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P. J. Singh

A. D. Onuschak

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A COMPREHENSIVE, COMPUTERIZED METHOD FOR TWIN-SCREW ROTOR
PROFILE GENERATION AND ANALYSIS

Pawan J. Singh and Anthony D. Onuschak
Ingersoll-Rand Research, Inc.
Princeton, NJ

ABSTRACT

The end profile shapes of a twin-screw compressor's rotors have a great effect on the compressor's performance and reliability. Only a very limited number of profiles are currently in use in the industry. The process of new profile generation and determination of its effect on the machine's geometry and performance is an arduous and time-consuming task. This paper presents a new, comprehensive, and computerized approach to twin-screw rotor profile generation and analysis. Using this method, a user, starting with a rough sketch, can generate a profile, determine all important geometrical parameters such as leakage lengths, blow-hole area and discharge-port area, and analyze a machine's performance using this profile in a matter of one day rather than a month or so. The method can be used for new profile generation, adjustment of existing profiles, parametric studies and profile optimization. The paper follows the example of one profile and takes the reader through all the steps required for complete analysis.

INTRODUCTION

Rotary twin-screw compressors are widely used in the industry. The compressor's helical rotors, generally called male (driver) and female (driven) rotors, have specific end profile shapes. The profile shapes, hereafter called profiles, govern to a great extent for given tolerances the machine's geometrical and performance characteristics. While several profile patents exist, the industry generally uses SRM (Svenska Rotor Maskiner) profiles popularly known as SRM A and SRM C profiles. However, several new profiles have appeared on the scene and even SRM has come out with a new profile called SRM D.

The importance of profile shape was clearly demonstrated when the industry

switched from symmetric profiles to the current asymmetric profiles about fifteen years ago. The asymmetric profile greatly reduced one primary source of leakage, the blow-hole area, resulting in a 5 to 10 percent gain in adiabatic efficiency. Although such large gains in performance with further profile modifications may not be likely, many new profiles claim better performance through shorter rotor-to-rotor seal line, near-zero or zero blow-hole area, larger discharge port area, etc. Profiles also govern the magnitude and time variation of rotor torque and bearing loads, machine capacity, inlet and discharge port shapes and sizes, and male to female driving characteristics.

Profile generation and analysis in the past has been a laborious task. While profiles have been generated with dedicated computer programs, profile analysis such as determination of filling curves, discharge and inlet port areas, etc., has mostly been performed graphically. This limits the number of profiles that can be practically evaluated.

Adding to the complexity, and perhaps excitement, to the process of profile determination is that a very large number of profiles are likely candidates for a certain application. The selection of an optimum or near-optimum profile out of these requires that considerable information about each profile be available. With current high energy prices, even gains in performance of 1 to 2 percent can be very attractive, particularly for larger stationary machines. It is likely that in the future the industry will use different profiles for different applications or use a 'flexible' profile in which small changes in a basic profile are made according to the use.

This paper presents a comprehensive, interactive, computer-assisted approach where both male and female rotor profiles can be rapidly generated and analyzed on

a computer. This method provides a new and powerful capability of profile selection and evaluation before testing and a flexibility to tailor the profile according to the application. In addition, for a given profile, the method can be used to determine the best combination of the machine's geometrical parameters such as wrap angle, L/D ratio and built-in pressure ratio for an optimal performance. The method can also be used to generate input data for a machine performance computer program, like the one presented in Reference 1.

METHOD OVERVIEW

The user starts with a rough, hand-drawn sketch of the profile and follows a series of interactive steps on the computer terminal to finally arrive at the predicted performance of a machine using that profile. The computer program is written in BASIC language and is divided into a series of subprograms in order to fit them in the 64K memory of the Tektronix 4054 computer used. This computer was particularly selected for this purpose because of its large 19 inch high resolution (13 million addressable points), vector-graphic storage screen. The plots on the screen appear smooth even with a limited number of profile points, and very small discrepancies in the profile such as a mismatch of points can be easily noticed. In addition, the section of profile plots can be windowed or expanded to any magnification in order to examine the critical sections of the profile in great detail. The computer is also connected to a hard copy and high resolution (.001 inch) Tektronix 4663 plotter to give multicolored plots of any size up to C size (17 inch by 22 inch). Figure 1 shows the computer and plotter. Almost all the plot figures in this paper have come directly from the computer program.

The initial profile sketch gives the user a baseline profile to start from and encompasses his past experience and new ideas in order to narrow the vast selection available to him. The user then uses the program to calculate precise coordinates of intersection of various segments, generate and plot the complete profiles, calculate blow-hole area, calculate and plot filling and discharge curves, rotor-to-rotor and rotor tip-to-housing contact line lengths and discharge port shape and area and its variation with rotor angle. This information is then fed into the performance program described in Reference 1. The flow-chart shown in Figure 2 outlines the sequence in which various programs are used.

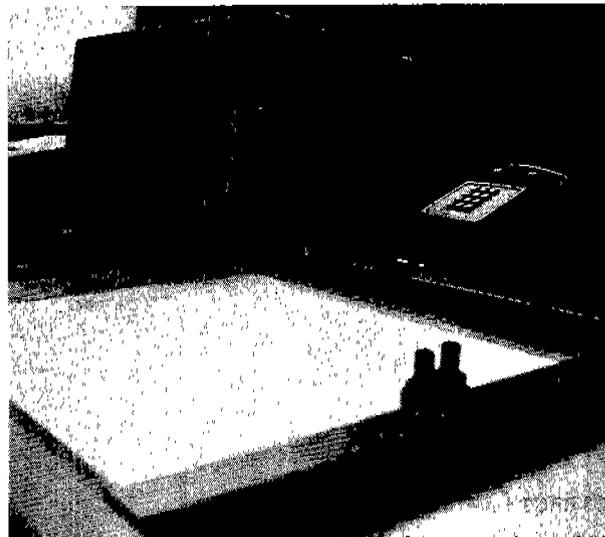


Figure 1: Tektronix Computer and Plotter

The program capabilities can best be illustrated by following an example through various steps. For that purpose, an unequal bore profile with four male lobes and six female lobes has been selected. This profile is just for illustration purposes and is not a profile that has been used in any machine. It should be obvious that this work is based on complex mathematics and innovative programming. However, space limitations do not allow details of the underlying theory to be presented. That may be published separately at a later date.

PROGRAM DETAILS

This section describes all the subprograms (hereafter called programs for easier reading) and their purpose. The user divides his profile sketch into segments and marks the segment type such as circular arc or straight line. The user also selects which profile segment on one rotor generates the corresponding segment on the other. Since the profiles must mesh smoothly, or in mathematical terms, be conjugate, the profile of one rotor is generated by the other and vice-versa.

Pre-Generation Programs

A typical profile is made up of many segments, mostly straight lines and circular arcs. Before the profile generation can begin, these segments need to be defined adequately. For a circular arc, e.g., center point coordinates, radius and the beginning and end angles

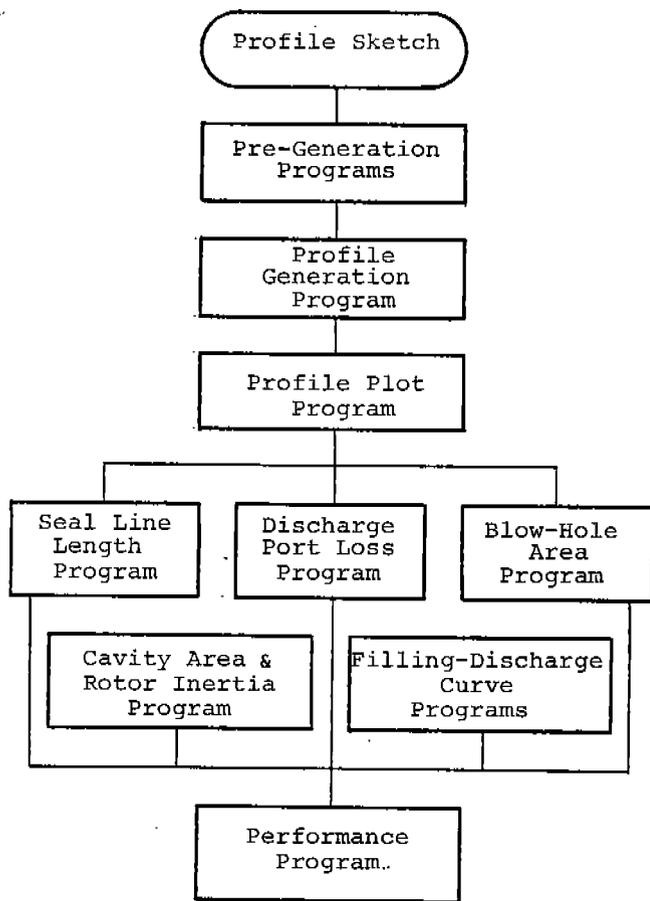


Figure 2: Flow Chart For Program Sequence

with respect to a given coordinate system need to be known. This program calculates all this necessary information for straight line and circular arc segments. It is a very versatile program and follows the same procedure as a draftsman will use to draw a profile. In short, if a draftsman can draw a segment, the program can supply all the information the user may need about that segment including intersection points with other segments. It can also compute an intersection point or a tangent point of an epitrochoid (point-generated curve) or a circular arc. If the profile has segments other than circular arc, straight line, or point or arc-generated curves such as elliptical arc, additional work outside these programs may be necessary before profile generation can begin. However, any type of segment can be used in the profile generation programs through the data-fit curve option as explained in the next section.

Profile-Generation Program

This program can virtually generate any profile made up of known type of profile segments. The segments on any one of the rotors could be of the following type:

- o Straight line
- o Circular arc
- o Polynominal-fit curve
- o Point
- o Data-fit curve

The program then generates the corresponding segments on the other rotor.

The data-fit curve could be any arbitrary curve in the form of discrete digitized points along the curve which are fit with a spline curve. The spline-fit coefficients are then used by this program to obtain a generated curve. In one test case, elliptical and involute segments of one profile were generated in this manner and yielded an accuracy of fourth decimal point in profile coordinates with an input of 30 points for spline fit. In addition, segments can be digitized from the plotter or the screen and data fed right into the computer. For instance, one could take a profile sketch and digitize points along the profile without knowing the actual nature of segments. The program can then be used to generate the conjugate profile.

The program also plots both the generating and the generated segments as they are created for verification. Following completion, the profile points are stored on a tape and then used by various other programs. This program also offers an option to modify one or more segments of an existing profile or add new segments without creating the whole profile again. The program can then plot one or more segments of each profile or the complete lobes in meshed position.

We will follow by way of an example the generation and analysis of a profile combination with the following characteristics:

Male Rotor Diameter	= 266 mm
Female Rotor Diameter	= 222 mm
No. of male/female lobes	= 4/6
Wrap Angle (degrees)	= 300
Length (L/D = 1.65)	= 439 mm

Figure 3 shows one lobe each of both rotors with segments marked and numbered. Segments numbered 1, 2, 4 and 5 on the female rotor are circular arcs and they generate segments numbered 1, 2, 3 and 4 respectively on the male rotor. Segment number 3 on the female rotor is generated by a point on the male rotor.

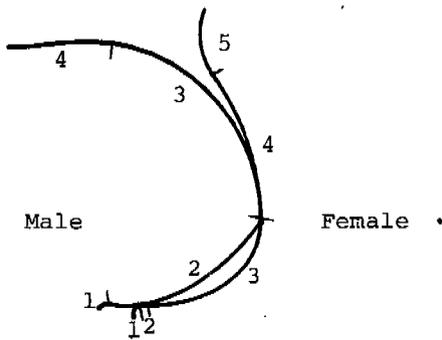


Figure 3: Profile Segments

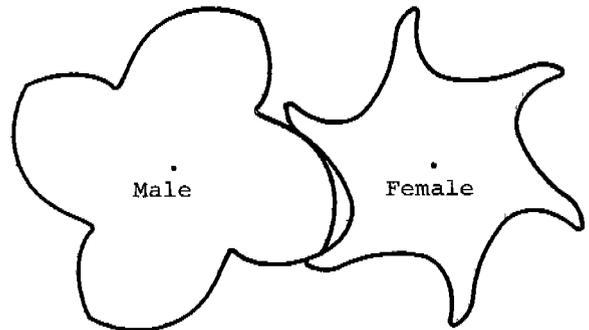


Figure 4: Meshed Rotors

Profile Plot Program

This versatile program reads the profile points from tape and can make the following plots on the screen or on the plotter:

- o Individual rotors
- o Meshed rotors - any rotated position
- o Housing bores and pitch diameters
- o Window (blow-up) any small section of the above to any defined size

This program is of great help in examining special features of a given profile as well as in judging the accuracy of generated profiles. The window feature is easy to use and can be used to examine the minutest details, particularly the areas near the contact points. To use it, the user defines two points across the area of interest with the screen cursor and the program then blows up a rectangular area with diagonal vertices at the cursor-defined points to the whole screen size. The user can define several such areas from the rotor plot at one time and then expand and examine them one by one. The program also offers flexibility to plot only half of the male and female rotors in order to save plotting time. Figure 4 shows a computer plot of the meshed rotors.

Cavity Area Inertia Program

This program reads the profile data from tape and then calculates the male and female lobe areas and theoretical displacement (assuming given overlap constant or 1 if not given) at a specified male rotor tip speed or male rpm. The program also calculates male and female rotor profile inertias as well as the root diameters inertias to evaluate relative rotor stiffness. For our

example, the following values were calculated:

- o Male lobe area = 7802.7 sq. mm
- o Female lobe area = 3049.2 sq. mm
- o Male displacement/RPM = 12532.7 cu. mm
- o Female displacement/RPM = 20412.4 cu. mm
- o Male rotor I_z = 1.70×10^8 mm⁴
- o Female rotor I_z = 6.34×10^7 mm⁴
- o Male rotor I_x or I_y = 8.49×10^7 mm⁴
- o Female rotor I_x or I_y = 3.17×10^7 mm⁴

Filling-Discharge Curve Programs

Two programs under this category determine the cavity volume versus male rotor rotation angle relationship over the whole filling and discharge cycle. The first program plots the housing bores and the two rotor profiles at different relative angular positions. At each such position, the user identifies the cavity areas of interest by pointing a built-in screen cursor at significant points along the boundary. For example, a typical area may be bounded by parts of the male and female profiles and parts of the housing bores. The user will input three points: male-female contact point, male rotor-housing point and female rotor-housing point. The computer then automatically determines the points around that area boundary, prints out the marked points and intermediate points, and calculates and prints the area and assigns it to the proper rotation angle.

At each rotor position, several areas of interest are simultaneously determined.

This procedure is repeated for various rotor positions until the cavity areas over the whole θ range ($\theta=0$ to $\theta=360(1+1/N_m)+\text{Wrap Angle}$) are calculated. These areas are then integrated to produce a volume - θ plot and to calculate overlap constant, inlet port closing angle and discharge port opening angle. Figure 5 and 6 show the cavity area versus θ and cavity volume versus θ for our example case. Four such cavities get filled and discharged during every male rotor revolution.

Blow-Hole Area Program

The blow-hole is a small triangular-shaped area formed by the housing cusp and male and female rotor tips. The area is geometrically quite complex and is generally estimated approximately. A special exact screw compressor geometry theory was developed which defines the complete helical rotor surfaces. This theory can be used to calculate volume- θ relationship described in the last section directly without screen interface, time-varying bearing loads, and blow-hole area. This theory will be published later in a separate paper elsewhere.

The blow-hole area is computed by locating two points where the male and female rotors intersect the housing cusp. The third point is the nearby male-female contact point. These three points form a curvilinear triangle in space whose area is calculated and printed. A numerical scheme automatically scans all the contact points in the cusp's vicinity, calculates areas, and then identifies the minimum area. This area is then projected in a direction normal to the female rotor tip helix to yield the final blow-hole area. The blow-hole area for our example according to this theory is equal to 3.165 sq. mm.

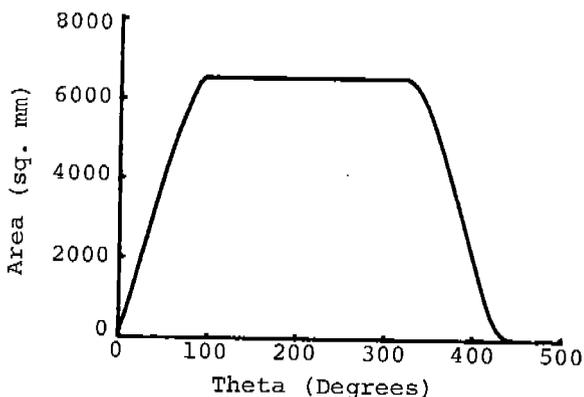


Figure 5: Cavity Area versus θ

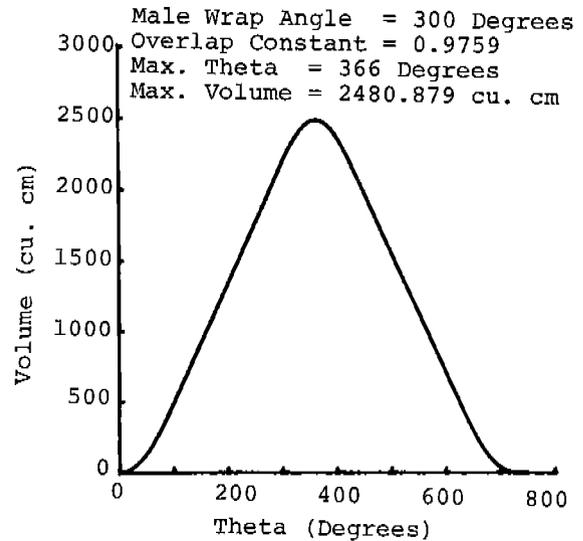


Figure 6: Cavity Volume versus θ

Seal-Line Length Program

This program calculates male-female rotors contact line length and rotor tip-housing seal line lengths as a function of θ . This data is printed in a tabular form and it can be plotted on the screen or on the plotter. This data along with the blow-hole area is essential in determining the leakage from one cavity to the neighboring cavities. The program also plots contact line in X-Y, X-Z and Y-Z planes where the Z coordinate runs along the rotor length and the X-Y plane contains the end profile shape.

Figure 7 and 8 show the X-Y and Y-Z planar projections of the contact line of our example case. Figure 9 shows the plot of contact line, and male and female rotor seal line length distribution with θ .

Discharge Port Area Program

The discharge port generally consists of two parts: axial and radial. The axial port is formed by parts of the rotor profile, housing, and the contact line. This program, depending on the discharge port opening angle calculated earlier, defines and plots the axial port. The radial port follows the male and female rotor tips at the opening angle. The program calculates both the axial port and radial port areas.

However, the available discharge port area for a particular cavity depends on the cavity position or angle θ . The area open to the cavity at a particular angle is calculated by superimposing the plot of meshed rotors at the correct angle θ on the discharge port plot. This is done by

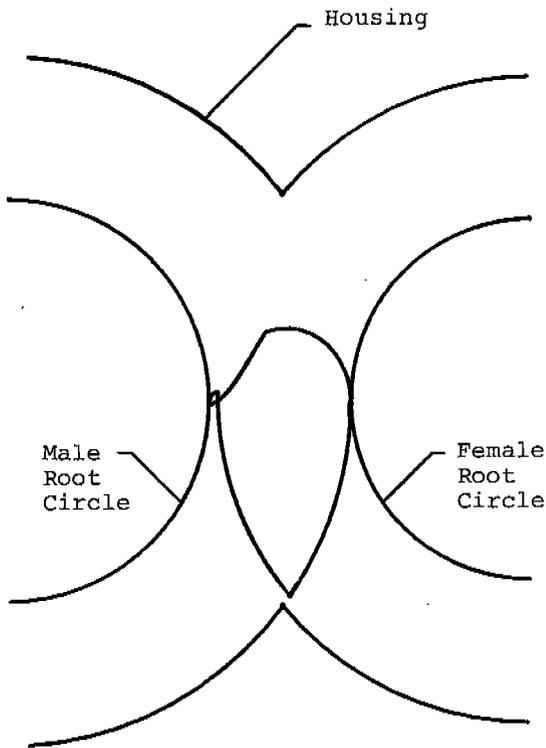


Figure 7: Contact Line Per Lobe In X-Y Plane

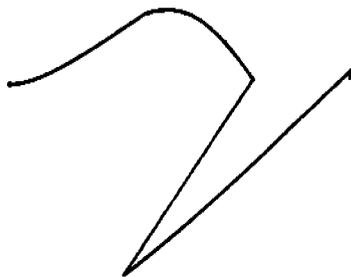


Figure 8: Contact Line Per Lobe In Y-Z Plane

the program itself. The user marks two or three points on each area open to the discharge port with the help of the screen cursor. The program then calculates both the axial port as well as radial port area. At certain θ angles, more than one cavity can be open to the discharge port. All such areas can be identified in one plot and the program automatically assigns the correct angle for each area. If the above scheme fails for a certain angle for a very complicated port shape, there is even a back-up scheme in which the user can identify many points along the area's boundary, and the program, working like a planimeter, calculates the area. However, the main scheme has always worked for all test cases.

Figure 10 shows a plot of the axial discharge port for the example case and Figure 11 shows the plot of meshed rotors superimposed on the discharge port. The cross-hatched regions in Figure 11 are the axial areas available for fluid discharge and computed by the program. Figure 12 shows a plot of the discharge port area variation with angle.

Discharge Port Loss Program

At high tip speeds, discharge port losses form a significant part of the overall horsepower losses in the machine. Although these losses are included in the performance program to be explained next, a separate program was written to provide a quick measure of port losses and to identify pressure oscillations during the discharge process. It was also necessary to separate it from the main program because of memory limitations. The computation starts at the port opening angle where the cavity pressure is assumed to be the same as the discharge pressure. From there on, the port pressure is calculated at small time increments and the model takes account of fluid inertia and capacitance, orifice pressure loss at the discharge port and assumes a non-reflective wave in the discharge pipe. The fluid can be assumed as gas or a uniform mixture of oil and gas for wet compressors. The pressure-time history is plotted and an average power loss calculated. Figure 13 shows a typical plot of the discharge port pressure variation.

Performance Program

All the information compiled up to this point can be used to compare relative merits of different profiles, but one of the best measures for evaluating a profile is the machine's performance in which it is used. The details of a performance program used for such an analysis are

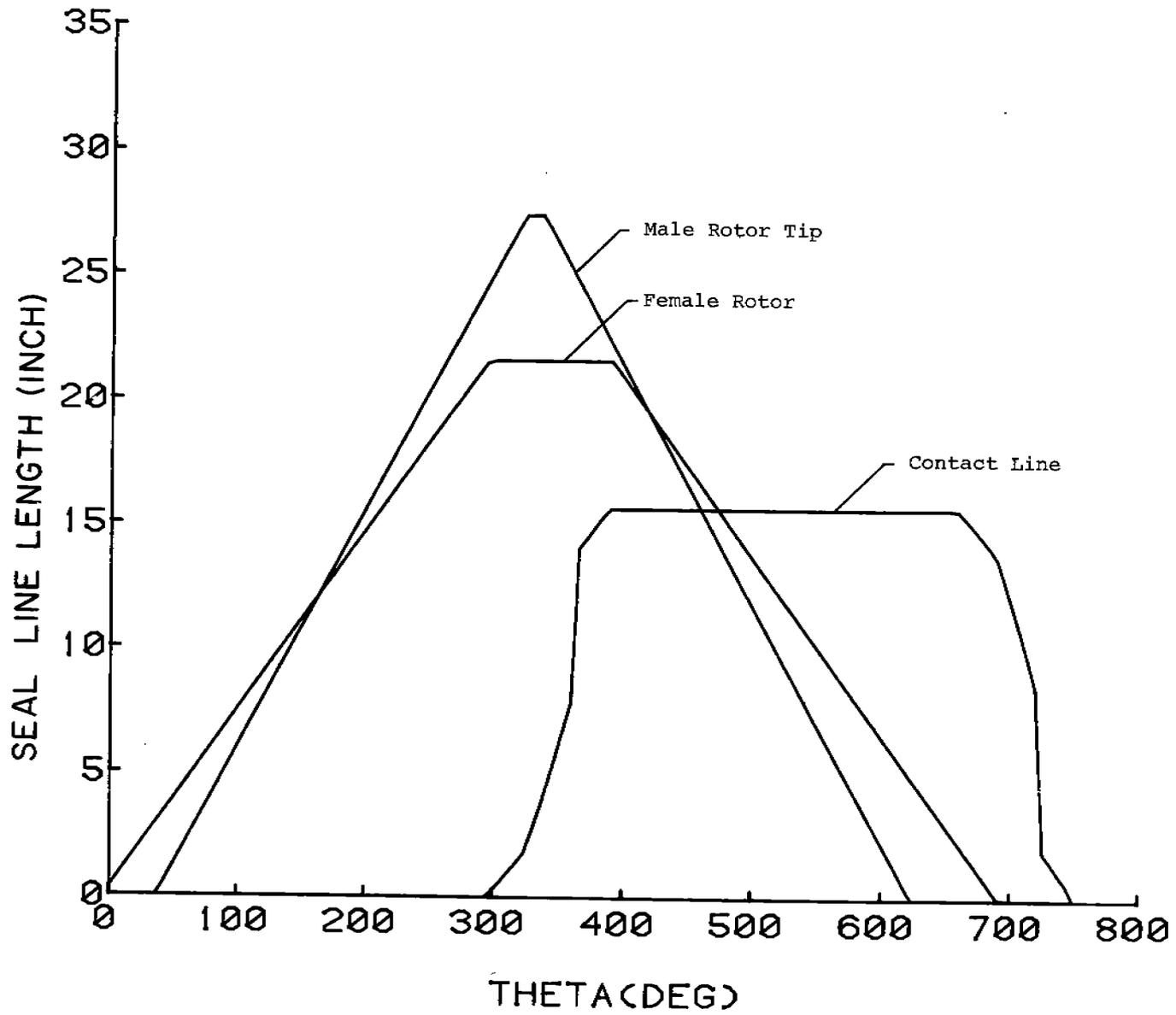


Figure 9: Contact Line and Seal Line Length Variation

Discharge Port Area
 Axial = 4359.8 sq. mm
 Radial = 89.3 sq. mm

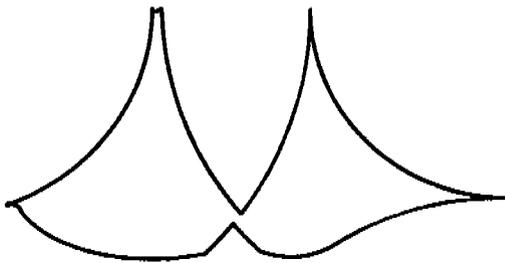


Figure 10: Axial Discharge Port Shape

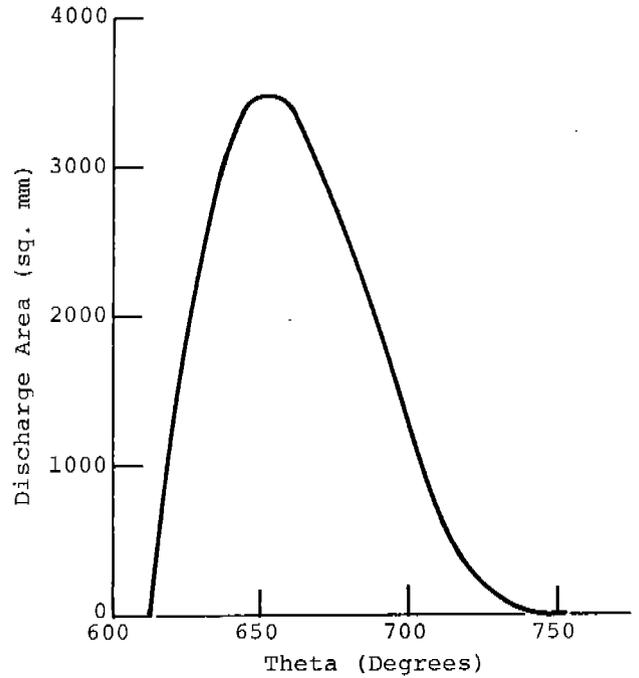


Figure 12: Discharge Port Area Variation

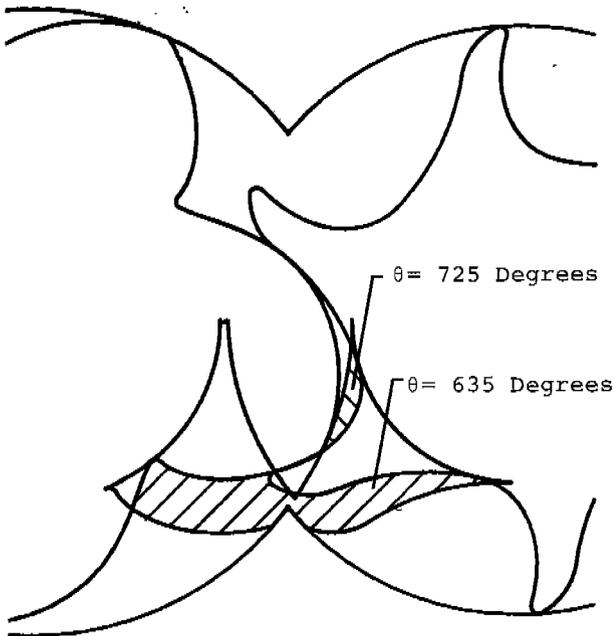


Figure 11: Axial Discharge Port Areas
 For Indicated Rotation Angles

Discharge Pressure (PSIA) = 114.7 (Nominal)
 Average Pressure (PSIA) = 122.504
 Power Lost (HP/100CFM) = 0.986

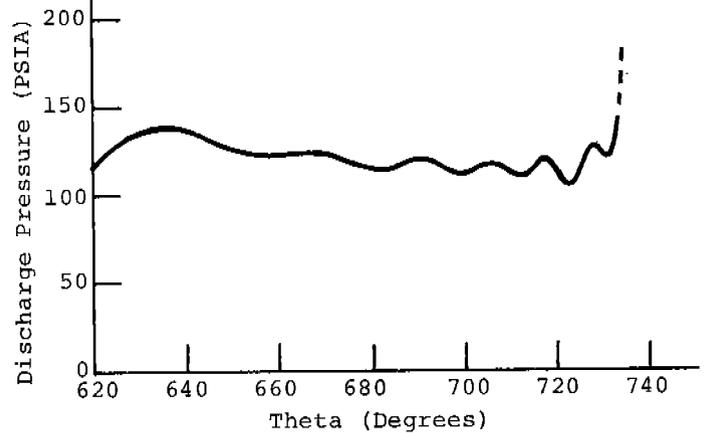


Figure 13: Discharge Port Pressure Variation

being presented separately in this conference (Reference 1). This performance program has been checked for several machines with entirely different profiles and shown to give good agreement with test data. The performance program can also be used for determining relative merits of different profiles for a given application.

CONCLUSIONS

A rapid, flexible, computer-assisted technique to generate and completely analyze twin-screw rotor profiles has been developed and used to demonstrate its capabilities through an example. This method reduces the time for the whole process from profile definition to performance prediction from an estimated several man-months to a typical one man-day. This powerful capability can be used in many ways:

- o It can be instrumental in inventing and analyzing entirely new profiles or modifying the existing profiles to match a particular application.
- o It can be used in optimizing a machine's geometrical parameters such as number of lobes, wrap angle, L/D ratio, built-in pressure ratio, etc., for a given use.
- o It can aid in better design of the machine through providing understanding of the importance of different leakage areas and power losses.
- o It is used in generating input data such as contact line length and blow-hole area for the performance program given in Reference 1.
- o It can be applied directly to many other meshed-rotor machines such as gears, blowers, etc.

The model has been used successfully numerous times for all kinds of applications including profile generation, analysis and evaluation. The profile types investigated had a wide range of profile shapes, number of male/female lobes (3/4 to 6/8 and in between), wrap angles (150 to 350 degrees), L/D ratios (0.8 to 2) and built-in pressure ratios (4 to 10).

ACKNOWLEDGEMENTS

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SYMBOLS

L	= Rotor Length
N _m	= Number of Male Lobes
θ	= Male Rotor Rotation Angle A cavity starts at θ=0 and completely discharges at θ=360(1+1/N _m) + wrap angle
L/D	= Length/Male Diameter Ratio.
x,y,z	= x,y,z coordinate system with z along the rotor length.
I _x ,I _y	= Area Moment of Inertia about x or y axis.
I _z	= Polar Moment of Inertia

REFERENCE

1. Singh, P.J., and Patel, G., "A Generalized Performance Analysis of Oil-Flooded Twin-Screw Compressors", Purdue Compressor Technology Conference, 1984.