A GENERALIZED THEORY
FOR THE DESIGN OF
CONTRACTION CONES AND
OTHER LOW-SPEED DUCTS

by Raymond L. Barger and John T. Bowen

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A generalization of the Tsien method of contraction-cone design is described. The design velocity distribution is expressed in such a form that the required high-order derivatives can be obtained by recursion rather than by numerical or analytic differentiation. The method is applicable to the design of diffusers and converging-diverging ducts as well as contraction cones. The computer program is described and a FORTRAN listing of the program is provided.
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SUMMARY

A generalization of the Tsien method of contraction-cone design is described. The design velocity distribution is expressed in such a form that the required high-order derivatives can be obtained by recursion rather than by numerical or analytic differentiation. The method is applicable to the design of diffusers and converging-diverging ducts as well as contraction cones. The computer program is described and a FORTRAN listing of the program is provided.

INTRODUCTION

For incompressible flows in ducts of slowly varying radius the one-dimensional flow relation between the velocity and the cross-sectional area can be used to predict the velocity distribution in a given duct or to design a duct for a desired velocity distribution.

However certain applications, such as the contraction cone for a wind tunnel, require short ducts with a relatively rapid variation of the wall radius. For such applications the one-dimensional relation no longer suffices, and a solution of the differential equation of the flow must be sought. Tsien (ref. 1) derived a solution for the stream function in terms of a prescribed axial velocity distribution, and applied this solution in the design of a wind-tunnel contraction cone.

It should be mentioned that such a design, obtained from the incompressible-flow equations, is a conservative design in the sense that when it is operated at off-design compressible conditions, the ratio of exit velocity to entering velocity is higher than the design ratio.

The major difficulty in applying Tsien's solution arises from the stringent requirements on the form of the input axial velocity distribution. These requirements are such that only a small class of functions can be used to describe the design velocity distribution. This problem has been considered in reference 2, where a form of velocity distribution different from that of reference 1 is used.
This form allows more freedom in shaping the design velocity function, but it introduces the problem of requiring hand calculations in analytic form of many derivatives of the function. Other analyses have utilized different formulations of the solution of the differential equation according to the way the variables are separated in solving the equation. The method of reference 3 assigns an exponential type of variation in the axial direction, and so is limited to a single design velocity distribution. References 4 and 5 use a periodic axial velocity distribution, but inasmuch as the flow is not periodic, this formulation gives rise to errors near the beginning and the exit of the contraction cone. An additional problem with this latter method is that the finite-term trigonometric approximation to a function is in general a function that oscillates about the desired function, and such a "wavy" distribution is not very satisfactory for design purposes. The three forms of solution for the stream function are given explicitly in reference 5.

The present analysis represents a generalization of the method of reference 1, in that a wide range of design velocity distributions is permitted so that the method is no longer restricted to a specific contraction cone but may be applied to the design of a wide variety of ducts. Greater accuracy is obtained through the use of an electronic computer and by retaining a large number of terms in the series solution.

SYMBOLS

\[ A, B, c, d_n \quad \text{arbitrary parameters and coefficients in expression for design velocity} \]

\[ f_d = f_g - f_p \]

\[ f_g \quad \text{general form of design velocity distribution at centerline} \]

\[ f_p \quad \text{preliminary form of design velocity distribution at centerline (eq. (3))} \]

\[ f_0 \quad \text{design velocity distribution at centerline used in reference 1} \]

\[ G \quad \text{total velocity} \]

\[ H_n \quad \text{nth Hermite polynomial} \]

\[ k \quad \text{upper summation index} \]

\[ m, n \quad \text{indices} \]

\[ x, r \quad \text{cylindrical coordinates} \]
ANALYSIS

Tsien's solution (ref. 1) for the axial and radial velocities in incompressible axisymmetric flow is

\[
\begin{align*}
  u &= \sum_{0}^{\infty} \frac{(-1)^{n} f_0^{(2n)}(x)}{2^{2n(n+1)^2}} r^{2n} \\
  v &= \sum_{1}^{\infty} (-1)^{n-1} f_0^{(2n-1)}(x) n^{-2n-1} 2^{2n(n+1)^2}
\end{align*}
\]

where \( f_0(x) \) is the prescribed velocity on the axis. The stream function can be obtained by integration. Its \( k \)-term approximation is

\[
\psi = \sum_{1}^{k} \frac{(-1)^{n-1} f_0^{(2n-2)}(x) r^{2n}}{2^{2n-1} n [(n - 1)!]^2}
\]

The kind of functions \( f_0(x) \) which are appropriate for describing the axial velocity distribution will now be examined. It is apparent that if the series is truncated at the
nth term 2n - 2 derivatives of \( f_0 \) are required. Therefore, \( f_0 \) must be such that these derivatives can be obtained in analytic form because it is generally impossible to obtain high-order derivatives numerically with accuracy. Furthermore, as has been pointed out in reference 2, the simplest way to insure that conditions at infinity upstream and downstream be uniform is to require that all the derivatives of \( f_0 \) vanish as \( x \to \pm \infty \), but of course \( f_0 \) must not itself vanish at \( x = \pm \infty \).

Thus it is seen that the class of functions that can be used to describe the axial velocity is severely limited.

In reference 1 this velocity distribution is prescribed by the function

\[
\bar{u}_{r=0}(x) = f_0(x) = 0.55 + \frac{0.9}{\sqrt{2\pi}} \int_0^x e^{-\frac{x^2}{2}} \, dx
\]  

(2)

The following analysis generalizes the procedure of reference 1 so that a much larger variety of design velocity distributions is permitted and in such a way that the series can be carried out to an arbitrary number of terms without any penalty except a trivial increase in machine computing time.

The basic preliminary form of the design velocity function is chosen to be

\[
f_p(x) = A + \frac{2cB}{\sqrt{\pi}} \int_0^x e^{-c^2x^2} \, dx
\]  

(3)

which is only a slight generalization of equation (2). The derivatives of this expression can be obtained by recursion, following a development similar to that of reference 1: Let

\[
\Phi(x) = \frac{c}{\sqrt{\pi}} e^{-c^2x^2}
\]

then the \( m + 1 \) derivative of \( f_p \) is

\[
f_p^{(m+1)}(x) = 2B \Phi^{(m)}(x)
\]

Substitute

\[
\begin{align*}
x &= \frac{z}{c} \\
z^2 &= c^2x^2
\end{align*}
\]

(4)

then

\[
\Phi^{(m)}(x) = \frac{c}{\sqrt{\pi}} c^m \frac{d^m}{dz^m} e^{-z^2} = \frac{c^{m+1}}{\sqrt{\pi}} (-1)^m e^{-z^2} H_m(z)
\]
or

\[ \phi^{(m)}(x) = (-1)^m c^m \phi(x) H_m(z) \]  

where \( H_m(z) \) is the mth Hermite polynomial (see eq. (29) on p. 91 of ref. 6). The recurrence formula for Hermite polynomials is

\[ H_m(z) = 2z H_{m-1}(z) - 2(m - 1) H_{m-2}(z) \]

Multiply both sides by \((-1)^m c^m \phi(x)\) and then equation (5) becomes

\[ \phi^{(m)}(x) = 2z(-1)^m c^m H_{m-1}(z) - 2(m - 1)(-1)^m c^m H_{m-2}(z) \]

\[ = -2c^2 \left[ (-1)^{m-1} z c^{m-1} H_{m-1}(z) + (m - 1)(-1)^{m-2} c^{m-2} H_{m-2}(z) \right] \]

\[ = -2c^2 \left[ x \phi^{(m-1)}(x) + (m - 1) \phi^{(m-2)}(x) \right] \]

which is the desired recurrence formula for the derivatives.

Now consider a more general design velocity function \( f_g(x) \), obtained by adding terms to \( f_p(x) \). Since the initial and final velocities are determined by the coefficients in \( f_p(x) \), these additional terms and all their derivatives must vanish at \( \pm \infty \). They should also be such that an arbitrary number of differentiations can be performed analytically in a simple manner. These conditions are satisfied by the form:

\[ f_g(x) = f_p(x) + \sum_{0}^{k} d_n e^{-x^2} H_n(x) \]  

(6)

The factor \( e^{-x^2} \) in each term of the series assures that the conditions at \( \pm \infty \) will not be affected. The derivatives of these terms are obtained by the recurrence formula:

\[ \frac{d}{dx} \left[ e^{-x^2} H_n(x) \right] = -e^{-x^2} H_{n+1}(x) \]

(ref. 7, p. 786, where the stated formula contains an extraneous factor of 2).

The coefficients \( d_n \) can be determined as follows by means of the orthogonality property of the Hermite polynomials. Denoting

\[ f_d(x) = f_g(x) - f_p(x) \]
and substituting in equation (6)

\[ f_d(x) = \sum_{k}^{k} d_n e^{-x^2} H_n(x) \]  

(7)

multiplying by \( H_m(x) \) and integrating, yields

\[ \int_{-\infty}^{\infty} f_d(x) H_m(x) \, dx = \sum_{n=0}^{k} d_n \int_{-\infty}^{\infty} e^{-x^2} H_n(x) H_m(x) \, dx = \sum_{n=0}^{k} \delta_{mn} 2^n n! \sqrt{\pi} d_n \]

Thus

\[ d_m = \frac{1}{2^m m! \sqrt{\pi}} \int_{-\infty}^{\infty} f_d(x) H_m(x) \, dx \]

where the finiteness of the integral is assured by the nature of \( f_d(x) \). Of course the series in equation (7) will, in general, only approximate \( f_d(x) \) since only \( k \) terms are used.

A simpler, but less accurate, approximation could be obtained by matching the function \( f_d(x) \) at \( k \) points and obtaining the coefficients as solutions of \( k \) simultaneous linear equations.

Actually, neither of these methods for determining the coefficients has been used so far. Rather, the calculation of \( f_g(x) \) was programed for visual display, and various values of the coefficients were tried until a close approximation to the desired \( f_g(x) \) was obtained.

A description and listing of the computer program is given in the appendix.

DESIGN PROCEDURE

The basic considerations that govern the design of a contraction cone from a prescribed axial velocity distribution have been discussed in reference 2. In general the same considerations are applicable to the design of other kinds of ducts.

After selecting an appropriate axial velocity function the next step in the procedure is to determine several streamlines by solving the equation for the stream function,

\[ \psi = \sum_{n=0}^{k} (-1)^{n-1} r^{2n-2} (2n-2)!(x) \frac{r^{2n}}{2^{2n-1} n \left[ (n-1)! \right]^2} \]
where

\[ f_g(x) = A + \frac{2cB}{\sqrt{\pi}} \int_0^x e^{-c^2x^2} dx + \sum_{n=0}^{k} d_n e^{-x^2} H_n(x) \]  

(8)

for \( r \) at the designated \( x \)-stations with fixed values of \( \psi \). A computer program library routine, utilizing interval-halving, was used for this purpose. It may be noted that, in accordance with Descarte's rule of signs, there may be as many as \( k \) positive solutions of equation (1) for \( r^2 \) and so for \( r \) (for fixed \( \psi \) and \( x \)). However, any possible ambiguity in the solution can be avoided by making an initial estimate of the radius from the one-dimensional approximate relation between velocity and area ratio, after one point on the streamline has been computed.

As successive streamlines are determined, the velocity distributions along the streamlines are also computed. These display a greater radial variation in regions of larger curvature, eventually leading to an adverse velocity gradient in regions of inward turning of the wall. Of course some radial velocity gradient is normally acceptable, and generally a slight adverse velocity gradient can be tolerated by the boundary layer. These factors must be considered when selecting a streamline for the actual duct contour inasmuch as the duct length is shortened by taking larger values of the stream function. Since a short duct implies savings in material, space, and wall-friction losses, the usual design goal is to have the shortest possible duct compatible with acceptable flow quality.

DISCUSSION AND EXAMPLES

The form of the design velocity distribution is determined by the choice of the various parameters in equation (8) in a manner which can be readily demonstrated. Using the identity \( \int_0^\infty e^{-c^2x^2} dx = \frac{\sqrt{\pi}}{2c} \), one readily computes that upstream, at \( x = -\infty \),

\[ f_{g,i} = A - B \]

and downstream, at \( x = +\infty \),

\[ f_{g,f} = A + B \]

Consequently \( A = \frac{1}{2}(f_{g,i} + f_{g,f}) \), the average of the initial and final velocities, and \( B = \frac{1}{2}(f_{g,f} - f_{g,i}) \). When \( d_n = 0 \) for all \( n \) the velocity is \( A \) at \( x = 0 \); and, inasmuch as the odd-order Hermite polynomials are odd functions of \( x \), the presence of the terms containing these polynomials does not change the velocity at the origin. The even-order
polynomials, on the other hand, influence the velocity function in a symmetric (even) manner and, consequently, affect the velocity at the origin.

The nature of the exponential factor \( e^{-c^2x^2} \) in the integral term of \( f_g(x) \) and \( f_p(x) \) assures that \( f_p(x) \) will be essentially flat outside of some neighborhood of \( x = 0 \). Inasmuch as the terms of the summation each contain a factor of \( e^{-x^2} \), the neighborhood of \( x = 0 \) over which these terms alter \( f_p(x) \) depends on the magnitude of \( c \) compared to 1.

An example is shown in figure 1. Here an axial velocity distribution obtained by using only the two terms of \( f_p(x) \) (eq. (3)) is compared with one obtained with the same values for the parameters except with \( d_1 = 0.1 \). Thus, the initial and final velocities and the velocity at the origin are all unchanged, but the variation of velocity throughout the design region is radically changed. This distribution (with \( d_1 = 0.1 \)) has appropriate characteristics for a contraction-cone design, that is, it is relatively short between the flat ends with smoothly varying curvature. Figure 2 shows a contraction cone designed from this velocity distribution together with several internal streamlines. Figure 3 shows the distributions of velocity along these streamlines. As expected the radial variation of velocity is greatest near the entrance where the curvature is greatest.

A different kind of design velocity distribution is shown in figure 4. Here the initial and final velocities were prescribed to be 0.5 and 1.0, respectively, with the terms with Hermite polynomials all chosen to have zero coefficients except \( d_0 = 0.6 \). Thus the maximum velocity occurs at \( x = 0 \), where \( f_g = A + d_0 = 1.35 \). Such a velocity distribution (one with the peak velocity between the ends) cannot be described with the original Tsien formulation.

A duct designed from this velocity distribution is shown in figure 5 together with some streamlines, and the wall velocity distribution is shown in figure 4. The radial variation of velocity is noticeable at the minimum, where the curvature is relatively large. This result may be compared with that of figure 3 for the contraction cone where the relatively small curvature at the minimum results in a nearly uniform flow there.

CONCLUDING REMARKS

A method for generalizing the Tsien procedure of contraction-cone design has been presented. The class of design velocity distributions is enlarged in such a way that conditions far upstream and downstream are unchanged, and so that the derivatives required in the calculation can be obtained by a recurrence formula rather than by numerical dif-
ferentiation. The generalized method is no longer restricted to contraction cones but now permits the design of diffusers and converging-diverging ducts.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., September 26, 1972.
APPENDIX

COMPUTER PROGRAM FOR LOW-SPEED DUCT DESIGN

A computer program has been developed which will calculate the wall contour for a subsonic duct. The program is written in the FORTRAN IV language for use on CDC 6000 series computers. Since it was desired to take an interactive approach to the problem, the program has been implemented on the LRC interactive graphics system using the CDC 250 Cathode Ray Tube (CRT). The program listing and a description of its input and output are presented in this appendix.

Description of Program

The program is basically divided into two parts. Part I of the program builds an I x 4 design table where the stream function $\psi$, the axial coordinate $x$, the radial coordinate $r$, and the number of derivative terms $N$ are column vectors; $I$ is the number of row entries. The program computes the value of the stream function at any point $x,r$ or the value of $r$ for an arbitrary value of $\psi$ at some specified axial coordinate. By employing these two computations (each of which stores an entry in the design table), the user can determine the neighborhood of the desired solution and approximate the boundaries of its convergence.

Part II of the program computes the radial coordinates which agree with some specified range of the axial coordinates and a fixed value of the stream function (streamlines). In addition, it gives the corresponding velocity distribution in the duct and its axial and radial components. The streamlines are visually displayed on the CRT with a visual cue at the point where the velocity is no longer monotonically increasing. The plotting specifications are variable and may be input during program execution.

Subprogram Index

The following is an index of the subprograms called by this program and their sources. AUTHOR denotes routines written by the authors of this paper. CALCOMP indicates routines available as a part of the CalComp graphic output system. CRT indicates routines which are a part of the LRC interactive graphic system. LIBRARY denotes routines which are on the LRC computer complex system tape. The functions of the authors' routines are also given.
<table>
<thead>
<tr>
<th>Subprogram</th>
<th>Source</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>LIBRARY</td>
<td></td>
</tr>
<tr>
<td>AXES</td>
<td>CALCOMP</td>
<td></td>
</tr>
<tr>
<td>CALPLT</td>
<td>CALCOMP</td>
<td></td>
</tr>
<tr>
<td>CDC250</td>
<td>CRT</td>
<td></td>
</tr>
<tr>
<td>DAYTIM</td>
<td>LIBRARY</td>
<td></td>
</tr>
<tr>
<td>DERIV</td>
<td>AUTHOR</td>
<td>Computes the derivatives of (f_g(x)), equation (6)</td>
</tr>
<tr>
<td>ENCODE</td>
<td>LIBRARY</td>
<td></td>
</tr>
<tr>
<td>EXP</td>
<td>LIBRARY</td>
<td></td>
</tr>
<tr>
<td>FACT</td>
<td>AUTHOR</td>
<td>Computes the factorial of an integer</td>
</tr>
<tr>
<td>FLOAT</td>
<td>LIBRARY</td>
<td></td>
</tr>
<tr>
<td>FOFR</td>
<td>AUTHOR</td>
<td>Evaluates (\psi - f_g(x)) for routine ITR2</td>
</tr>
<tr>
<td>FUNC</td>
<td>AUTHOR</td>
<td>Evaluates the integral in (f_g(x))</td>
</tr>
<tr>
<td>IFIX</td>
<td>LIBRARY</td>
<td></td>
</tr>
<tr>
<td>ITR2</td>
<td>LIBRARY</td>
<td></td>
</tr>
<tr>
<td>LEROY</td>
<td>CALCOMP</td>
<td></td>
</tr>
<tr>
<td>LINPLT</td>
<td>CALCOMP</td>
<td></td>
</tr>
<tr>
<td>MESAGE</td>
<td>CRT</td>
<td></td>
</tr>
<tr>
<td>MGAUSS</td>
<td>LIBRARY</td>
<td></td>
</tr>
<tr>
<td>NEXT</td>
<td>CRT</td>
<td></td>
</tr>
</tbody>
</table>


APPENDIX - Continued

<table>
<thead>
<tr>
<th>Subprogram</th>
<th>Source</th>
<th>Function</th>
</tr>
</thead>
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<td>NOTATE</td>
<td>CALCOMP</td>
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</tr>
<tr>
<td>PARAMS</td>
<td>CRT</td>
<td></td>
</tr>
<tr>
<td>PNTPLT</td>
<td>CALCOMP</td>
<td></td>
</tr>
<tr>
<td>REcin</td>
<td>LIBRARY</td>
<td></td>
</tr>
<tr>
<td>REcout</td>
<td>LIBRARY</td>
<td></td>
</tr>
<tr>
<td>RVALUE</td>
<td>AUTHOR</td>
<td>Computes $r$, velocities $u$ and $v$, and $G$ for $\psi$ at $x$</td>
</tr>
<tr>
<td>SCREEN</td>
<td>CRT</td>
<td></td>
</tr>
<tr>
<td>SIGN</td>
<td>LIBRARY</td>
<td></td>
</tr>
<tr>
<td>SQRT</td>
<td>LIBRARY</td>
<td></td>
</tr>
<tr>
<td>STREAM</td>
<td>AUTHOR</td>
<td>Computes $\psi$ at any point $x,r$</td>
</tr>
</tbody>
</table>

Program Input

The first two cards should contain the velocity distribution function (free field). It will be printed as a part of the header on the first page of program output.

The next input block should contain the velocity distribution function parameters and the parameters used in the iterative method to determine the radius of the duct. These variables should be input under the FORTRAN IV Namelist format. A description of these variables and the corresponding names used by the source program are as follows:

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$FPARAM</td>
<td></td>
<td>Name required by input routine</td>
</tr>
<tr>
<td>AG1</td>
<td></td>
<td>Lower bound on the neighborhood of $r$</td>
</tr>
<tr>
<td>AG2</td>
<td></td>
<td>Upper bound on the neighborhood of $r$</td>
</tr>
<tr>
<td>C2</td>
<td>$c^2$</td>
<td>Velocity distribution function parameter</td>
</tr>
</tbody>
</table>
APPENDIX – Continued

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
</table>
| DELR |        | Initial size of the scanning interval \( r_{i+1} = r_i + \text{DELR} \)  
If \( r_i < r < r_{i+1} \), \( \text{DELR} = \text{DELR}/2 \) |
| D1   | \( d_1 \) | Velocity distribution function parameter (see eq. (6)) |
| D2   | \( d_2 \) | Velocity distribution function parameter (see eq. (6)) |
| EPS1 | \( \Sigma_1 \) | Relative error criterion for determining convergence. If  
\[ |r_i| > \Sigma_1, \quad \left| \frac{r_i - r_{i-1}}{r_i} \right| \leq \Sigma_1 \]  
implies convergence |
| EPS2 | \( \Sigma_2 \) | Absolute error criterion for determining convergence. If  
\[ r_i \leq \Sigma_1, \quad \left| r_i - r_{i-1} \right| \leq \Sigma_2 \]  
implies convergence |
| MAXIT|        | Maximum number of iterations to be used |
| NACC | \( N \) | Number of derivative terms to be used |
| V1   | \( f_{g,i} \) | Desired initial velocity in the duct |
| V2   | \( f_{g,f} \) | Desired final velocity in the duct |

The next input section forms the basis for the design table. Each card should contain an axial coordinate (columns 11-20, F10.4) and a radial coordinate (columns 21-30, F10.4). These coordinates should be chosen such that the stream function is specified throughout the entire field of interest. The value of the stream function is computed at these points and stored in the design table ordered on decreasing values of \( \psi \).

The final input block is to be input at the CRT station. The variables in this block may be changed at any time during execution of the program affording interactive control over the program. By varying these parameters the user may take advantage of program options to (1) add and delete entries in the design table, (2) make limited changes to the velocity distribution function, and (3) vary the iteration scheme to achieve convergence.
<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG1</td>
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<td></td>
</tr>
<tr>
<td>AG2</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>A</td>
<td>Velocity distribution function parameter (see eq. (3))</td>
</tr>
<tr>
<td>A2</td>
<td>$2\sqrt{2}cB$</td>
<td>Velocity distribution function parameter</td>
</tr>
<tr>
<td>C2</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>DELR</td>
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</tr>
<tr>
<td>DPSI</td>
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<td>Increment from PSIMIN to PSIMAX</td>
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<tr>
<td>DX</td>
<td></td>
<td>Increment from XMIN to XMAX</td>
</tr>
<tr>
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</tr>
<tr>
<td>D2</td>
<td>*</td>
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<td>EPS1</td>
<td>*</td>
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<td>EPS2</td>
<td>*</td>
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</tr>
<tr>
<td>GDIST</td>
<td></td>
<td>Length of Y-axis for velocity plot (in.)</td>
</tr>
<tr>
<td>GDV</td>
<td></td>
<td>Y-axis scale for velocity plot (units/in.)</td>
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<tr>
<td>GMAX</td>
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<td>Maximum velocity computed</td>
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<tr>
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<td>Minimum velocity computed</td>
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<td>GOR</td>
<td></td>
<td>Y-axis origin for velocity plot</td>
</tr>
<tr>
<td>I</td>
<td></td>
<td>Row number in design table</td>
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<tr>
<td>Name</td>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
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<td>--------</td>
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</tr>
<tr>
<td>IP1</td>
<td></td>
<td>Printing control for part I of program</td>
</tr>
<tr>
<td>IP2</td>
<td></td>
<td>Printing control for part II of program</td>
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<tr>
<td>MAXIT</td>
<td></td>
<td>Maximum streamline to be computed</td>
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<tr>
<td>NACC</td>
<td></td>
<td>Minimum streamline to be computed</td>
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<tr>
<td>PSI</td>
<td>$\psi$</td>
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APPENDIX – Continued

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**NOTE:**

The starred (*) variables are defined previously in the appendix.

A sample input follows:

\[
F(X) = A1 + A2 * I(SQRT(2PI)*E**(-C**2 * X**2))DX + E** - (X**2)*(D1*H0 + D2*H1)
\]

\[
I = \text{INTEGRAL FROM 0 TO X}
\]

\[
$FPARAM AG1 = 0.0, AG2 = 1.0, C2 = 1.0, DELR = 0.1, D1 = 0.0, D2 = 0.1, EPS1 = 1.0E-6, EPS2 = 1.0E-6, MAXIT = 200, NACC = 10, V1 = 0.133, V2 = 1.0$
\]

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Program Output

- On the first page of printed output, the velocity distribution function, its parameters, and the design table are printed.
- On the following pages, the radial distribution is shown for \( \psi = \text{PSIMIN} \) to \( \psi = \text{PSIMAX} \) incremented by DPSI over an axial range of \( X = \text{XMIN} \) to \( X = \text{XMAX} \) incremented by DX. The resultant velocity \( G \) and its axial \( u \) and radial \( v \) components are also included.
- The plotted output included the radial distribution curves, the velocity distribution curves, and the centerline velocity curve. They are displayed on the CRT during program execution with the capability of saving them for post-processing on the Calcomp plotter. The plot format is similar to that of the figures shown in the main body of the paper.
- Following is the printed output which corresponds to the input previously presented. Streamlines are shown for \( \psi = 0.003, 0.006, 0.009, 0.012, \) and 0.013. The centerline
velocity distribution is shown at $\psi = 0.0$. The proposed wall contour is streamwise $\psi = 0.013$. Finally, the source program listing is presented.

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**VELOCITY DISTRIBUTION FUNCTION**

$$F(x) = A_1 + A_2 \frac{1}{\text{sqrt}(2\pi x)} e^{-\left(\frac{(x-2)^2}{2x}\right)}$$

$$I = \text{INTEGRAL FROM 0 TO X}$$

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DATE 0

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APPENDIX - Continued
APPENDIX - Continued

R AND G DISTRIBUTION FOR CURVE 1

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| D1= | 0.0000 | D2= | 1.0000 | PLOT NO. = | 1 |

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APPENDIX - Continued

PROGRAM CNCCON (INPUT=1001, OUTPUT=1001, TAPE5=INPUT, TAPE6=OUTPUT, TAP1E8)

C LOW SPEED DUCT DESIGN
C
DIMENSION PSI(100), A(100), RA(100), MESS(10), TONF(2), XPLT(500)
1, YPLT(500), NAC(100)
DIMENSION ORG(2), DV(2), DIST(2), JACO(2)
DIMENSION DAT(2), FCT(2,2)
EQUIVALENCE (PDR, ORG(1)), (GDR, ORG(2)), (HDF, DV(1)), (GDV, DV(2))
1(DIST, DIST(1)), (GDIST, DIST(2))
COMMON /YQ/ HFLR, EPS, EPS2, MAXIT
COMMON /YO?/ MACC, PST, X, R, U, V
COMMON /YD3/ A1, A2, C2, D1, D2
COMMON /YD4/ AG1, AG2
NAMELIST/FPARAM/ AG1, AG2, C2, DELP, D1, D2, EPS1, EPS2
1 MAXIT, NACC, V1, V2
C PROGRAM INITIALIZATION
C CALL CDC250
CALL LEROY
CALL SCFEN (1.0, 0.0, 0.0)
$2=SQRT(2.0)
MNA=100
MPT=500
IP1=IP2=0
JNK1=0, JNK2=-1
LPLT=0
CALL DAYTIM (DATE)
READ 110, FCT
110 FORMAT (8A10)
READ (S, FPARAM)
C CALL PARAMS
CALL PARAMS (YPS), (PSI)
CALL PARAMS (X, XI, LI, T1, T2)
CALL PARAMS (DEL, DEL, SL, MAXT, MAXT)
CALL PARAMS (EPS, EPS, EPS, EPS)
CALL PARAMS (PLA, A1, PLA, A2)
CALL PARAMS (NACC, NACC)
CALL PARAMS (LAG, AG1, LAG2, AG2)
CALL PARAMS (LPI, LIP, LII, LII)
CALL PARAMS (V1, V1, V2, V2, V2, V2)
CALL PARAMS (DI1, DI1, DI2, DI2)
CALL MESSAGE (1.36, INSERT INITIAL VALUES FOR PSI EDIT. 36)
CALL MESSAGE (1.25, ANY FN KEY WILL CONTINUE. 25)
CALL NEXT (KEY)
J3=1
C U TO 510
J2=1
C 120 CONTINUE
APPENDIX – Continued

PART I

GENERATE INITIAL PSI DISTRIBUTION TABLE

130 READ 140, X, R

140 FORMAT (10X, 2F10.4)

150 NA = NA + 1

160 IF (NA .LE. MNA) GO TO 170

170 CALL STREAM

180 IF (NA .GT. MNA) NA = MNA

J1 = 27

ENCODER (J1, 19, MESG, NA)

190 FORMAT (1X, I5, 25H INITIAL PSI COMPUTED)

CALL MESSAGE (1, MESG, 11)

ORDER INITIAL PSI TABLE (DESCENDING)

J3 = NA - 1

200 CONTINUE

210 J1 = J1 + 1

220 J2 = J2 + 1

230 J3 = J1 - 1

240 CONTINUE

DISPLAY INITIAL PSI TABLE

250 CALL MESSAGE (1, 33, ANY FN KEY WILL CONTINUE DISPLAY, 33)

CALL EXIT (KEY)

C
APPENDIX – Continued

C EDIT INITIAL PSI TABLE

C CALL MESEGE (1.25H END OF PSI RANGE DISPLAY, 25)  
GO TO (270, 620), JRT  

270 CALL MESEGE (1.24H BEGIN EDIT RANGE OF PSI, 24)  
CALL MESEGE (1.27H VARIABLES ARE X, R, 1.27)  

280 CALL MESEGE (1.27H FN KEY 1 WILL COMPUTE PSI AT X AND R, 37)  
CALL MESEGE (1.26H FN KEY 2 WILL INSERT PSI, X, AND R, 36)  
CALL MESEGE (1.23H FN KEY 6 WILL DELETE 1, 23)  
CALL MESEGE (1.39H FN KEY 4 WILL DISPLAY PSI, X, AND R AT 1, 39)  
CALL MESEGE (1.32H FN KEY 7 WILL DISPLAY PSI RANGE, 32)  
CALL MESEGE (1.36H FN KEY 8 WILL END EDIT AND CONTINUE, 36)  
CALL MESEGE (1.37H FN KEY 9 WILL DELETE ENTIRE TABLE, 38)  
CALL MESEGE (1.33H FN KEY 10 WILL COMPUTE AI, A2, 33)  
CALL MESEGE (1.38H ANY OTHER FN KEY WILL DISPLAY OPTIONS, 38)  

C CALL NEXT (KEY)  
IF (KEY, EQ, 1) GO TO 290  
IF (KEY, EQ, 2) GO TO 310  
IF (KEY, EQ, 3) GO TO 400  
IF (KEY, EQ, 4) GO TO 430  
IF (KEY, EQ, 5) GO TO 220  
IF (KEY, EQ, 6) GO TO 540  
IF (KEY, EQ, 7) GO TO 440  
IF (KEY, EQ, 8) GO TO 420  
IF (KEY, EQ, 9) GO TO 490  
IF (KEY, EQ, 10) GO TO 500  
GO TO 290  

C COMPUTE PSI  

290 CALL STREAM  
ENCOD (50, 30H, MESG) PSI, X, R, NACC  
300 FORMAT (5H PSI=Fi16, 4, 3H X=Fi8, 4, 3H R=Fi8, 4, 3H N=14)  
CALL MESEGE (1, MESG, 50)  
GO TO 290  

C INSERT PSI IN TABLE  

310 IF (NA, EQ, MNA) GO TO 390  
IF (PSI, LT, PSI (1)) GO TO 320  
J1=1  
GO TO 340  
320 U0 330 J1=2, NA  
IF ((PSI, GE, PSI (J1-1)) .AND. (PSI, GE, PSI (J1))) GO TO 340  
330 CONTINUE  
J1=NA+1  
GO TO 340  
340 U0 35H J2=J1+1 

26
APPENDIX – Continued

J3=NA-J2+1
PSIA(J3+1)=PSIA(J3)+A(J3)+RA(J3+1)=RA(J3)
NA(J3+1)=NA(J3)

350 CONTINUE
360 PSIA(J1)=PSIA(J1)=RA(J1)=N=NA
NA=NA+1

370 ENCODE(7A+3A+MESG) NA,N1,NA(J1)+PSIA(J1)+A(J1)+RA(J1)
380 FORMAT(9H TOTAL I=14+3H J=14+3H N=14+4H PSI=F16.6+4H X=F16.6)

CALL MESSAGE(1+MESG,30)
CALL MESSAGE(1+MESG,47)
GO TO 290
390 CALL MESSAGE(4+23H MAX I HAS BEEN REACHED+23)
GO TO 290

C
C
C
C

CALL DELETF (I in PSI TABLE)

DU 410 J2=1+NA
PSIA(J2)=PSIA(J2+1)
A(J2)=A(J2+1)
RA(J2)=RA(J2+1)
NA(J2)=NA(J2+1)

410 CONTINUE
NA=NA+1
ENCODE(39+42+MESG) NA,1

420 FORMAT(9H TOTAL I=15+18+HH DELETED)
CALL MESSAGE(1+MESG,30)
GO TO 290
C
430 J1=1
GO TO 370
C
C
C
C

CALL PVAVLUE (lCODE)
ENCODE(50+46+MESG) PSI*X

450 FORMAT(5H PSI=F16.8+SH X=F16.8)
CALL MESSAGE(1+MESG,42)
ENCODE(50+46+MESG) R+G

460 FORMAT(3H R=F16.8+SH G=F16.8)
CALL MESSAGE(1+MESG,40)
ENCODE(50+46+MESG) U+V

470 FORMAT(3H U=F16.8+SH V=F16.8)
CALL MESSAGE(1+MESG,41)
ENCODE(50+46+MESG) NACC+CODE

480 FORMAT(3H N=12+12H ERROR CODE=13)
CALL MESSAGE(1+MESG,20)
CALL MESSAGE(1+25H ANY FN KEY WILL CONTINUE+25)
CALL .EXIT (KEY)
GO TO 290

490 NA=0+PSIA(1)=PSIA(2)=9+E10
CALL MESSAGE(1+14H TABLE DELETED+14)
GO TO 290

C

500 J3=Z
GO TO 510
APPENDIX - Continued

C COMPUTE FUNCTION PARAMETERS A1 A2

C

510 C2=ARS(C2)
    A1=0.5*(V1+V2)
    A2=52*SORT(C2)*(V2-V1)
    ENCODE (100*5,4, MESSG) V1, V2, C2, A1, A2

520 FORMAT (12H INIT. VEL. = , FR. 4, 12H FINAL VEL. = , FR. 4, 4H C2 = , F10.6, 6X,
    14H A1 = , F16.8, 4H A2 = , F16.8)
    CALL MESSAGE (1, MESSG, 40)
    CALL MESSAGE (1, MESSG(5) + 20)
    CALL MESSAGE (1, MESSG(7) + 40)
    ENCODE (34, 53, MESSG) D1, D2

530 FORMAT (4H D1 = , F13.6, 4H D2 = , F13.6)
    CALL MESSAGE (1, MESSG, 34)
    GO TO (120, 280) J3

C

C

C END INITIAL PSI EDIT

540 CALL MESSAGE (3, 2RH REPEAT FN KEY 6 TO END EDIT, 28)
    CALL MESSAGE (1, 3RH ANY OTHER FN KEY WILL DISPLAY OPTIONS, 3H)
    CALL NEXT (KEY)
    IF (KEY .NE. 6) GO TO 80
    IF (IP1 .NE. 0) GO TO 610

C

C OUTPUT INITIAL PSI TABLE

DO 600 J1=1, N1
    IF (MOD(J1-1, 35) .NE. 0) GO TO 595
    PRINT 550, DATE(1)

550 FORMAT (1H \ 5X, *CONTRACTION CONE DESIGN TABLE*, 15X, *DATE*,
    1 5X, A10)
    PRINT 550, ECT

560 FORMAT (/10X, 70HV VELOCITY DISTRIBUTION FUNCTION, 5X, R1A10/45X, R1A10)
    PRINT 570, V1, V2, A1, A2, C2

570 FORMAT (/70X, 11H INIT. VEL. = , FR. 4, 5X, 11H FINAL VEL. = , FR. 4, 5X, 3H1 = , F9.4,
    19X, 5X, 3HA2 = , FR. 4, 5X, 5HC = , FS. 2)
    PRINT 571, D2

571 FORMAT (53X, *N1 = , FR. 4, * N2 = , FR. 4)
    PRINT 571

580 FORMAT (/72X, 1H1, 17X, 3HPSI, 19X, 1H1, 19X, 1HR, 5X, 1HN)
    CONTINUE
    PRINT 590, J1, PSI4(J1) + AA(J1) + RA(J1), NAC(J1)

590 FORMAT (2R X, 1K.3F20.5, 16)
    CONTINUE

600 CONTINUE

610 CONTINUE

C
APPENDIX – Continued

SET-UP

CALL PARAMS (4LXMIN,XMIN,2LDX,DX*4LXMAX,XMAX)
CALL PARAMS (4LPSIMIN,PSIMIN,4LDPsi,DPSI,6LPSIMAX,PSIMAX)
CALL PARAMS (1LROK,ROR,3LRDV,ROV,5LRODIST,RDIST)
CALL PARAMS (3LGOH,GOH,3LGOV,GOV,5LGDIST,GDIST)
CALL PARAMS (1LXM1N,XMIN,3LXDV,XDV,5LXDIST,XDIST)
CALL PARAMS (4LXMIN,XMIN,4LXM1N,XMIN)
CALL PARAMS (4LXMIN,XMIN,4LGMAX,GMAX)

PARAMETERS

XMIN=-4.040X=.44XMAX=4.0
PSIMIN=0.0PSIMAX=1.0PSIMAX=0.07
J8=8
JDATA=JPS=JGS=0
CALL CALPLT (0.0,0.0,-3)
TMN=1.007MH=0.1
JXCOE=14X8XHGT=4.0J/15.0JN=I
XDIST=10.0RDIST=10.0GDIST=10.0
JBCD(1)=1HSH=JGCD(2)=1HGS=JN=1
JSYM=0.0JSIZE=19PY=0.1
MCURVF=11

C

CALL MESSAGE (1.32H FN KEY 1 WILL DISPLAY PSI RANGE+32)
CALL MESSAGE (1.27H FN KEY 2 WILL COMPUTE DATA+27)
CALL MESSAGE (1.46H VARIABLES ARE XMIN,DX,XMAX,PSIMIN,DPsi,PSIMAX,4)

CALL MESSAGE (1.37H FN KEY 3 WILL SCALE PSI DISTRIBUTION+37)
CALL MESSAGE (1.42H VARIABLES ARE XOR,XDV,XDIST,XOR,ROV,RDIST+42)
CALL MESSAGE (1.37H FN KEY 4 WILL PLOT PSI DISTRIBUTION+37)
CALL MESSAGE (1.35H FN KEY 5 WILL SCALE G DISTRIBUTION+35)
CALL MESSAGE (1.31H VARIABLES ARE GOP,GOV,GOIST+31)
CALL MESSAGE (1.35H FN KEY 6 WILL PLOT G DISTRIBUTION+35)
CALL MESSAGE (1.44H FN KEY 7 WILL DISPLAY NON-MONOTONE VELOCITY+44)
CALL MESSAGE (1.26H FN KEY 8 WILL END PROGRAM+26)
CALL MESSAGE (1.39H FN KEY 9 WILL RETURN TO PSI RANGE EDIT+39)
CALL MESSAGE (1.25H FN KEY 10 WILL NORMALIZE+25)
CALL MESSAGE (1.38H ANY OTHER FN KEY WILL DISPLAY OPTIONS+38)
CALL NEXT (KEY)

IF (KEY,EO,1) GO TO 630
IF (KEY,EO,2) GO TO 640
IF (KEY,EO,3) GO TO 416
IF (KEY,EO,4) GO TO 636
IF (KEY,EO,5) GO TO 1090
IF (KEY,EO,6) GO TO 630
IF (KEY,EO,7) GO TO 1120
IF (KEY,EO,8) GO TO 1170
IF (KEY,EO,9) GO TO 870
IF (KEY,EO,10) GO TO 850
GO TO 620

29
APPENDIX – Continued

C
C DISPLAY INITIAL PSI TABLE
JRT=2
GO TO 230
C
C COMPUTE RADIAL DISTRIBUTION
RCURVE=(PSIMAX-PSIMIN)/DPSI
JNK1=JNK1+1
LPLT=LPLT+1
C CHECK FOR MAXIMUM NUMBER OF CURVES
IF (RCURVE.LE.FLOAT(MCURVE-1)) GO TO 660
ENCOD (37,65,‘MEG) RCURVE,MCURVE
650 FORMAT (2X,F12.5,‘MORE THAN *IS,7H CURVES)
CALL MESAGE (4,‘MSEG,37)
GO TO 620
660 KPT=(XMAX-XMIN)/DX
C CHECK FOR MAXIMUM NUMBER OF POINTS
IF (KPT.LE.FLOAT(MPT-1)) GO TO 680
ENCOD (37,67,‘MEG) KPT,MPF
670 FORMAT (2X,F12.5,‘MORE THAN *IS,7H POINTS)
CALL MESAGE (4,‘MSEG,37)
GO TO 620
680 I=IFX(RCURVE+1,5)
N=IFX(KPT+1,5)
REWIND IB $ JTONF=E
RMAX=0 MAX=-1.39
RMIN=0 MIN=1.39
PSI=PSIMIN
C
C DO J=1,ICURVE
GTONF=-1.9
I=0 $ J3=-1
X=XMIN
ICODE=1
C
C DO J=1,ICURVE
C COMPUTE RADIUS
CALL OVALUE (ICODE)
IF (ICODE.EQ.0) D=R
CALL REOOUT (1+1,1+1,F2,J1,PST,X,R,U,V,G)
C CHECK FOR NON-MONOTONE VELOCITY
IF (G.GT.GTONF) GO TO 690
TONF=(1)=J2+TONF (2)=J1+TONF (3)=PSI+TONF (4)=X
TONF (5)=R+TONF (6)=U+TONF (7)=V+TONF (8)=G
JTONF=1
GO TO 700
690 GTONF=G
700 CONTINUE
C CHECK FOR MINIMUM AND MAXIMUM YPLOT VALUES

30
APPENDIX - Continued

IF (IK.LT.PMIN) KMIN=P
IF (IK.GT.PMAX) KMAX=P
IF (G.LT.GMIN) GMIN=G
IF (G.GT.GMAX) GMAX=G
IF (IP2.NE.0) GO TO 770
J3=J3+1
C OUTPUT CURVE J2
IF (MOD(J3,15).EQ.0) GO TO 765
PRINT 710, J2, DATE(N), PMIN, PIMAX, XMIN, XMAX
710 FORMAT (1I1//'47X,34H AND G DISTRIBUTION FOR CURVE 13,20X,4HDA
1TE,5X,A10//20X,4HPSI = *F14.6,5X,2HT+F14.6,10X,3H= *F14.6,5X,2HT
20+F14.6)
PRINT 720, PSI
720 FORMAT (5HPSI=*F14.6)
PRINT 730, V1, V2, A1, A2, C2, NACC
730 FORMAT (5H,4X,1IH,3H,3HT,14X,4HFINAL VEL. = *F8.4,5X,3HT=A1=*,F8
1.4,5X,3HT=A2=*,F8.4,5X,3HT=C2=*,F8.4,5X,3HT=CHT=*,F8.4,5X,3HT=CN
PRINT 740, D1, D2, PLT
740 FORMAT (5H,4X,1H,3H,3HT=*,F8.4,5X,3HT=*,F8.4,5X,3HT=*,F8.4,5X,3HT=*
750 FORMAT (5H,4X,1H,3H,3HT=*,F8.4,5X,3HT=*,F8.4,5X,3HT=*,F8.4,5X,3HT=
765 CONTINUE
PRINT 760, J1, J2, DATE(N), PSIMIN, PSIMAX, XMIN, XMAX
760 FORMAT (6H RMIN=,F14.6,RMAX=,F14.6,CIMIN=,F14.6,GMAX=,F14.16)
CALL MESSGE (I,16H DATA COMPUTED,16)
CALL MESSGE (I,MESG(41)
CALL MESSGE (I,MESG(42)
JOATA=1
GO TO 670
C
C IF (JOATA.NE.0) GO TO 620
CALL MESSGE (I,29HCANNOT SCALE NO DATA COMPUTED,29)
GO TO 620
C
C COMPUTE X AND R SCALES
APPENDIX — Continued

820      AOR=XMIN
GOOD=XMAX-XMIN)/XDIST
RHMIN
RDV=(XMAX-RMIN)/RDIST
ENCODE (3x+3x, MENG) XOR+IDV
830      FORMAT (5H XOO=+F12.5,7H XDV=+F12.5)
ENCODE (3x+3x, MENG(4)) ROR, RDV
840      FORMAT (5H ROO=+F12.5,7H RDV=+F12.5)
CALL MESSAGE (1, MENG(4)+36)
JRS=1
GO TO 620
850      JPLT=1
IF (JNK1.NE.JNK2) GO TO 920
DO 900 J1=1,NPT
XPLOT(J1)=XPLOT(J1)/YPLOT(NPT)
YPLOT(J1)=YPLOT(J1)/YPLOT(NPT)
IF (MOD(J1-1,75).NE.0) GO TO 900
PRINT 660, DATF(1)
PRINT 870
FORMAT (1H1//7X,46M(NORMALIZED) CURVE FOR LAST MONOTONE STREAM LINE 1+10X*4945.5X*AT10)
PRINT 720, PSI
PRINT 870
FORMAT (1H1//33X,2HP1+19X+1HX*19X,1HV)
PRINT 890, J1, XPLOT(1), YPLOT(J1)
890      FORMAT (25x#110+2F20.5)
900      CONTINUE
C
ENCODE (R0+91x,user)+XPLOT(1)+XPLOT(NPT)+YPLOT(NPT)+YPLOT(1)
910      FORMAT (4H, X1=+F13.6+4H, X2=+F13.6+4H, X3=+F13.6+4H, X4=+F13.6)
CALL MESSAGE (1, MENG(40))
CALL MESSAGE (1, MENG(5)+34)
CALL MESSAGE (1, 36H INPUT SCALE FACTORS PRESS ANY KEY, 36)
CALL NEXT (KEY1)
JNK2= JNK1
920      CONTINUE
GO TO 950
C
READ PLOT DATA JPLT=1, XPLT=2, GPLT
C
930      JPLT=KEY/5+1
IF ((JPLT.EQ.0).AND.((JRS.EQ.0))) GO TO 940
IF ((JPLT.EQ.2).AND.((JRS.EQ.0))) GO TO 940
GO TO 950
940      CALL MESSAGE (1, 36H CANNOT PLOT. DATA HAS NOT BEEN SCALING, 39)
GO TO 620
C
950      CALL AXES (0,0,0,0,0,0,XHGT*JNX)
CALL AXES (0,0,0,0,0,0,110, JPLT), ORG(JPLT), DV(JPLT), TMAJ, TMIN, JR
1CU(JPLT), XHGT, JNX)
APPENDIX – Continued

REWIND IH
UU 990 J2=1
IF ( KEY , EU , 10 ) GO TO 970
UU 990 J1=1
CALL PECIN (1D1,1C1,JC1,JPT,PST*X+R*U+V+G)
APLOT (J1)=X
YPLOT (J1)=Y
IF ( JPLT . F0 . 2 ) YPLOT (J1) = C

CONTINUE

C

APLOT (NPT+1)=X
YPLOT (NPT+1)=Y
CALL PECIN (1D1,1C1,JC1,JPT,PST*X+R*U+V+G)

CONTINUE

C

PLT
J3=17
ENCOD (J3,98V,MEG) PSI

FURTHER (4+PS1,+F13.6)
PHT=0.1
PY=FLAT (J2-1)*(PHT+1,2)
PX=PY=0.5
CALL NOTATE (-PX1,Py1,PHT,MEG+0,0,J3)
PX=(6.0/7.0)*FLAT (J3)*PHT+0.14-PX1
PY=PY+0.04
CALL PNTPLT (PX, Py, J3-1)
IF ( KEY , EU , 10 ) GO TO 991

CONTINUE

C

NOTATE PLT

ENCOD (14*10=0*MEG) V1

FURTHER (3V1,+F13.6)
PY=DIST (JPLT)-PHT
CALL NOTATE (-PX1,Py1,PHT,MEG+0,0,16)
ENCOD (14*10+0*MEG) V2

FURTHER (3V2,+F13.6)
PY=PY-2.0*PHT
CALL NOTATE (-PX1,Py1,PHT,MEG+0,0,16)
ENCOD (14*10+0*MEG) C2

FURTHER (5HS+2,+F13,6)
PY=PY-2.0*PHT
CALL NOTATE (-PX1,Py1,PHT,MEG+0,0,18)
ENCOD (14*10+0*MEG) D1

FURTHER (3H1,+F13.6)
PY=PY-2.0*PHT
CALL NOTATE (-PX1,Py1,PHT,MEG+0,0,16)
ENCOD (14*10+0*MEG) U2

FURTHER (3H2,+F13.6)
PY=PY-2.0*PHT
CALL NOTATE (-PX1,Py1,PHT,MEG+0,0,16)
ENCOD (14*10+0*MEG) A1

FURTHER (3H3,+F13.6)

33
APPENDIX - Continued

PY=PY-2.0*PHT
CALL NOTATE (-PX1*PY,PHT,MESG,0.0,16)
1060 FORMAT (3H4A?,=,F13.6)
PY=PY-2.0*PHT
CALL NOTATE (-PX1*PY,PHT,MESG,0.0,16)
ENCODE (14,1070,MESG,LPLT)
1070 FORMAT (9HPLT NO. ,15)
PY=PY-2.0*PHT
CALL NOTATE (-PX1*PY,PHT,MESG,0.0,14)
C
IF (J TONE.EQ.3) GO TO 1080
IF (KEY.EQ.10) GO TO 1080
C FLAG NON-MONOTONE VELOCITY ON PLOT
PX= (TONE(4)-XDR)/XDV
PY= (TONE(3)JP1 T+2) - PRT(JPLT1)/AV(JPLT)
CALL PNTPLT (PX,PY,11,3)
1080 CALL CALPLT (14,0,0,-3)
GO TO 620
1090 IF (JDATA.NE.0) GO TO 1100
CALL MESSAGE (?29HCANNOT SCALE. NO DATA COMPUTED.24)
GO TO 620
C COMPUTE G SCALES
1100 GOR=GMIN
GDV=(GMAX-GMIN)/GIST
ENCODE (3A,1110,MESG) GOR, GDV
1110 FORMAT (5H GOP=,F12.5,5H GDV=,F12.5)
CALL MESSAGE (1,MESG,34)
JGS=1
GO TO 620
1120 IF (J TONE.NE.1.) GO TO 1130
CALL MESSAGE (1,23H VELOCITY IS MONOTONE.23)
GO TO 620
C DISPLAY NON-MONOTONE VELOCITY
1130 ENCODE (4A,1140,MESG) TONE(1), TONF(2)
1140 FORMAT (7H CURVE =F3.0,5H PT=F4.0,22H NON-MONOTONE VELOCITY)
CALL MESSAGE (1,MESG,41)
ENCODE (5A,1150,MESG) TONE(3), TONF(4), TONE(5)
1150 FORMAT (5H PST=F12.5,5H X=F12.5,4H K=F12.5)
CALL MESSAGE (1,MESG,50)
ENCODE (5A,1160,MESG) TONE(6), TONF(7), TONE(8)
1160 FORMAT (3H U=F12.5,5H V=F12.5,6H 6=F12.5)
CALL MESSAGE (1,MESG,60)
GO TO 620
C
C NORMAL PROGRAM STOP
1170 CALL MESSAGE (4A,31H REPEAT FN KEY A TO END PROGRAM.31)
CALL MESSAGE (4A,43H ANY OTHER FN KEY WILL DISPLAY OPTIONS.38)
CALL NEXT (KEY)
IF (KEY.NE.8) GO TO 620
PRINT 1180
APPENDIX – Continued

1180 FORMAT (ZSH1 NORMAL END OF JOB)
STOP
END

SUBROUTINE STREAM

C
C COMPUTE VALUE OF THE STREAM FUNCTION PSI AT X AND R
C
C X = AXIAL COORDINATE
C R = RADIAL COORDINATE
C
COMMON /YD1/ NACC, PSI, X, R
C
COF(J) = (-1.0) ** (J-1) * R ** (2*J) / (2.0 ** J2 * FLOAT(J) * FACT(J-1) ** 2)
C
PSI = 0.0
DO 10 J1 = 1, NACC
J2 = 2 * J1 - 2
PSI = PSI + COF(J1) * NDERIV(J2)
CONTINUE
PSI = 0.5 * PSI
C
RETURN
END

SUBROUTINE RVVALUE (ICODE)

C
C COMPUTE U, V AND G FOR PSI AT X
C
G IS THE RESULTANT VELOCITY
C U IS THE AXIAL COMPONENT
C V IS THE RADIAL COMPONENT
C USE INTERVAL-HALVING METHOD
C
COMMON /YD1/ NACC, EPS1, EPS2, MAXIT
COMMON /YD2/ NACC, PSI, X, R, U, V, G
COMMON /YD4/ AG1, AG2
EXTERNAL F0FR
COF(J) = (-1.0) ** (J-1) * R ** J2 / (2.0 ** (2 * J - 3) * FACT(J-1) ** 2)
COFF(J) = (-1.0) ** (J-1) ** 3 / (2.0 ** (2 * J - 2) * FLOAT(J) * FACT(J-1) ** 2)
C
CALL ITR2 (R, AG1, AG2, DELR, F0FR, EPS1, EPS2, MAXIT, ICODE)
IF (ICODE .EQ. 0) GO TO 10
R = U = V = G = -0.99 * G
RETURN
C
10 U = V = 0.0
DO 40 J1 = 1, NACC
J2 = 2 * J1 - 2
J3 = 2 * J1 - 1
C
IF (((J2, NF, 0), (AR(S(R), G1, 1, 1, -1))) GO TO 20
U = 2.0 * NDERIV(J2)
G0 TO 30

35
APPENDIX - Continued

```
20  CONTINUE
   U=U+COF(J1)*DFRIV(J1)
30  CONTINUE
   V=V+COF(J1)*DFRIV(J1)
40  CONTINUE
   U=0.5*U
   V=0.5*V
   C
   G=SQRT(U**2+V**2)
   RETURN
   END

FUNCTION FACT(J)
C
   FACTORIAL FUNCTION
   FACT=1.0
   IF (J.EQ.0) RETURN
   IF (J.EQ.1) RETURN
   DO 10 J1=2,J
       FACT=FACT*FLOAT(J1)
   10  CONTINUE
   RETURN
   END

FUNCTION FOFR(R)
C
   EVALUATE FUNCTION FOR IT=2
   COMMON /YN2/ MACC_PST,X,R
   SAV1=PSI
   KR=R
   CALL STREAM
   FOFR=PSI
   PSI=SAV1
   FOFR=PSI-FOFR
   RETURN
   END

FUNCTION HEPI(J)
C
   COMMON /YN3/ MACC_PST,X
   COMMON /YN3/ MACC_PST,X
   DIMENSION HER(50),HERM(50),F0FX(1),ANS(1)
   EXTERNAL FUNC
   C
   COMPUTE JTH DERIVATIVE OF VELOCITY FUNCTION
   SHR=SORT(2.0*3.14159265)
   EX=EXP(-C2*X**2)/SHR
   EX1=EXP(-X**2)
   HERM(1)=EX
   HERM(2)=-2.0*C2*X*HERM(1)
   HERM(1)=1.0
   HERM(2)=2.0*X
   HERM(3)=4.0*X**2-2.0
```
APPENDIX – Concluded

HER(4)=8.0*HER(3)-12.0*HER(2)
C
C
IF (J, NE, 0) Go To 20
ML1=0.0$4X=L
IF (X$4L1, 10, 6) Go To 10
ML1=X$4L2=0.0
10 CONTINUE
CALL MGGAUS (JL1, ML2, 10, ANS, Func, F0FX, 1)
DERIV=A1*SIGN(1.0, X)*A2*ANS+EX18*(A1*HER(1)+A2*HER(2))
RETURN
C
20 IF (J, NE, 1) Go To 30
DERIV=A2*FX-EX18*(A1*HER(2)+A2*HER(3))
RETURN
C
30 IF (J, NE, 2) Go To 40
DERIV=-2.0*A2*C2*X*EX18*(A1*HER(3)+A2*HER(4))
RETURN
C
40 HER(J+1)=2.0*HER(J)-2.0*FLOAT(J)+HER(J-1)
HER(J+2)=2.0*HER(J)-2.0*FLOAT(J)+HER(J)
C
IF (J, EQ, 3) Go To 50
HERM(J+1)=-2.0*C2*X*HERM(J+2)+FLOAT(J)+HERM(J-3)
50 HERM(J)=-2.0*C2*X*HERM(J-1)+FLOAT(J)+HERM(J-2)
SI=1.0
IF (MOL(J, 2, NE, 0)) SI=-1.0
DERIV=A2*HERM(J)+SI*FX18*(A1*HER(J+1)+A2*HER(J+2))
RETURN
END
SUBROUTINE Func (X, F0FX)
DIMENSION F0FX(1)
COMMON /Yn/v al.A<?.C?
EVALUATE VELOCITY FUNCTION FOR MGGAUS
FX=SORT(2.0*3, 14159265)
F0FX=EXP(-C2*X**2)/50
RETURN
END
REFERENCES


Figure 1. Axial velocity used for contraction-cone design ($d_1 = 0.1$) compared with that obtained with $d_1 = 0$. Nonzero parameters: $A = 0.5665$; $B = 0.4335$; $c = 1$. 
Figure 2.- Coordinates of wall contour and some streamlines for design velocity of figure 1.
Figure 3.- Velocity distributions along centerline, wall, and streamlines of figure 2.
Figure 4.- Design (centerline) and wall velocity distribution for duct with an area minimum. Nonzero parameters: $A = 0.75; \quad B = 0.25; \quad d_0 = 0.6; \quad c^2 = 0.5$. 
Figure 5.- Wall contour and some streamlines for the design velocity of figure 4.
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