RETURN
END
C
C ****************************