COMPUTER AIDED DESIGN AND MANUFACTURING OF CENTRIFUGAL PUMP IMPELLERS

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ABSTRACT

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A computer aided design method for the conventional centrifugal pump impellers, which was already developed in the Mechanical Engineering Department of Middle East Technical University (METU), is used to design two different prototype impellers. The impellers are selected such that both the code can be assessed and the available CAM facilities of the University are utilised fully. One of the impellers has double curvature surfaces with apparent three dimensionality. The design code uses a different semi-emprical technique in which some of the design parameters are interpolated from the pump manufacturers' data, to supplement classical design calculations.

The impeller geometry obtained as the Centrifugal Pump Impeller Design Code, which works on a PC, is transferred to the workstations of the

CAD/CAM/ROBOTICS Research and Application Centre of METU. Software package ICEM is then used as a design environment and the final shape of the impeller is generated including toolpaths and Cutter Location (CL) files. For the milling machine Deckel FP5cc/T a 5-axis post processor is written to translate the CL files to G-Codes.

The impellers produced are mounted on the test set-up for performance evaluation . The test results show that final products satisfy initial design specifications.

Key Words : Centrifugal Pumps, Turbomachinery, CNC Machining, Geometric Modelling, Pump Tests, CAD/CAM.

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ÖZ

POMPA ÇARKLARININ BİLGİSAYAR DESTEKLİ TASARIMI VE İMALATI

PEKKAN Kerem

Yüksek Lisans Tezi, Makina Mühendisliği Ana Bilim Dalı

Tez Yöneticisi: Prof. Dr. Cahit ERALP

Şubat, 1994, 132 Sayfa

İki farklı prototip pompa çarkı, daha önce ODTÜ Makina Mühendisliği Bölümünde geliştirilmiş bilgisayar programı kullanılarak tasarlanmıştır. Çarkların geometrisi, hem programın doğru çalıştığını kanıtlayabilecek, hem de üniversitedeki bilgisayar destekli tasarım ve üretim tesislerinin tamamen kullanılmasına imkan verecek şekilde seçilmiştir. Tasarım kodu, klasik tasarım hesaplarına ek olarak, bazı tasarım parametrelerini pompa üreticilerinin verilerinden yarı deneysel bir teknik kullanarak çıkartmaktadır.

Kişisel bilgisayarlar üzerinde çalışan Santrifuj Pompa Tasarım Kodundan elde edilen çark geometrileri, ODTÜ Bilgisayar Destekli Tasarım ve İmalat Merkezindeki (ODTÜ-BİLTİR) işistasyonlarına transfer edilmiştir. Burda ICEM adlı paket program kullanılarak çarkların son şekli verilmiş, üretim için gerekli olan

dosyaları G- Koduna transfer edebilmek için kullanılan freze için (Deckel FP5cc/T) 5- eksen bir son işlemci yazılmıştır.

Üretilen pompalar performans değerlendirmesi için deney düzeneğine bağlanmıştır. Test sonuçları göstermiştirki, son ürünler tasarım spesifikasyonlarını sağlamıştır.

Anahtar Kelimeler: Santrifüj Pompalar, Turbomakinaları, Bilgisayar Kontrollü Üretim, Geometrik Modelleme, Pompa Testleri, Bilgisayar Destekli Tasarım ve İmalat.

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NOMENCLATURE

b	breadth (m)
d	diameter (m)
f	wrap angle (degrees)
g	gravitational acceleration (m / s^{-2})
i	angle of incidence (degrees)
r	Radius (m)
s	distance, thickness (m)
t	pitch (m)
z	number of blades
A	area (m^2)
B	number of blades, tilt axis register (degrees)
C	rotary axis register, velocity (m / s)
D	diameter (m)
H	head ($m\ H_2O$)
K	velocity coefficient
N	rotational speed (rpm)
P	Power (kW)
Q	capacity, flowrate (m^3 /s)
R	radius (m)
S	suction specific speed, stream surface
U	peripheral velocity (m /s)

V	velocity
W	relative velocity of flow (m /s)
Z	number of blades

α	angle, absolute fluid angle (degrees)
β	relative fluid angle (degrees)
δ	angle (degrees)
η	efficiency
ρ	density (kg /m^3)
ϕ	construction coefficient, blokage factor
Ω	angular velocity (rad /s)
θ	angle of overlap (degrees)
ω	rotational speed (rad /s)

C_m	components of the absolute velocity normal to the peripheral velocity
C_p	Pfleiderer ' s correction factor
H_u	corrected head (m)
$\dot{m}$	mass flowrate (kg /s)
P_1	power at motor terminals
P_N	shaft power
P_u	corrected fluid power
Q_u	corrected flowrate
$\overline{v}_{\theta 2}$	mean peripheral velocity at exit

CHAPTER I

INTRODUCTION

In this thesis Computer Aided Design (CAD) and Manufacturing (CAM) methods are used to produce two pump impellers. Pump geometry depends on specific speed. As specific speed increase blade geometry becomes difficult to manufacture and highly curved. Basic requirements for a satisfactory pump performance are :

- high efficiency
- high flow capacity per unit frontal area
- high head
- optimum length, exit diameter and weight
- mechanical design and manufacturing should be reliable

The produced impellers are designed using the Centrifugal Pump Impeller Design Code (CPID), which was already developed in METU Mechanical Engineering Department [16]. This program classifies the conventional pumps into single and double curvature types. In parallel the specifications of produced impellers are:

Impeller S

Single Curvature Bladed Impeller

$N_s = 0.392$

$\eta = 0.630$

P = 8.65 kW

Q = 0.0139 m^3/s

H = 40 m

N = 2800 rpm

Impeller D

Double Curvature Bladed Impeller

$N_s = 0.499$

$\eta = 0.630$

P = 6.27 kW

Q = 0.0139 m^3/s

H = 29 m

N = 2800 rpm

The aim is to clarify and develop an experience in the design and manufacturing of these highly three dimensional components. Although, there are many design methods in literature, about production there is little written and practical aspects are not released by the manufacturers.

Although pumps are generally cast, for rapid prototyping CNC milling became a feasible alternative. It should be mentioned that centrifugal compressors which are similar to centrifugal pumps are usually milled.

Impeller S requires a minimum of three axis controlled NC machine tool and an indexer or a rotary table. On the other hand to produce impeller D a minimum of four axis and a rotary table is required. Moreover for high quality surface finish and fast machining all the five axis must be continuously controllable. This is the case for the milling machine used in this work Deckel FP5cc/T.

The design methods in the literature are reviewed, the one that is developed in Mechanical Engineering Department of METU (CPID) is selected mainly because, with the results of performance tests CPID code can be assessed. Besides CPID gives fast responses for trial and error based approach. Moreover every detail of the theory used are available, and it is in the form of a user friendly ready to use Computer code.

In the design trial and error implies that the CPID program to be ran several times since the available test facilities, limitations of 5-axis Deckel milling machine at CAD/CAM Center (e.g. the rotary table can be tilted 45^{o} forward but only 15^{o} backwards) and impeller D must have double curvature surfaces with apparent three dimensionality, moreover the surfaces must be hard to manufacture, this means they must force the limits of available machine tools (for example in the CAD/CAM center the machine tools are very well oriented for these kinds of parts, a design output from the CPID code which requires a tool axis orientation more than 45^{o} cold not be realized using the available milling machine).

Both during design and manufacturing the resources of CAD/ CAM is used extensively, impeller D is the first part produced that uses 5- axis machining option of the Deckel milling machine, in METU CAD/ CAM Center.

The CPID program works on PC. Its output is transferred to Cyber 910 workstation of CAD/CAM center, on this machine, ICEM a powerful design and drafting program is used as a design environment and final shapes of the impellers are generated including tool paths and cutter location files. For the milling machine used a 5-axis postproscessor is written to translate CL-files to G-code files.

Finally assembled impellers are mounted on the test set-up for performance evaluation. The test results are also presented in this thesis.

CHAPTER II

DESIGN OF CENTRIFUGAL PUMPS

2.1 Review of Current Design Procedures

There are three approaches to the design of a turbomachine: Semiemprical, direct and inverse. The direct methods are analysis based where a geometric configuration is specified and the flow fields are sought. The inverse design approach is based on specifying part of the geometry and part of the flow field, the solution provides the remaining part. In the semiemprical procedure the major dimensions of the impeller are calculated by the use of some correlations determined experimetally.

In Industry turbomachinery manufacturers use all these methods in their design processes. Figure. 2.1 contains design systems of that kind . In literature, for pumps, such schemes are very scarce, likewise the sophisticated design methods are not used unless it is a special application. This is due to the complexity of flow and geometry that application of full 3D codes becomes extremely difficult and time consuming for a trial and error based design approach. Above all, experimental pump design data are complete and a plenty of correlations are available for the oldest turbomachinery type. Individual companies favor to use the correlations based on their own experience, and new designs are generally obtained using the laws of similarity.

The main change in pump design in the recent years is that the details of the correlations are purified and computational techniques are improved. Also the graphical visualisation methods are frequently used in the presentation of the results. The future trend is the application of computational fluid dynamics in the analysis part and adaptaion of existing radial compressor design schemes to centrifugal pumps. In parallel two of the three CAD/CAM procedures shown in Figure 2.1 are for radial compressors.

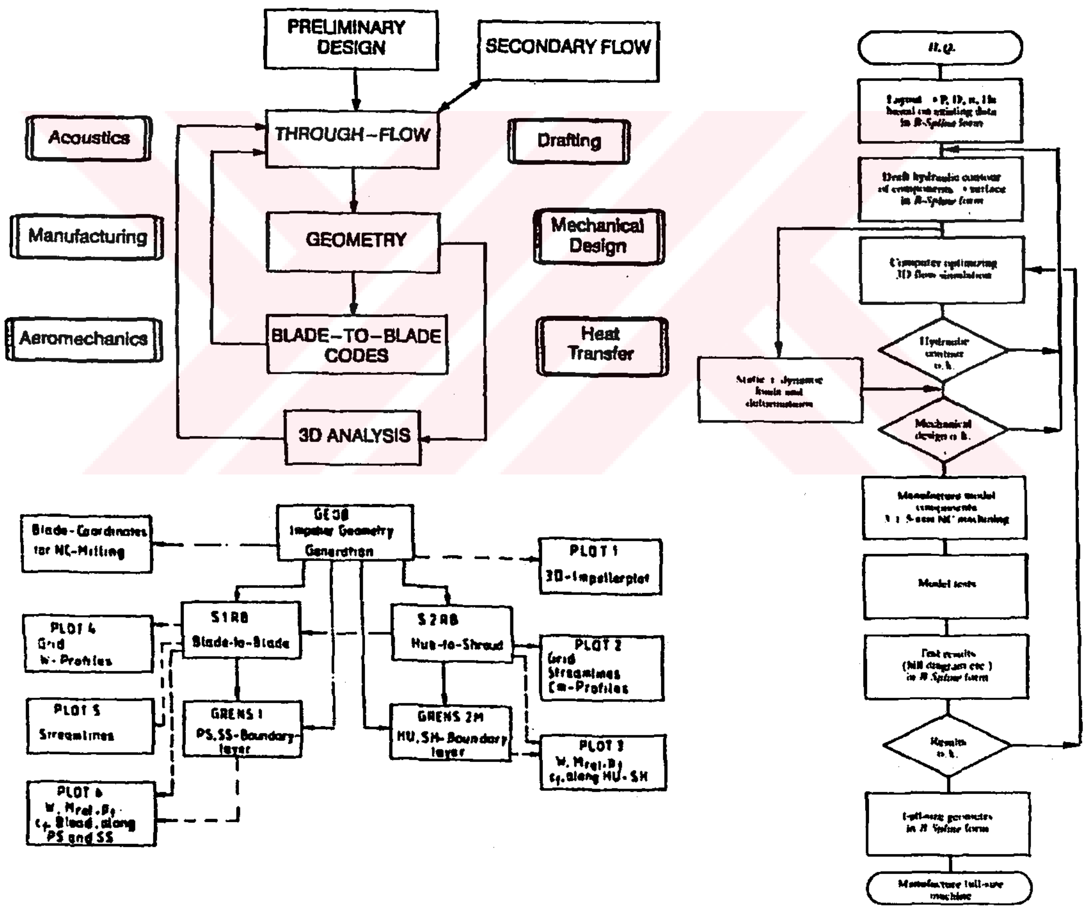


Figure 2.1. Block Diagrams of Impeller Design Procedures (Krain, Sulzer, GE)

Each design step requires output with different degree of accuracy and defining the surface geometry is vital both for the interface and for the design approach itself. The importance of preliminary design provides the selection of initial geometry from a large number of alternatives.

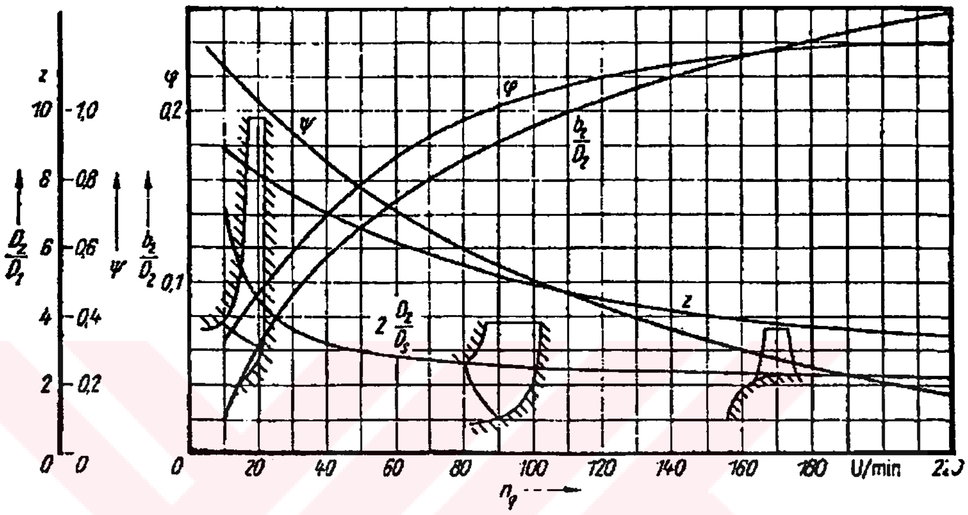


Figure 2.2 Pump Type and Geometry Based on Specific Speed nq [3]

A trivial example is the correlation of pump type and specific speed, Figure 2.2. Here the pump type and the maximum efficiency available is fixed for the given specific speed. Even if the best CFD tools are used, the efficiency can not be increased very much above the value at that specific speed. Preliminary design uses a one dimensional mean line method of analysis, with the aid of accumulated company experience, the result is a few percent accuracy in the performance parameters [1]. A cavitation performance check is provided at this step.

Throughflow calculations outputs the flowpath boundaries, vector diagrams, layout of the blades, and the variation of stream tube thickness through the selected sections. The success of throughflow calculation however depends on the empirical data used. The rest is the detailed design system where the computational techniques are utilized to analyze the performance levels set by the throughflow results.

Computational schemes with different approximations are being used in recent years, however the important aspects of the problem is generally neglected. Potential methods only considered historically. Miner(1992) et. al. determined the velocity field within a laboratory centrifugal pump, using 2D potential flow approximation [2]. The results agreed with experiments to within 17% for velocity magnitude and 2^{o} for flow angle. In turbomachinery analysis, the so called Quassi-3D method, introduced by Wu (1952) forms the analytical foundation, Figure 2.3. Where the steady flow solution is calculated on two families of intersecting surfaces (Blade-to-blade (S_1) and Throughflow (S_2 surfaces)). Iteration is performed between a mean S_2 stream surface (S_{2m}) and several S_1 surfaces until the flow parameters on the same points of both surfaces are equal. Ribaut (1988) [6] and Zhengming (1988) [7] introduces the present state of the method. Although Quassi- three dimensional approach is still the basic and widely applied tool, due to some modeling limitations, e.g., the need to iterate between throughflow and blade- to- blade calculations, Denton [3] suggests the use of full 3D calculations, after obtaining throughflow results.

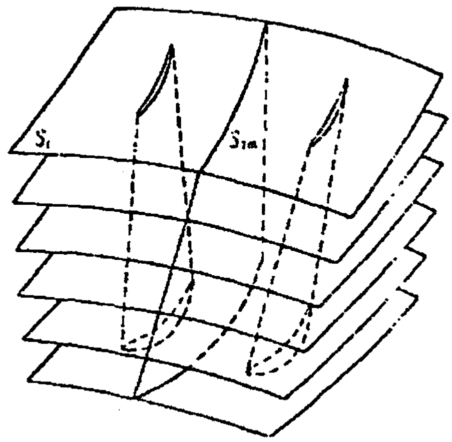


Figure 2.3 Wu's Stream Surfaces [7]

Krain (1984) [4], applied Q3D solution to centrifugal compressors. The block diagram was given in Figure 2.1.. The key points of this approach are:

- Design tools must be quick and reliable in generating smooth impeller discharge flows, since flow range characteristics and efficiency improvements strongly depends on the impeller discharge flow. For this task current advanced aerodynamic calculation methods although suitable, due to three dimensional flow effects such theories are difficult to apply. Moreover impeller design optimization is an iterative process where the key variables are storage and central processor unit time, even for todays computer technology.

- Simple input data preparation and easily understandable output presentation.
- Reliable experiments provide the quantitative check with existing impellers running under the same operating conditions.

- Design package has a modular structure.
- A boundary layer calculation is involved.
- For plotting the results several plot modules are available.
- The blade geometry generated meets the requirements of numerically controlled 5-axis milling machines.

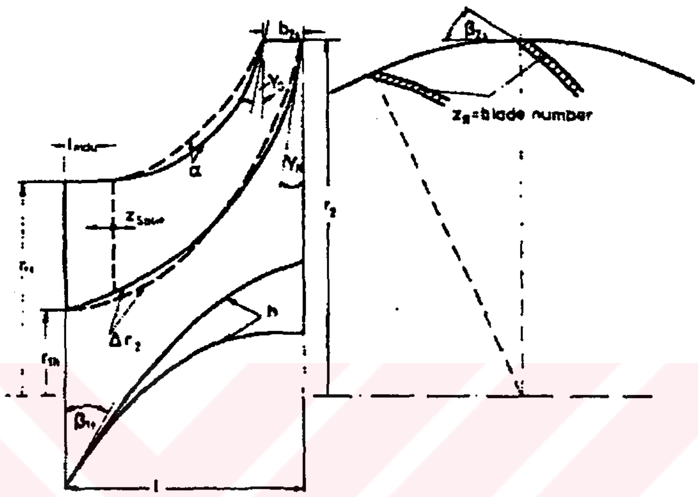


Figure 2.4 Krain 's Parametric Geometry Definition [4]

- The algorithm includes two parts, after the impeller geometry is generated by a parametric geometry definition, Figure 2.4. The fluid dynamic quantities within the impeller passage are calculated by a Quassi- 3D iterative solution based on Wu' s stream surface approach, After the velocity and pressure distributions along the casing walls and blade surfaces are known, rapid accelerations and decelerations are corrected by the designer, by adjusting the input data which takes care of meridonial contours and the blade geometry. This generation of geometry and analysis procedure is repeated until the desired velocity distribution is obtained.

"Krain ' s iterative process is time consuming and depends on the art of the designer, moreover the selected range of blade geometry is limited and between the performance and geometry there is not an obvious connection." [5] he inverse design methods as a component of a CAD system represents another advance to the blade geometry creation problem. However in literature Inverse Design methods are generally used to design compressors and gas turbines, where the Mach number distribution over the blade gains importance. For the sake of completeness and considering the further applicability of the method to pumps, a survey of the available literature will be presented. Borges [8], reviews the historical development of the method and applies it to the design of a radial inflow turbine rotor. (The important quantities are; the number of blades, mean swirl distribution, blade stacking position, and pressure distribution). Basic idea is to replace blades with sheets of vorticity, thus during the passage from the suction to pressure surface of blade a jump in velocity occurs.

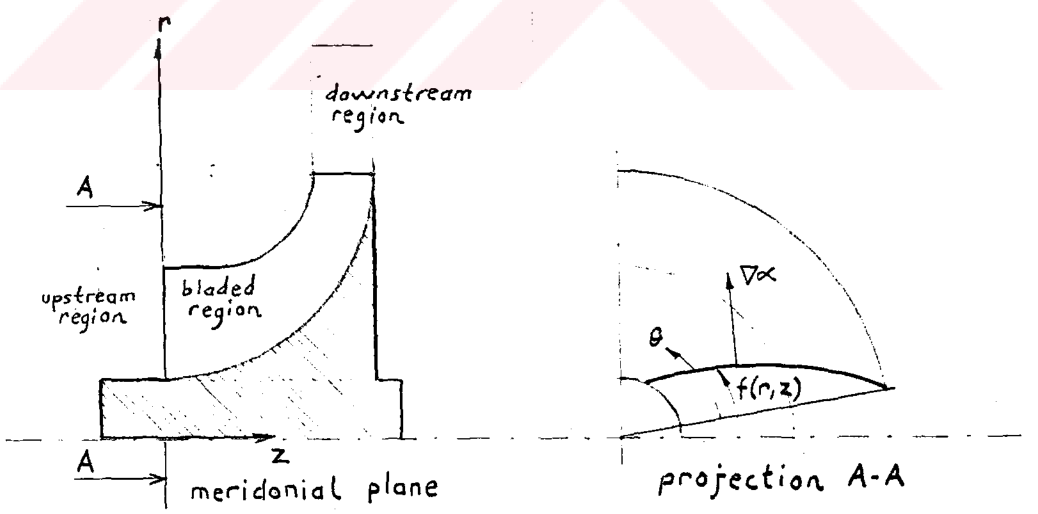


Figure 2.5 Blade Wrap [11]

The blade coordinates are introduced using an auxiliary coordinate, α Figure 2.5 where,

$$\alpha = \theta - f(r, z) \qquad (2.1)$$

α takes values $2m\pi/B$, where m= ..., -1, 0, 1, 2, ... and **B** is number of blades, hence the equation of the blade surfaces is obtained.

f is called wrap angle and for a radial impeller the blade wrap should be as small as possible for ease of manufacture as well as for mechanical stress considerations. [9]

In the formulation the primary input quantity is $r\bar{v}_\theta$, the tangentially averaged swirl distribution, Physically $r\bar{v}_\theta$ gives the mean angular momentum per unit mass, thus it is related to the work imparted to the fluid as it moves through the machine [8]. In design since the power requirement is known, overall change in the pitch averaged tangential velocity across the rotor is available via Euler Turbine equation, $P = \dot{m}\omega(r_2\bar{v}_{\theta 2} - r_1\bar{v}_{\theta 1})$. Moreover since $r\bar{v}_\theta$ can only be changed by a tangential force, its local variation along the blade surface in the streamwise direction gives the local pressure jump (or pressure loading) across the blade [10]. After overall change in $r\bar{v}_\theta$ is determined, its variation through the bladed region must be specified this is called swirl schedule, and different designers prescribe different schedules in their studies (e.g. forced vortex, free vortex, or arbitrary) [11]. In addition to the swirl schedule, the hub and shroud geometries, number of blades, blade leading and trailing edge locations, blade stacking position, and blade rotational speed are required initially.

The specified values of $r\bar{v}_\theta$ is related to the strength of vorticity, through an expression involving blade coordinates [8]. The so called Clebsh formulation is used to convert the known vorticity field in the flow region to corresponding velocity field. The blade shape can then be obtained by aligning it with the local velocity vectors. Since vorticity distribution is also depends on the finally obtained blade shape the procedure is iterative [8].

Chally [9], made a parametric study of the response of the blade shape, flow field, and pressure field to the number of blades, mean swirl distribution, blade stacking position. The solution of inverse formulation not only gives the blade geometry and blade surface pressure distributions, but also the entire flow field.

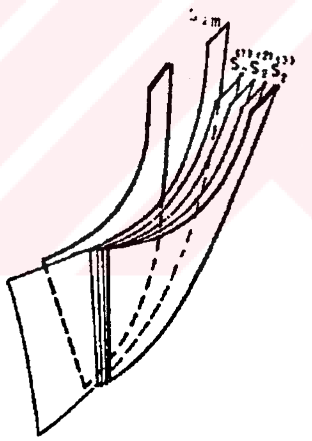


Figure 2.6 Converging S^2 Surfaces [5]

The approximate aerodynamic method of Zhao [5] again for centrifugal compressors should also be pointed, for similar to the inverse design methods, flow field is generated parallel with the blade geometry; From a planer S_{2m} stream surface blade surfaces are formed progressively by a Taylor series expansion, Figure 2.6.

So this method is applicable to radial turbomachines which has high number of blades.

2.2 Geometric Definition of Surfaces

During both manufacturing and design processes of centrifugal pumps, specification of the machine geometry is essential. After one dimensional calculation along a mean line through the machine, the blade geometry would be very incomplete, further analysis techniques such as 2D and 3D flow, detailed stress and vibration analysis require geometric information. This blade or passage geometry information should be easily manipulated, should produce different geometries, satisfy necessary constraints and should support not only the impeller blades, but also the other parts such as the inlet and volute. Finally manufacturing of prototypes, casting masters, or forging dies require the toolpaths from the geometry information.

The Centrifugal Pump Impeller Design program that is used to design the produced impellers, generates the geometric information for both single and double (mixed flow) curvature blades. After the selection of proper velocities and blade angles for maximum efficiency and input performance parameters, the code generates the vane layout, and pattern crosssections for cast impellers.

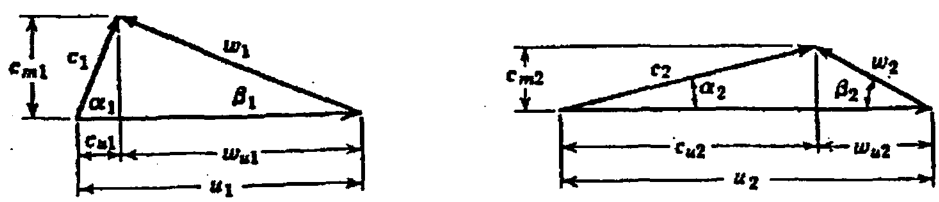


Figure 2.7 Inlet and Exit Velocity Triangles [12]

The enterance and exit velocity triangles, Figure 2.7 are the minimum design elements necessary to define the impeller proportions, from this starting point different layouts that will differ in performance can be constructed depending on the skill and experience of the designer [12].

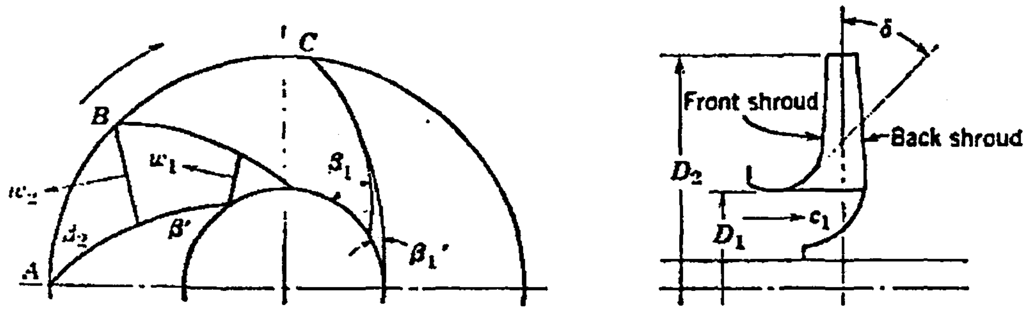


Figure 2.8 Plain Vane Faults [12]

The meridonial and plan view of a double curvature bladed impeller is shown in Figure 2.8. Due to the curvature of the front shroud and to have a shockless entry, the inlet vane angle, β_1 differs from the one that is drawn in the plan view, β_1', by the pure geometric relation:

$$\tan\beta_1' = \tan\beta_1 \cos\delta \tag{2.2}$$

For a plain vane impeller the angle between the vane and shroud is an acute angle. From the point of view of stress, manufacturing and end- wall boundary layer development the vane is preferred to be perpendicular to the front and back shroud surfaces, so the vane is extended to the inlet eye. Then for each streamline on the vane surface relative blade angle, β_1 will vary from hub to shroud.

In Figure 2.9 a mixed flow impeller is shown, assuming the channel is narrow the blade geometry can be represented by three streamlines (hub c_1c_2, shroud a_1a_2, mid b_1b_2). Following points must be considered during the geometry generation:

- Efficiency can be improved by extending the vanes towards the inlet eye, to an optimum position.
- Change of meridonial velocity from inlet (c_{m1}) to discharge (c_{m2}) should be gradual.
- Both front and back shroud curvature should change gradually to minimize uneven pressure and velocity distribution.
- The edge of the vane is determined so that the angles formed with the shrouds on the elevation view are approximately 90^{o}.
- Depending on the impeller size flow lines (hub c_1c_2, shroud a_1a_2, mid b_1b_2) are drawn providing that they divide the flow into equal parts Figure 2.9. Then the normals to the flow lines are generated (n_an_c, m_am_c, p_ap_c, q_aq_c) along which the meridonial velocities remains constant. In the figure, since inlet edge of the blade is not coinciding with the normals, meridonial velocity varies along the blade edge.

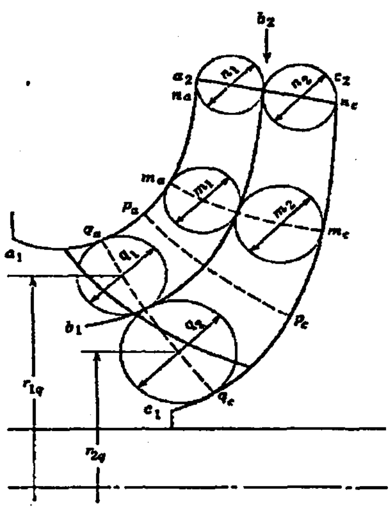


Figure 2.9 Mixed Flow Impeller Profile [12]

Figure 2.10 shows the back shroud curve of a mixed- flow blade, and the error triangles formed by the intersection of blade element f, meridonial g, and radial h sections.

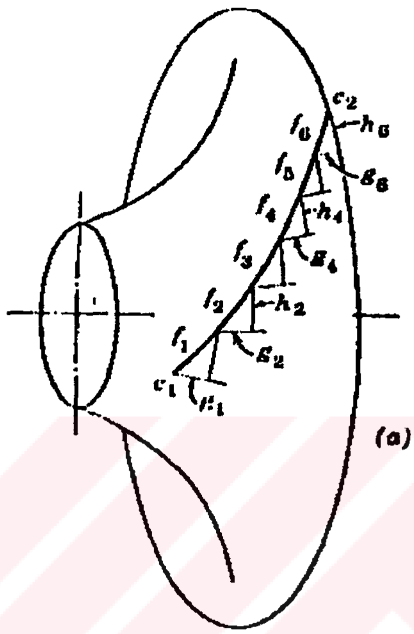


Figure 2.10 Impeller Flowline Development [12]

If these triangles are mapped on a two dimensional plane Figure 2.11.b, then the plane development of the curve which will be used in analysis and construction will be obtained. The vane thickness s is also plotted, which may vary from one flow line to other, for reasons of strength or flow quality. In the plane development the flow lines should be smooth and evenly spaced at the tips, to have a smooth edge projection also at the plan view Figure 2.11.c

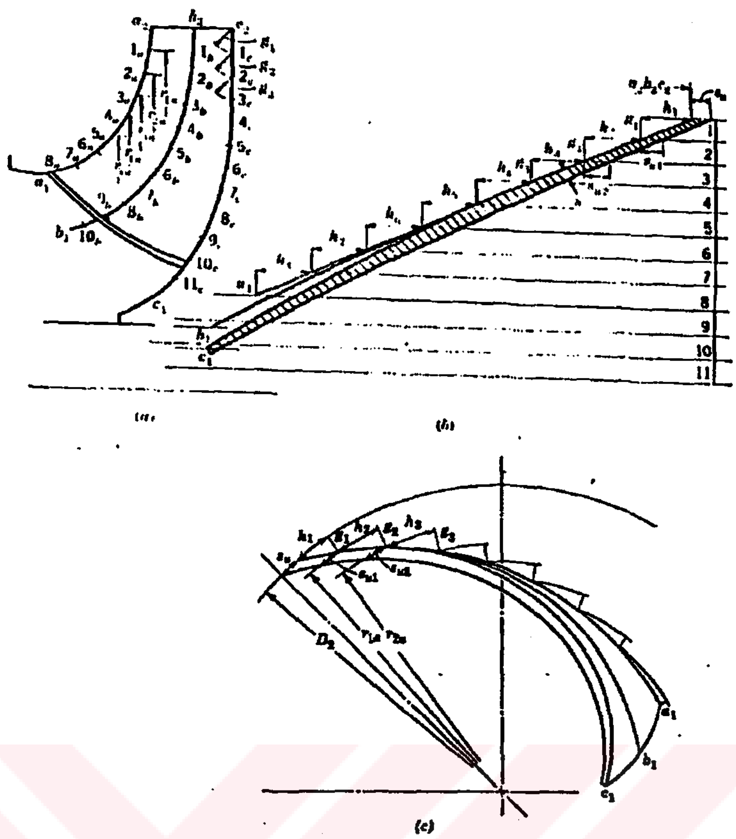


Figure 2.11 Plane Development of Flowlines [12]

The vane patterns for molding processes are obtained by drawing the view of normal planes (A, B, C, D) on the plan view Figure 2.12. These contour lines on the plan view completely determine the shape of the vanes.

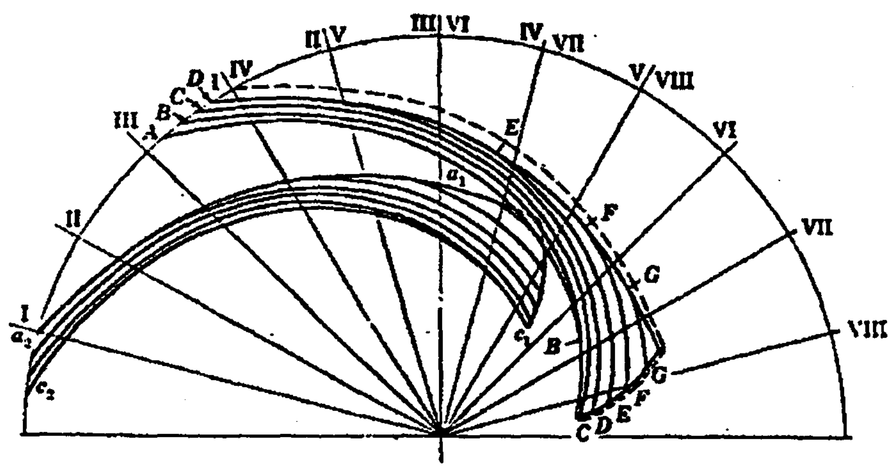


Figure 2.12 Vane Pattern Sections [12]

This procedure which is also used by CPID program to describe the shape of the produced impellers, is suitable for cast impellers to facilate an easy pattern making. Although the geometric data from CPID program is easily applied to CAD/CAM environment, following techniques, which use recent geometric modeling and CAM concepts efficiently are also available for describing multiply curved, three dimensional shapes encountered in turbomachinery.

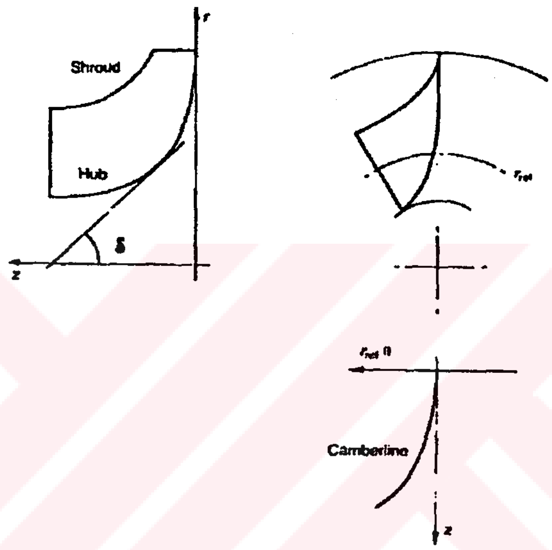


Figure 2.13 Meridonial Plane Projection and Camberline of a Radial Turbomachine Blade

The two planes; meridonial r-z, θ - z plane at a reference radius (camber surface) are presented in Figure 2.13. to obtain the relation between relative blade angle, camber angle for surface definition blades are projected on these surfaces. A surface type that is used mainly in radial turbines, offers many advantages for manufacturing, centrifugal bending, and thermal stresses. The surface elements are straight radial fibers, between hub and shroud curves. The camberline of such a blade is same for any $r_{ref}\theta$ - z plane.

Considering geometry of radial blade fibers [13], the blade angle variation with radius is

$$\frac{\tan\beta}{r} = \frac{\tan\beta_{ref}}{r_{ref}} \tag{2.3}$$

A blade with radial fibers, is a kind of ruled surface, as the blade elements are straight, the surface can be machined by the side of the milling cutter quicker than an arbitrary surface defined by B - Splines.

If the blade fibers are permitted to lean away at an angle ν, then three dimensional hub and shroud curves are not enough to describe the blade geometry, likewise a reference surface for the camberline, because the camberline shape will depend on the radius of the section from which it is projected $r_{ref}\,\theta_{ref} = f(z)$, and the angle of lean ν of the blade to the radial direction at any point is needed. In most general case $\nu = f(r, z)$. The blade angle is given by:

$$\tan\beta_1 = \tan\phi_1 \tan\psi_1 + \tan\nu_1 \tan\psi_1 \tag{2.4}$$

Aerodynamic advantages of back swept blades at the exit of the impeller, implies the use non- radial fibered blades.

2.2.1 Functional Representation of 2D- Curves

Hub and shroud curves in the meridonial view, camberline and non-radial blade angle, Figure 2.13 can be represented as curves of 2D parametric functions.

Overall dimensions of the machine, fixes the positions of end points of these curves. The blade angles or the need to match other components smoothly determines the slopes at these points. These corresponds to four parameters, but the designer requires extra to play with the general form of the curve.

When various components are defined piecevisely (such as inlet, bladed region and vaneless space), at blend points discontinuity in curvature is undesirable due to boundary layer development on the adjacent surfaces. This implies the use of higher order curves.

An example is Lamé ovals [13], given by following implicit equation (2.5)

$$\left(\frac{z+a}{b}\right)^{p}+\left(\frac{x+c}{d}\right)^{q}=1 \qquad (2.5)$$

$x=r$, for hub and shroud lines in meridonial view.

$x = r_{ref}\theta_{ref}$, for the camberline.

$x = \nu$, for non- radial blade angle.

Where a, b, c, d are obtained from the end conditions $(x_1, x_1'), (x_2, x_2')$ at z_1 and z_2. By varying p and q a series of analytic curves satisfying these conditions can be obtained. For two slopes $x_1' = 0$ and $x_2' \to \infty$ corresponds to hub and shroud lines of axial inlet and radial outlet centrifugal pump impeller. Figure 2.14 corresponds to this condition where the curves are plotted for different p and q values. Other constants are $a = -z_1$, $b = z_2 - z_1$, $c = -x_1$, $d = x_1 - x_2$.

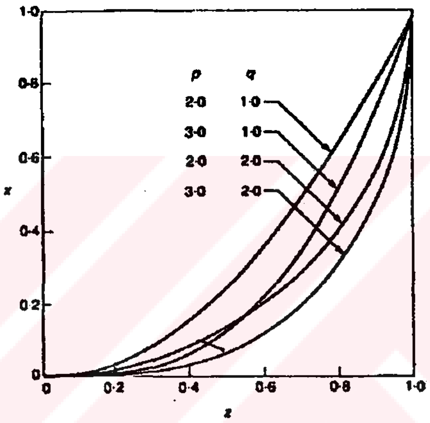


Figure 2.14 Lame Ovals Radial Exit [13]

If a finite x_2' is required, for instance in mixed flow pumps, implicit equation is presented as follows and plotted in Figure 2.15

$$\frac{p}{x_2'(z_2 - z_1)}\left[1-\left(\frac{x_2+c}{x_1+c}\right)^q\right]+\frac{q}{x_1+c}\left(\frac{x_2+c}{x_1+c}\right)^{q-1}=0$$

$$a = -z_1 \qquad d = x_1 + c \qquad (2.6)$$

$$b = (z_2 - z_1)\left[1+\left(\frac{x_2+c}{x_1+c}\right)^q\right]^{-1/p}$$

The radius of curvature, important in both manufacturing and analysis is:

$$R_c = \frac{\left[1+(dx/dz)^2\right]^{3/2}}{d^2x/dz^2}$$

where (2.7)

$$dx/dz = -\frac{p}{q}\,\frac{d}{b}\left(\frac{z+a}{b}\right)^{p-1}\left(\frac{x+c}{d}\right)^{1-q}$$

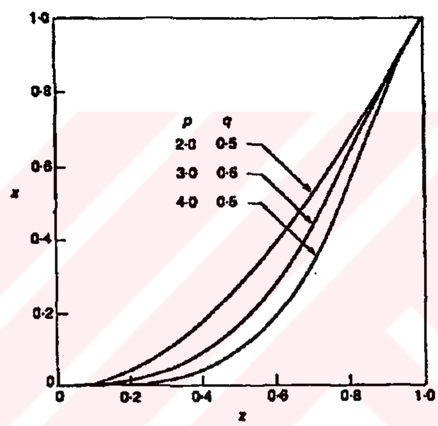


Figure 2.15 Lame Ovals Non Radial Exit [13]

Application to camberlines using rotated coordinates are explained in ref [13].

2. 2. 2 Geometry Definition by Three Dimensional Surfaces:

The trend in turbomachinery blading geometry both for modeling and for interfacing with NC machine tools is to use doubly curved surfaces, which are called "patches". A blade or any other component can be defined by a single patch, sometimes inevitable oscillations results in the curves due to large changes in curvature in leading and trailing edges then the surface is made up by a set of adjoining low order patches with no change in curvature or slope at junction or segment. A patch is defined by four parametric boundary curves, a point on the surface patch is associated with two parameters u, v which range from zero one. Each Cartesian coordinate of surface point is represented by a different function f,

$$x_1 = f_1 (u, v)$$
$$x_2 = f_2 (u, v) \qquad (2.8)$$
$$x_3 = f_3 (u, v)$$

The four parametric boundary curves follows from the above equations with values of (u = 0, v), (u = 1, v), (u, v = 0) and (u, v = 1). If for f1, f2, f3, bicubic polynomials are used, there will be 48 coefficients to be determined by fixing the slopes at the common boundaries $\frac{\partial x_i}{\partial u}, \frac{\partial x_i}{\partial v}, \frac{\partial^2 x_i}{\partial u \partial v}$, and continuity of curvature $\frac{\partial^2 x_i}{\partial u^2}, \frac{\partial^2 x_i}{\partial v^2}$.

Not only the blade geometry, but also other components may be defined by patches. Figure 2.16 shows the meridonial view of a multi stage radial machine, including inlet exit ducts, stators and rotors. After the channel geometry is satisfactorily defined, the locations of blade leading and trailing edges are specified [13].

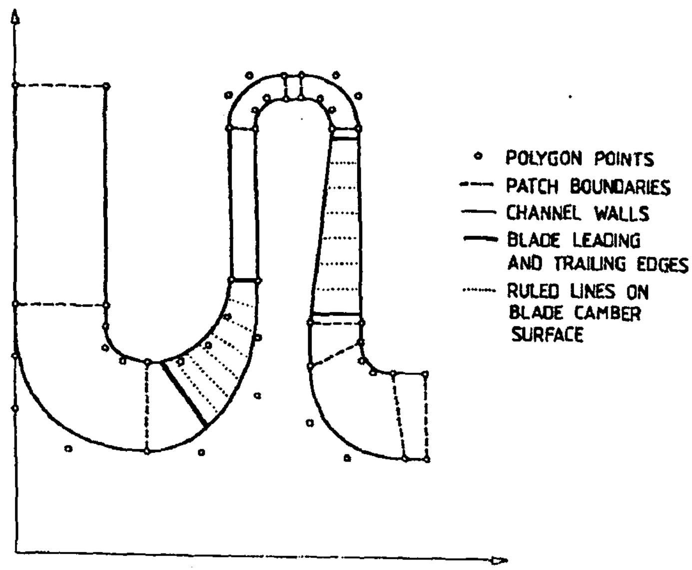


Figure 2.16 Radial Compressor Annulus Defined by Bezier Curves [14]

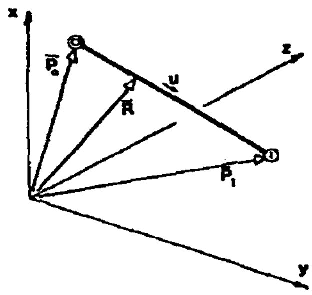
2. 2. 2. 1 Bezier Surfaces

To define the surface it is required to find analytic equations for functions in eq (2.8). These functions may be straight or parabolic as it is generally the case in turbine blade profile [14]. It is seldom necessary to go higher than cubic.

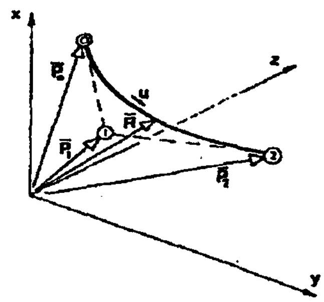
Four control points P_0, P_1, P_2, P_3 make up a Bezier Polynomial of order three:

$$P(u) = (1-u)^3 P_0 + 3u(1-u)^2 P_1 + 3u^2(1-u) P_2 + u^3 P_3 \quad (2.9)$$

Equations for higher orders are given in [15].



Bezier curve of order 1



Bezier curve of order 2

Figure 2.17 Bezier Curves of Order One and Two [14]

Notable properties of Bezier curves are:

- Tangent to lines (P_0, P_1) and (P_2, P_3) at predefined end points P_0 and P_3. Figure 2.17
- Location of P_1 and P_2 can be varied while keeping the slopes at the end points fixed.
- n^{th} derivative at an end point depends on the positions of the n intermediate points adjacent to that end [13].
- Control points P_0, P_1, P_2, P_3 envelopes the Bezier curve.

From Bezier curves, surfaces are generated by joining two Bezier curves by straight line elements Figure 2.18, or by higher order Bezier polynomials to generate the three dimensional arbitrary curved surfaces in the spanvise direction. Any point on the surface can be referred to by the values of its coordinates (u, v).

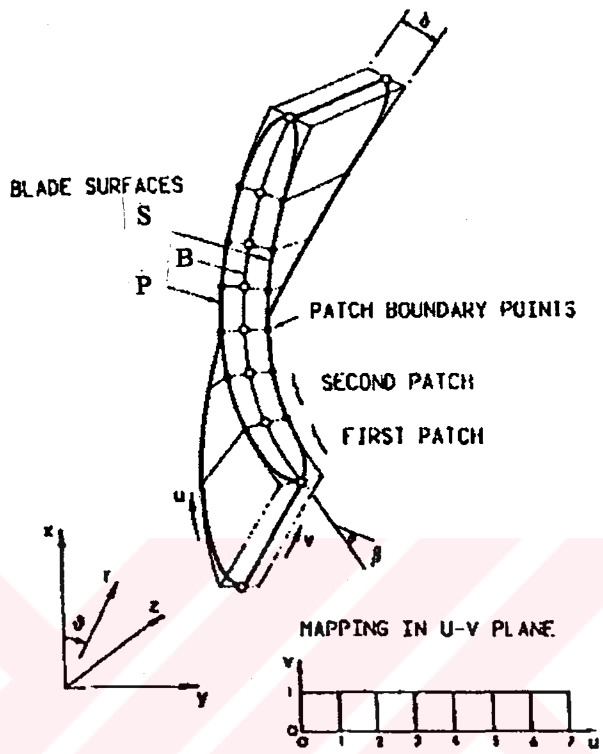


Figure 2.18 Bezier Surfaces to Define an Impeller Vane [1]

2.2.2.2 B- Spline Surfaces

In B- Spline surfaces, where Bezier surfaces is its subset, order of the curve and number of polygon points are independent by the use of interpolating functions.

The geometry of the produced impellers are defined mainly by B-Spline surfaces, via the use of ICEM utilities.

2.2.2.3 Blade Thickness, Leading and Trailing Surfaces:

Blade thickness is defined as a function of meridonial distance. Using this function pressure, P, and suction, S, surfaces are generated by placing them equidistant from the camber surface, C, Figure 2.18. Then analytic patches are fitted to each of these surfaces. If the camber surface has a curvature in the spanwise direction (similar to pump D that is produced), then the blade thickness is extended towards the local normal of the camber surface. Depending on the material, stress, and manufacturing method it is desirable to have thickness as small as possible. Although the produced impellers has a constant 3mm blade thickness, It was possible to design them with a tapered blade from hub to tip to reduce stress and increase flow area.

The patches at the leading edge and at trailing edge are rounded to reduce sensivity to incidence and the width of the wake. However for conventional pumps due to manufacturing costs the geometry at inlet and exit is left as it is or with a basic rounding. Plus intersection of patches with the hub surface requires manufacturing fillets.

The CPID program does not specify any leading or arbitrary edge geometry.

2.2.2.4 Ruled Surfaces

Although any Ruled Surface can be represented by a B- Spline Surface, this surface type bears a separate attention, for it can be machined by the side of a milling cutter, moreover if the spanwise length of the blade is small, as it is the case for many low specific speed industrial pumps. Prototype blades can be machined by a single pass, this leads to very low develop times. Besides to verify the 5- axis capability of Deckel milling machine and the 5- axis postprocessor that is written to facilate conversion of surface data to G- Codes, a ruled surface is created using ICEM.

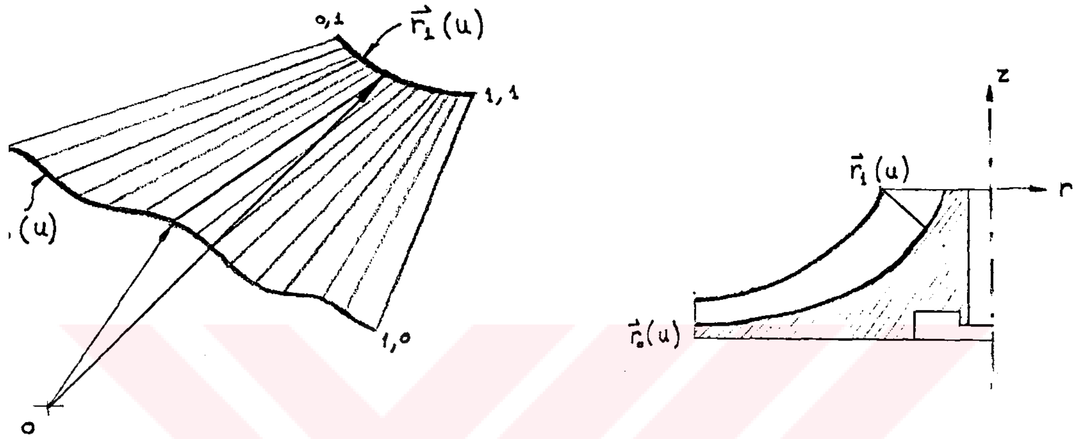


Figure 2.19 Ruled Surfaces

Making use of Figure 2.19 following vector equations can be derived:

$$\bar{r}(u,v) = \bar{r}_0(u) + v[\bar{r}_1(u) - \bar{r}_0(u)] \tag{2.10}$$

where the directices are given below, in cylindrical coordiates

$$r_0(\theta) = z(\theta)k + r(\theta)e_r + \theta e_\theta$$

$$z = f(r) \qquad \text{and} \qquad r = f(\theta) \tag{2.11}$$

2.3 Description of CPI Design Approach:

Both the double curvature (Impeller D) and single curvature (Impeller S) bladed impellers are designed using the code written by Talayhan (1989) [16]. This code unifies the classical pump design procedures of Stepanoff [12], Lazarkiewicz [17], and Pfleiderer [18], including the know-how developed by Hancıoğlu during the construction of Double suction pump (1984) [19].

In this section only a brief summary will be presented, focusing to the point of view of the user. The details of the formulas can easily be found in the references stated above.

The specific speed N_s is formulated non-dimensionally as:

$$N_s = \frac{\omega Q^{1/2}}{(gH)^{3/4}} \tag{2.12}$$

defines the shape of the impeller.

$N_s = 0.499$ for Impeller D.

$N_s = 0.392$ for Impeller S.

As N_s increase, three dimensionality of blade geometry becomes apparent. In parallel, impeller D has a high specific speed, so that it worths an accurate 5- axis milling, and also the CPID code assessment can be performed around this specific speed range.

Hydraulic efficiency is given by:

$$\eta_h = \frac{\eta}{\eta_m \eta_v} \tag{2.13}$$

Figure 2.20 shows the basic parameters and suggested equations to determine them.

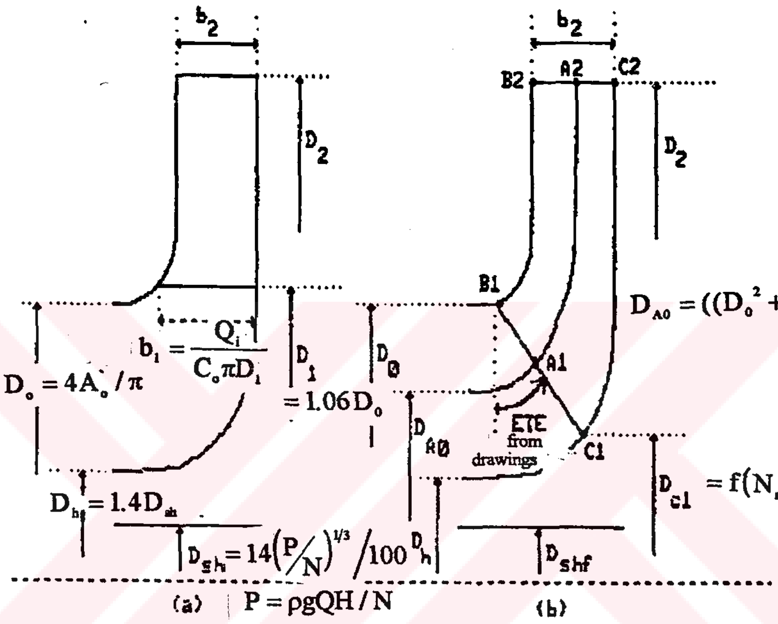


Figure 2.20 Meridonial Views for a) Single Curvature Bladed Impeller, b) Double Curvature Bladed Impeller [16]

Inlet velocity C_0 is given by:

$$C_0 = K_{cm1}(2gH)^{1/2}/\phi_1 \tag{2.14}$$

where

K_{cm1} : Presented interms of N_s in [6].

ϕ_1 : The inlet constriction coefficient

$$A_o = Q_i / C_0 \quad \text{where} \quad Q_i = Q / \eta_h \tag{2.15}$$

$$A_h = \pi D_h^2 / 4 \tag{2.16}$$

$$A_o' = A_o + A_h \tag{2.17}$$

Note that D_{e1} is found as a function of N_s based on well performing impeller designs.

The blade angles:

$$\beta_{1v} = \tan^{-1}(C_{m1}\,\phi_1 / U_1) \qquad \text{for SCBI} \tag{2.18}$$

$$\beta_{1vi} = \tan^{-1}(C_{m1}\,\phi_1 / U_{1i}) \qquad \text{for DCBI} \tag{2.19}$$

Initial assumption for ϕ_1 should be checked and corrected for the assumed number of blades z.

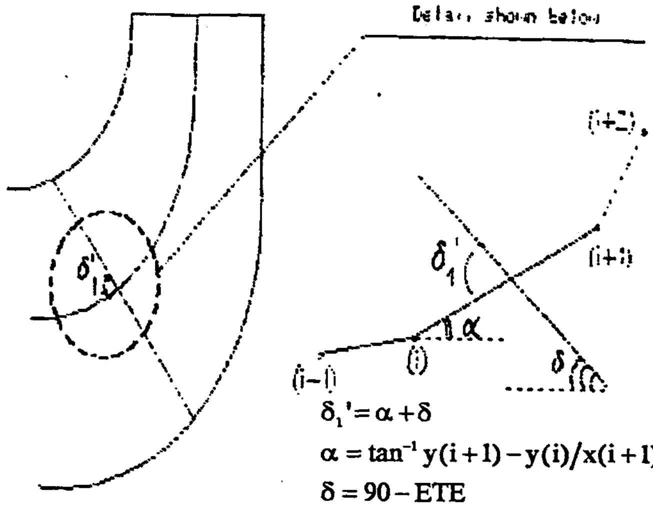
$$\phi_1 = t_1 / (t_1 - s_{u1}) \tag{2.20}$$

$$s_{u1} = s / \sin\beta_{1v} \tag{2.21}$$

$$t_1 = \pi / D_1\, z \tag{2.22}$$

z: the number of blades

s: blade thickness



$$\delta_1' = \alpha + \delta$$
$$\alpha = \tan^{-1} y(i+1) - y(i)/x(i+1) - x(i)$$
$$\delta = 90 - ETE$$

Figure 2.21 Meridonial View of Double Curvature Bladed Impeller [16]

For DCBI see Figure 2.21.

$$\frac{1}{\phi_1} = 1 - (s_2/t_1)\{1 + \cot^2\beta_1/\sin^2\delta_1'\}^{1/2} \tag{2.23}$$

2.3.1 Impeller Exit Dimensions

$$H_{th\infty} = (1 + C_p)H/\eta_h \tag{2.24}$$

C_p , Pfleiderer' s coefficient $C_p = 0.3$ for initial calculations.

After assuming β_2

$$U_2 = C_{u2} + (C_{u2}^2 + gH_{th\infty})^{1/2} \tag{2.25}$$

where

$$C_{u2} = K_{cm2}(2gH)^{1/2}/2\tan\beta_2 \tag{2.26}$$

K_{cm2} is presented as a function of N_s in [16].

$$D_2 = 60U_2/\pi N \tag{2.27}$$

$$b_2 = A_2/\pi D_2 \tag{2.28}$$

A_2 is determined considering the blockage of the blades [16].

2.3.2 Number of Blades

$$z = 13(r_m/e)\sin\beta_m \tag{2.29}$$

e : length of the center streamline A_1A_2

r_m : radius of centroid of central streamline A_1A_2

$\beta_m = (\beta_1 + \beta_2)/2$: mean angle of blade corresponding to A_1A_2

For single curvature bladed impellers :

$$r_m = (D_1 + D_2)/4 \tag{2.30}$$

$$e = (D_2 - D_1)/2. \tag{2.31}$$

For double curvature bladed impellers, as in [16] the streamlines are generated by Bezier polynomials, the radius of centroid is calculated using the pre defined segments.The flowchart for complete design procedure is given in Figure 2.22.

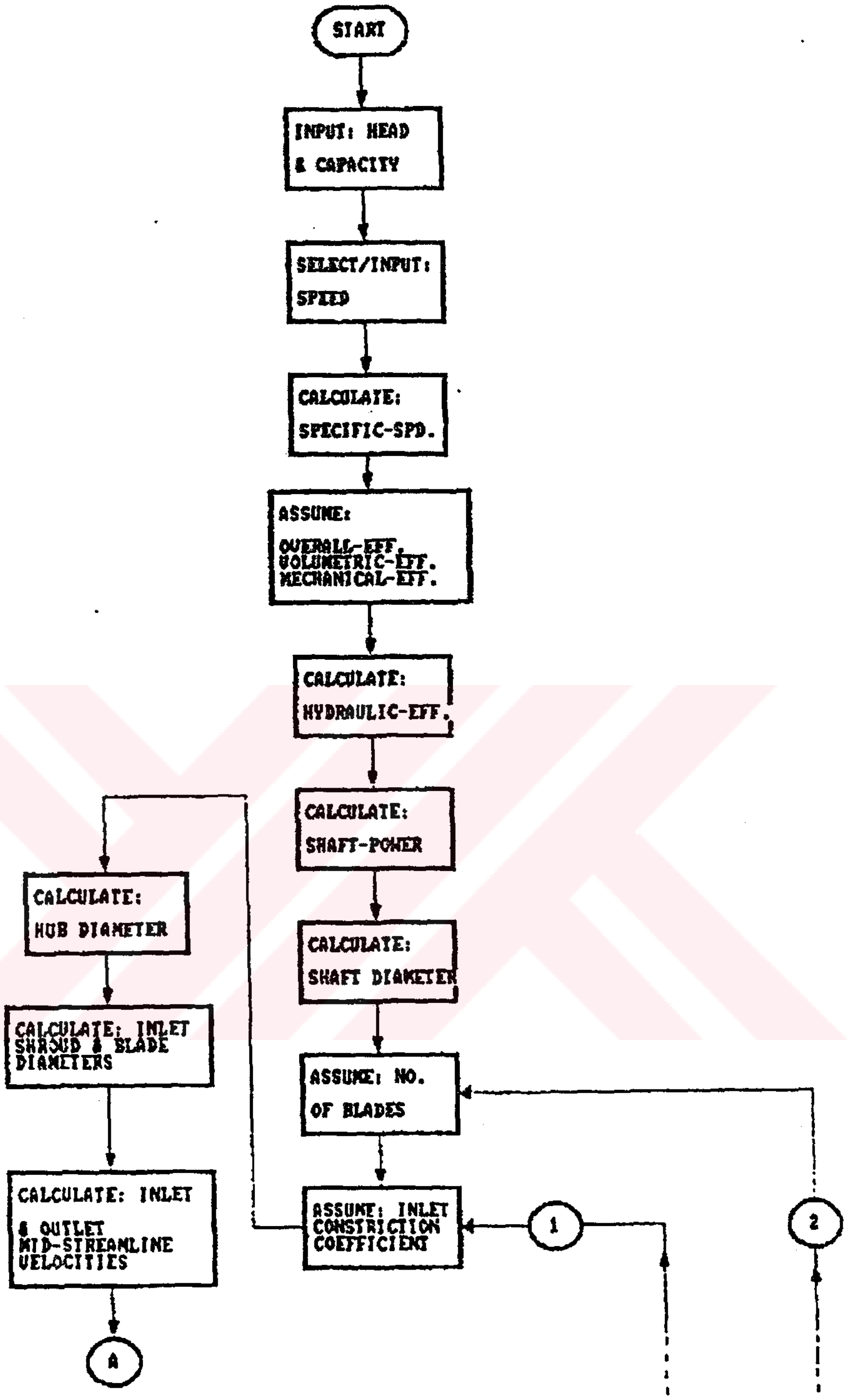


Figure 2.22 Design Algorithm [16]

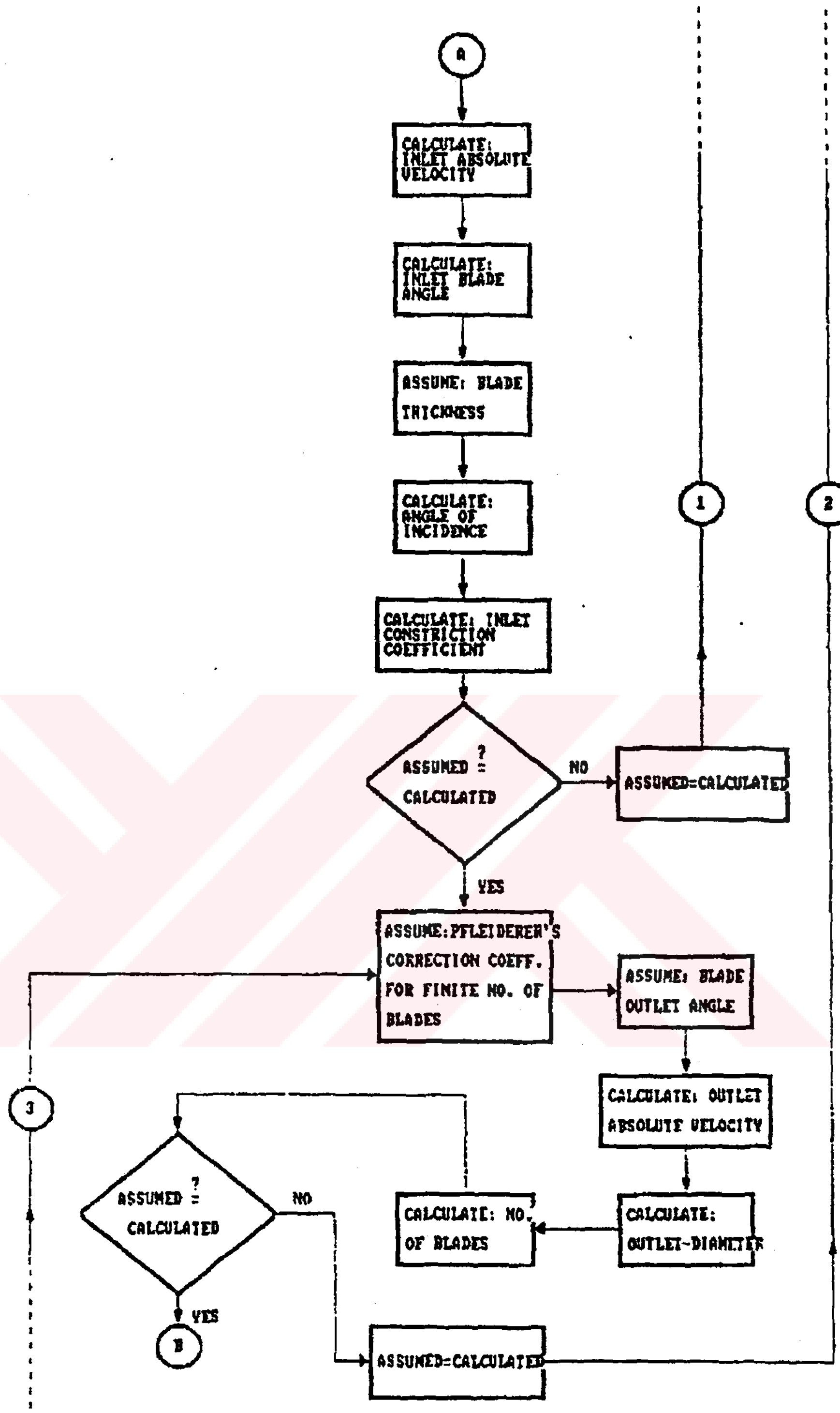


Figure 2.22 (cont'd)

The blade- to- blade surface is shaped using the point by point method introduced by Pfleiderer.

The criteria for the flow passage is to have continuous radius of curvature and flow area.

Although the design of single curvature bladed impellers are quite straightforward, due to competence in theory [16], The double curvature bladed impellers require experience and know-how, so these types of impellers are treated specifically in Talayhan 's work [16] by analyzing 36 practical and actual / original pump drawings, which has been designed and performing satisfactorily, to obtain correlations for the missing dimensions which are ;

wit2 (m) : the largest width of the blade seen from the meridonial view.

D_{c1} (m) : diameter of the blade leading edge at the hub.

ETE (^{o}) : end to end angle between inlet hub and shroud blade starting points.

2.3.3 Surface Definition of Single Curvature Bladed Impeller

2.3.3.1 Meridonial View

Figure 2.23 shows the mean velocity and relative velocity distributions, that are initially assumed as linear, then to reduce the blade length the relative velocity curve is curved downwards, by using appropriate factors of multiplication, the blade angle β and breadths at each point is calculated using these two distributions. Flow areas are checked using the calculated breadths whether they are linearly changing or not. Blade angle, breadth and cross-sectional area is calculated at the number of intervals specified by the user. As the number of intervals increases, meaning smaller increments, the smoothness of the curve also increases.

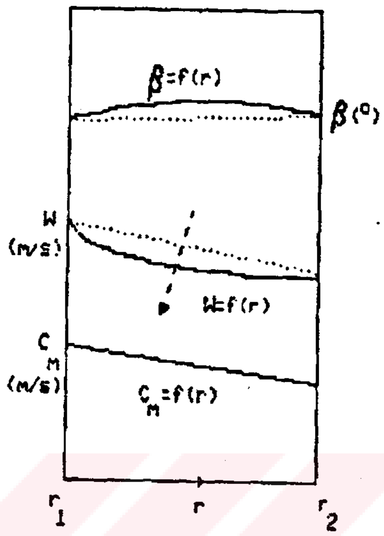


Figure 2.23 Changing of Linear Velocity Distribution [16]

2.3.3.2 Blade to Blade Profile

The relative velocity after the change shown in Figure 2.23 should be such that the flow is always in diffusion relative to the blades. Since $\beta = f(r)$ is known from β_1 to β_2 the blade profile in polar coordinates is obtained by integrating this function from r_1 to r_2.

$$\theta = \int_{r_1}^{r_2} \frac{1}{r \tan\beta} dr. \qquad (2.32)$$

2.3.4 Surface Definition of Double Curvature Bladed Impeller

2.3.4.1 Meridonial View

Second degree Bezier curves are used to generate the meridonial view of the blade, therefore for each streamline (hub, mid and shroud) three control points are required, making a total of nine points Figure 2.24.

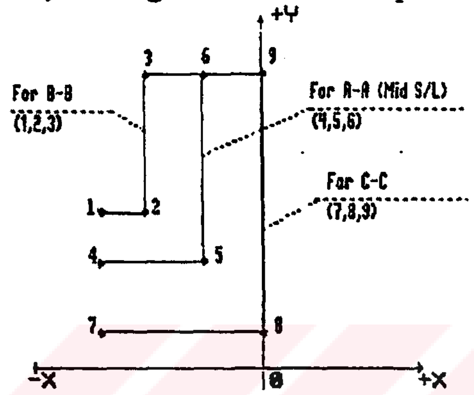


Figure 2.24 Nine Bezier Coordinates [16]

The coordinates of these control points are:

Shroud side,

$$P_1(-wit2, r_o)$$
$$P_2(-b_2, r_o) \qquad (2.33)$$
$$P_3(-b_2, r_2)$$

Hub side,

$$P_7(-wit2, r_h)$$
$$P_8(0, r_h) \qquad (2.34)$$
$$P_9(0, r_2)$$

Mid stream line is determined according to the principle of equal flow areas the details are given in [16],

$P_4(-wit2,\ r_h+b)$

$P_5\ (-b_2/2,\ r_h+b)$ (2.35)

$P_6(-b_2/2,\ r_2)$

where

$$b=\frac{-2\ r_o+(2(r_o^2+r_h^2))^{1/2}}{2}$$

Using these 9 control points, Bezier subprogram runs for each streamline to generate the meridonial curves.

2.3.4.2 Blade to Blade Profile

Similar to SCBI point by point method is applied three times for hub, shroud and mid streamlines. Realative velocity distribution is deviated from the linear to attain a longer shroud side blade, a shorter hub side blade and if possible to keep blades perpendicular to the shrouds, by the use of multiplication factors in quadratic functions.

CPID code produces graphical data for manufacturing the pattern and core box of the impeller with double curvature bladed impellers. The program optimizes some design parameters such as, inlet construction coefficient, and Pfleiderers correction for the effect of finite number of blades, and suggests reasonable values for many others, but it also leaves the designer free in his selection and guides him user friendly.

2.4 Application of the Code

The produced impellers are designed using the CPID program. Several runs were needed and many impellers were examined, since to demonstrate and verify the five- axis capability of the milling machine at the CAD / CAM center a geometry is seeked which is very hard to manufacture, with obvious three- dimensionality (this implied a high or medium specific speed) that requires 4- axis or for fast machining 5- axis milling. Besides the performance parameters Head, Flowrate and Rotational Speed are selected to suit the hydraulic pump test bench at the Fluid Mechanics Laboratory. In addition, as the design code is going to be assessed two pumps are designed and produced representing both the double and single curvature blade types. The design reports of both pumps prepared by the CPID are presented in Appendix A

The blade surface data, position of nine Bezier coordinates in the meridonial view and r - θ values of streamlines in the blade to blade surfaces, are then imported to the Design Drafting and NC Program ICEM which works under Cyber 910 workstations.

CHAPTER III

COMPUTER AIDED DESIGN ENVIRONMENT, ICEM DDN

3.1 Introduction:

ICEM DDN is an interactive design, drafting and numerical control software. In this thesis mainly the Design and Numerical Control features are used, these features will be presented in this chapter.

The starting data for the construction of Impeller D is Bezier co-ordinates of hub and shroud curves, and ten points on each of the three intermediate blade streamlines.

For Impeller S, the meridonial data, and only the two dimensional co-ordinates of the blade in r - θ plane are used. Blade thickness which is specified as 3 mm for both impellers is also included. Plots of various stages from the development of the construction of impellers are presented in Appendix B.

3.2 Advanced Design:

3.2.1 Advanced Design Modals:

Before starting the modals of advance design menu must be fixed. Since surfaces defined using different modals causes incompatibility and data base problems. The following are the set values of the advanced design modals:

Created Curve Type:	3- D Spline
Curve Tolerance:	0.3
Created Surface Type:	Cubic Blend
Refinement Level:	1
Composite Surface Type:	Non uniform
Conversion Tolerance:	0.1
Same Point Tolerance:	0.0001
Same Angle Tolerance:	0.0001

3.2.2 3- D Curves:

From the data points, using B- Spline menu two hub and shroud curves and three intermediate blade curves are generated. These curves are created by the interpolation /approximation feature as a single segment. The tangent at inlet and exit points are prescribed, moreover the curve is forced to pass through these points. To satisfy all the other points the order of the curve is increased as much as five, as for higher orders the maximal and mean deviation of the curve from the specified point set decrease, however nonsense and highly oscillating curves may result.

The multiple segment B- Spline curve creation function is not preferred, because the finally obtained surfaces can not be manipulated as freely as the single segment surfaces.

Sometimes for marking a region on a blade surface and the edges , or for surface edge modification a curve on the surface is needed. Isoparametric B- Spline creation is the fastest alternative.

During the design of inlet and trailing edges, as the geometry was not available from the CPID, Menu 15.2.7.2 for modifying B- Spline curves is used extensively:

MODIFICATION

1.POLYGON

2.CONSTRAINTS

3.DEFORMATION

4.ORDER

5.SEGMENT

6.PARAMETER

7.CURVE END

8.MATCHING

The vector option of ICEM is also placed under the 3D Curves menu (15.2 3D CURVES). Vectors are created to calculate and check maximum angle of the tool made with the horizontal plane. Table tilt limits this angle to the range 45^{o} up, 15^{o} down. Another application is during toolpath generation, nonsense toolpaths may be created, one remedy is to reverse the surface normal (15.2.6.13 REVERSE SURFACE NORMAL).

The following functions presented below by their menu number are also applied during design, and are offered by the 3D curves menu:

15.2.1 3D SPLINE

15.2.2 ISOPARAMETRIC SURFACE CURVE

15.2.3 INTERSECTION CURVE

15.2.4 DRAFT CURVE

15.2.5 COMPOSITE CURVE

15.2.9 OFFSET CURVE FROM A SURFACE

3.2.3 3D Surfaces

Vane surfaces are generated as a B- Spline surface, by using the blade streamline curve set. Although interpolation/approximation is selected (Menu 15.3.17.1.2), the surface is formed to pass through all the curves. By offsetting this surface towards both sides by the amount half of the blade thickness pressure and suction surfaces are obtained. Leading and trailing edges are closed as B- Spline surfaces, but by specifying the boundary curves.

Hub and shroud surfaces are created by rotating hub and shroud curves around z-axis.

The surfaces menu allows the designer to create various types of surfaces, However to avoid incompatibility, it is better to use one surface type (such as B- Spline or Curve Mesh Surface) during the whole drawing phase. B- Spline surfaces are preferable since ICEM offers a very involved and user friendly modification menu to be used with B- Spline surfaces.

To check the 5- axis post processor a ruled surface is created by sweeping straight lines between the ends of hub and shroud B- Spline curves. This surface is machined successfully as the first 5- axis milled part in the CAD/CAM Centre.

For toolpath generation, it is not needed to define fillet surfaces, however for good surface viewing the fillet surfaces are created between blades and the hub surface of revolution.

The following menu choices are also applied that are offered by the surfaces menu:

15.3.1 PLANE

15.3.10 CYLINDER

15.3.13 COMPOSITE SURFACE

15.3.15 PROJECTED SURFACES

15.3.19 TRIMMED SURFACE

3.3 Numerical Control

ICEM Numerical Control is used to generate toolpaths for:

17.6 SURFACE MILLING : A toolpath is generated to remove varying amounts of metal as the tool follows a geometric surface.

17.8 ABSOLUTE TOOL MOTION : Points and curves are generated using a ball- end cutter to flat- end cutter.

17.12 2-SURFACE PROFILE : This operation uses a ball- nosed end mill to generate a machine curve or toolpath between two surfaces.

17.7 5-AXIS SWARF MILLING : This operation machines a surface by cutting on the side of the cutting tool.

The generated toolpaths are verified and changed with the editor function, organised into a composite toolpath, and passed to a post processor through the CL- file generator (17.14 CLFILE/CLPRINT).

The toolpaths are generated by entering the characteristics of required machining operations to the system by a set of modals and responding prompts during the toolpath generation.

3.3.1 NC Modals:

Before starting the modals must be set so that the operations in 17. NUMERICAL CONTROL menu can be controlled. Some notes on important modals and their set values during the creation of toolpaths of impeller D is presented below:

17.1.2 MULTAX MODE : If machining operations require only x, y, z axes, multiple tool axis are not required, the multax should be off. However if multiple tool axis i, j, k is used the multax mode should be on. This causes the tool axes menu to be displayed during toolpath generation.

17.1.3 COOLANT : Set value is off.

17.1.4 SPINDLE DIRECTION : Controls the direction the spindle rotates. (Direction viewed as looking down the tool axis toward the tool tip)

17.1.5 SPINDLE SPEED and 17.1.6 FEED RATES : Default value can be taken because it is possible to suppress these values using milling machine controller.

17.1.7 CLEARANCE / RETRACT PLANE : Clearance is 5 mm and Retract plane is at z = -20 mm.

17.1.8 TOLERANCES :

For impeller D :

ruff intol = 0.13 mm (rough inside tolerance)

ruf outol = 0.13 mm

fin intol = 0.03 mm

fin outol = 0.03 mm

surf tol = 0.13 mm

For impeller S

ruff intol = 0.13 mm

ruf outol = 0.13 mm

fin intol = 0.02 mm

fin outol = 0.02 mm

surf tol = 0.02 mm

17.1.9 TOOL COMMAND SUPPRESSION : Suppressed. The post processor (Kerem 101) does not require the output of the tool, coolant, spindle and first rapid feedrate commands.

17.1.10 RAPID FEED MODE : Rapid

17.1.12 3D TOOLPATH SPACE : Workspace

17.1.15 SURFACING MODALS :

1.STEP SIZE : (Default is 25.4 mm) Specifies how far ahead the system should check from the tool ' s current position to determine if the tool will hold the surface tolerance.

A goto statement is not produced at every step size. When a step size has been taken and the tool is found to be out of tolerance, the system breaks up that step size until it finds a position that is in tolerance a goto point is then produced and the system finds the next position that is within tolerance.

2.NUMBER OF TOOL TEST POINTS : (Default is 4)

The number of tool test points is used to calculate where the tool contacts a surface. For both impellers:

STEP SIZE = 5 mm

TEST POINTS = 8

3.3.2 Surface Milling :

Due to the double curvature of the blades and interference of tool with other blades or hub, multiple axis milling is required. The blade surface for the suction side is divided into three sections.

1. Selection of FROM position. From this position the tool is forwarded to the specified surface which is to be cut, until the clearance distance (5 mm clearance plane) is reached. This motion is rapid. Then tool enters and cutting starts.

2. Indication of the surface to be machined.

3. The method of controlling the cutting depth of the tool must be selected. The system displays the retract height and maximum surface height. Then the start and end points of the first cut is specified.

4. Three types of containment curves are available (DRIVE, STOP, ON), they are used in the machining of impeller S. After fixing the containment curves the pass preparation are recommended for the surface.

For hub surface of impeller S :

PASS PREPARATION

1.Number of cuts = 120

2.Scallop height = 0.02 mm

3.Step over = 0.272 mm

5. Toolpaths are generated in the form LACE.

Other toolpath forms are :

LACE : To keep the tool on the surface to lace back and forth until the surface is completely machined.

NON LACE TO RETRACT : To move the tool to Retract plane at the end of each cut and then return it to the start side before beginning the next cut.

NON LACE NON RETRACT : To move the tool without retraction to the start side and then resume cutting in the same direction.

The system displays " Generating Toolpath PASS1, PASS2, ... " at the top of the screen. After a pause for calculations the path is displayed on the part geometry.

Generated toolpath is then appended to the current composite.

3.3.3 Other Toolpaths :

Both in 17.1 2 SURFACE PROFILE and 17.7 5- AXIS SWARF MILLING, toolpath generation is similar to surface milling. In the former two surfaces are specified, a toolpath is generated in which the tool is tangent to both surfaces (like blade and hub surfaces). 5- axis swarf milling, prompts the user a tool orientation, by varying also the surface unit vector, any side of the surface can be machined, the number of passes reduces considerably in this option.

CHAPTER IV

MANUFACTURING OF DESIGNED IMPELLERS

4.1 Introduction

Commercially pumps are manufactured by casting, for very high efficiency applications even precision casting is being applied. However the production of cores and their prints can be designed and manufactured by the method followed in this thesis, but it must be noted that in moulding there are many rules of thumb based on experience of pump manufacturers. Hancıoğlu [19] presents and describes the casting processes in pump industry.

In this thesis from solid block, the vanes are milled using a CNC machine tool, similar to the manufacturing of the blades of centrifugal and axial compressors. Since milling is used, the impeller is produced in two parts, shroud and the part where the vanes are located. The designed impellers has medium specific speeds, typical to conventional centrifugal pumps with closed vanes. Machining of both lower and upper parts are done on the same CNC tool. Although the traditional and cheap production method is casting, NC milling is ideal for rapid prototyping and further trial and error work.

Except basic turning of the stock materials all the manufacturing took place in CAD / CAM Robotics and Application Center, which leads the present stage of Surface modeling and manufacturing applications in Turkey, both in practice and research level.

Both pumps are milled using Deckel FP5cc/T machine, the other machine tools that are wire-cut EDM, EDM, CNC Turning center, welding robot. To supply tool location data for these machines, and to support other CAD/CAM applications main computational power is from various workstations. Naturally all the units are communicating via a local area network.

The output of ICEM which is in the form of cutter position plus tool orientation is given below

```
1          ICEM NC CLPRINT
            95/01/20 11.22          DDN   3.00

 PARTNO NO TITLE
 MULTAX/ON
 UNITS/MM
 INTOL/0.127000
 OUTTOL/0.127000
 FEDRAT/254.0000
 GOTO/-25.7230,91.3758,134.3503,0.6510,-0.0092,0.7590
 GOTO/-33.3447,82.8054,133.9319,0.5461,-0.0131,0.8376
 GOTO/-39.9296,74.3811,133.5638,0.4125,-0.0237,0.9107
 GOTO/-44.1886,68.1505,133.3414,0.2958,-0.0364,0.9546
 GOTO/-47.8738,61.9871,133.1822,0.1707,-0.0528,0.9839
 GOTO/-50.9984,55.8834,133.0974,0.0445,-0.0722,0.9964
 GOTO/-53.5742,49.8341,133.0926,-0.0753,-0.0935,0.9928
```

Since Deckel controller (Grundic 200) requires G-Codes, this cutter location data (CLTAPE files) are translated to G- Codes, by the use of a generic postprocessor (camgener). As such a postprocessor was not available for 5- axis machining using Camquest facilities a postprocessor is prepared.

The output of the ICEM NC function, cltape files must be converted to binary format by the use of a cutter translator code (ICEMCLT), before they are fed to 5- axis postprocessor (kerem101). The Postprocessed files (clfile.tap) are then transferred to the PC of the milling machine. At this node a software "happycam" manages the communication with the control unit of the machine tool.

4.2 Construction

4.2.1 Materials

Common materials used for pump impellers are cast iron, bronze and brass. Because of the production method some kind of fastening of two parts is required. First brass is considered but soldering would complicate the design of the shroud. Then plastic and composite materials are searched which are suitable for adhesive bonding. Polyamide and Delrin was available, the former is cheaper with satisfactory strength.

Some of the mechanical properties of Polyamide (Nylon) from [20] are:

Tensile Strength = 50 N/mm^2

Modulus of Elasticity = 2000 N/mm^2

Density = 1100 kg / m^3

4.2.2 Mechanical Design

A criterion for margin of safety against bursting [21], considering the plastic yielding which tends to equalize the stress intensity along the diametral plane, for a pierced disk is:

$$\sigma_a = \frac{\delta \omega^2 (R^3 - R_0^3)}{3g(R - R_0)} \tag{4.1}$$

Tests [21] have shown that rupture occurs when σ_a = Ultimate tensile strength of the material. On the other hand some materials fail at %60 lower values.

For impeller D maximum stress, σ_a = 355 k Pa, occurs along the perimeter of the hole and leads a factor of safety of four.

Since hub is made from a soft material bearing stress acting due to key way must be checked. Total shearing force F = T / R. The minimum factor of safety considering the shear and bearing stresses at top, bottom and sides comes out to be 1.1.

4.2.3 Adhesive Bonding

Strength of adhesive application depends on :

- Bond surface area
- Distance between two surfaces
- Surface cleaning

Epoxy is the selected adhesive type for polyamide. Tensile shear strengths are above 41.4 MPa for nylon- epoxy applications. [20] Other adhesive types that can be used with polyamide are Polyesters, Phenol- and Resorcinol-formaldehyde.

For nylon and epoxies a recommended surface preparation is solvent- wiping with acetone, abrading with emery paper and repeating the solvent- wipe.

4.3 5- axis Machining

Consider the part in Figure 4.1, where a three axis is needed to machine the top arbitrary surface, however to drill the 18° hole, one must tilt the table, B- axis, 18° upwards. But after tilting the tool cannot be forwarded to the exact drilling position. The registers x, y, and z are still relative to the initial coordinate system, tool moves as if the table is not tilted.

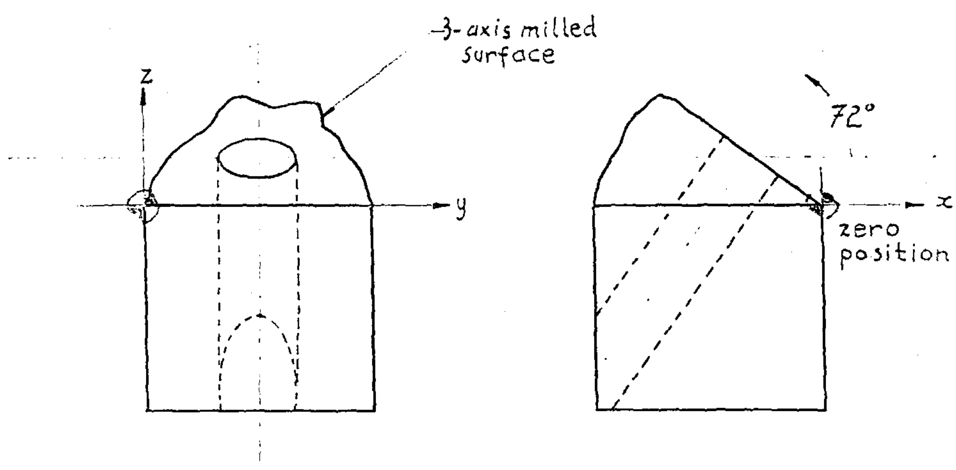


Figure 4.1 Arbitrary Surface and Hole

Below are two consecutive five- axis NC blocks

N180 X-52.985 Y100.341 Z218.456 B-22.892 C-65.649

N185 X-51.412 Y107.398 Z221.751 B-24.067 C-65.953

From the coordinates given at block N180 tool is moved to the set values at block N185, by linear interpolation.

Unlike five- axis machining, in three- axis machining the origin of coordinate system can be taken at any place on the table, that is to say you can fix the part wherever you like.

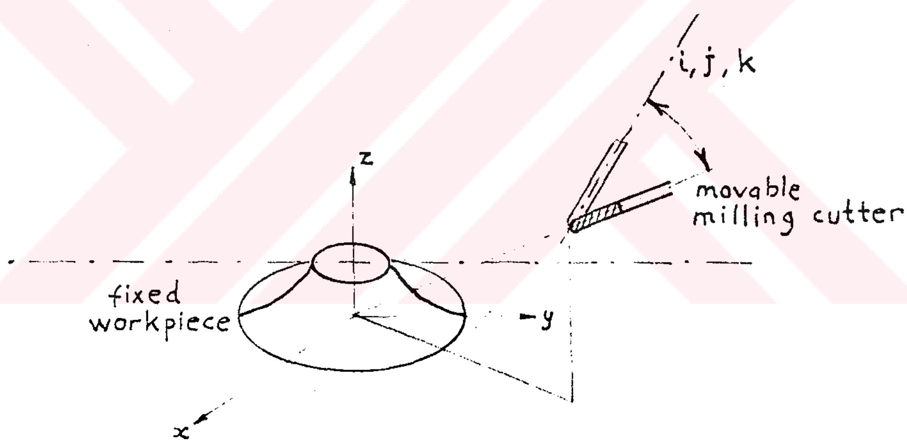


Figure 4.2 Tool and Workpiece Movements in ICEM

ICEM 's multi axis option produces data relative to a fixed part. Figure 4.2 In the form; x^{ic}, y^{ic}, z^{ic}, i, j, k. i, j, k are the components of unit normal vector in the tool direction and x^{ic}, y^{ic}, z^{ic} are the co-ordinates of tool tip. This cutter location data must be transformed to machine co-ordinates and table registers B and C. Milling machine used has a fixed head but tables are turning. Register B is for table tilting. It is in the range -45° to 15°. C is the rotary table register it can take any value including negatives to 9999°.

4.3.1 Geometry of 5- axis Machining:

Figure 4.3 shows linear interpolation in five- axis between the two points P1 and P2.

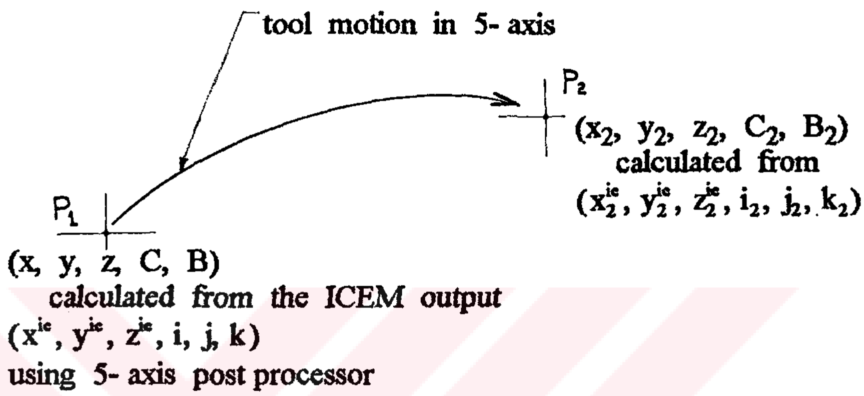


Figure 4.3 Linear Interpolation in Five Axis

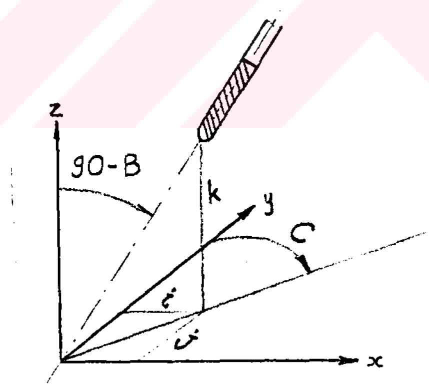


Figure 4.4 a Tool Orientation

Since B is the tilt of table, 90 - B represents inclination of tool with respect to workpiece. Starting point of following formulation is $x^{ic}, y^{ic}, z^{ic}, i, j, k$. x^{ic}, y^{ic}, z^{ic} are co-ordinates from ICEM.

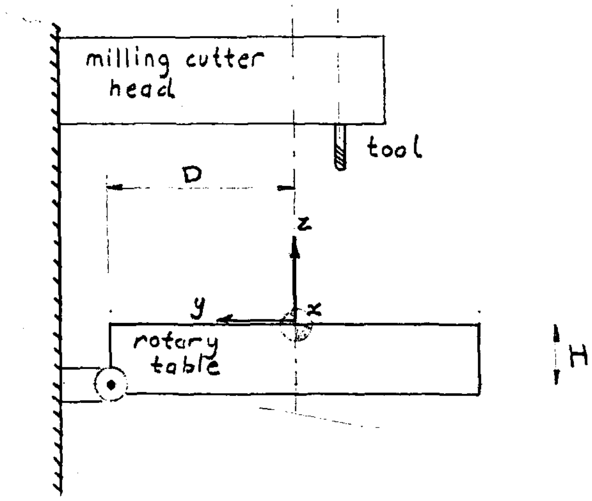


Figure 4.4 b Table Zero Position

The zero position for x, y, and z is set as the center of the rotary table. Also rotary table C, and tilt table B are set to zero in this configuration. Figure 4.4 b

First the tool is oriented by the rotation of C and tilt B.

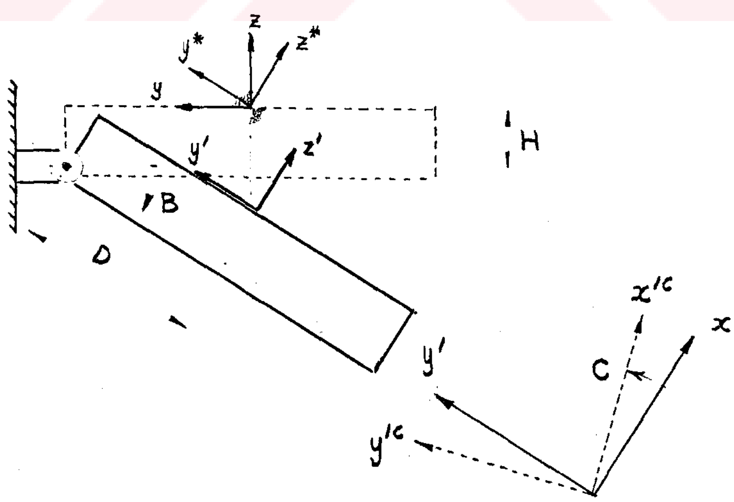


Figure 4.4 c

$$B = 90 \quad - \arctan\left(\frac{k}{\sqrt{(i^2 + j^2)}}\right) \tag{4.2}$$

$$C = (\pm 90) \mp \left(\arctan\frac{i}{j}\right), \text{ depending on the sign of i and j} \tag{4.3}$$

$$\begin{aligned} x^i &= \cos C\, x^{ic} - \sin C\, y^{ic} \\ y^i &= \sin C\, x^{ic} + \cos C\, y^{ic} \\ z^i &= z^{ic} \end{aligned} \tag{4.4}$$

$$\begin{aligned} x^* &= x^i \\ y^* &= y^i - D(1 - \cos B) - H \sin B \\ z^* &= (z^i + H) - D \sin B - H \cos B \end{aligned} \tag{4.5}$$

and

$$\begin{aligned} x &= x^* \\ y &= y^* \cos B - z^* \sin B \\ z &= y^* \sin B + z^* \cos B \end{aligned} \tag{4.6}$$

D = 239.925 mm and H = 169.960 for the Deckel FP5cc/T milling machine.

$$\begin{aligned} x &= f_1(x^{ic}, y^{ic}, z^{ic}, C, B) \\ y &= f_2(x^{ic}, y^{ic}, z^{ic}, C, B) \\ z &= f_3(x^{ic}, y^{ic}, z^{ic}, C, B) \end{aligned} \tag{4.7}$$

x, y, z are the values to be used in G- Codes.

From these equations it is obvious that the part to be milled must be mounted to the center of the table. Moreover the cutter location data, which is the output of ICEM NC should be generated according to these axis.

To be accurate, after the workpiece is mounted to the table, the distance to the table centre is measured and cutter location files are generated relative to that value.

The tilt table, axes A, is limited to the range +15 to -45 degrees, however tool inclination -45 to +45 can also be realized by rotating the workpiece, but naturally x, y, and z must be calculated for new C and A axes.

$$C_{new} = C + 180$$

$$B_{new} = -B$$

That is to say for a given tool axis orientation there are two sets of B and C values. The designer chooses one of them according to:

- Machine limitations, one must also calculate x, y, and z registers, for example head can not reach to y register.
- Tool angles at the previous NC Block. Since both registers should change continuously.

Another point is that, while reaching to the start point of machining, first the tables should be positioned and then the tool should approach.

4.3.2 Post processors

The cutter location files, which are the co-ordinates of tool nose x^{ic}, y^{ic}, z^{ic} and tool orientation i, j, k, should be converted to G- Codes applying the ideas in the previous section. For this task, in this thesis a generic postprocessor is used. Generic postprocessors are tools to write postprocessors for any NC machine tool. Ranging from turning centers to electro discharge machines. In parallel for three axis milling applications, the postprocessor "taksan03" is being used. For machining front shroud this processor is applied. To write a post processor both the process and specifications of machine tool should be known.

The name of Generic postprocessor software is ICAM. It consists of two parts, "Quest" and "Gener". Using quest questions about machine tool are answered. The short versions of these questions are presented in Appendix C for postprocessor "kerem101". After "quest" PDF files are generated. These files are required when running "gener", to create the production version of the postprocessor (called PP). The Disk facility is used to Print PDF files or they can be viewed by vi editor.

After the PP files are ready, the postprocessor can be used to translate CL files. First file to be processed should be entered, the extension of this file is cld., like clfile.cld. Then the post processor name is asked, this can be taksan03 or kerem101 for milling. The output of the postprocessor is a list file, clfile.lst, which contains information about machining and diagnostics. Hard copy of "clfile.lst" for 5- axis machining is presented in appendix D. The other output "clfile.tap" that contains G- codes is forwarded to the control system of the machine tool. The size of this file should be less than 320 kBytes, if uninterrupted machining is required. The size of tap files for the machining of a single blade is in the order of 180 kBytes.

Table positive directions and table offset dimensions are shown in the Figure 4.5.

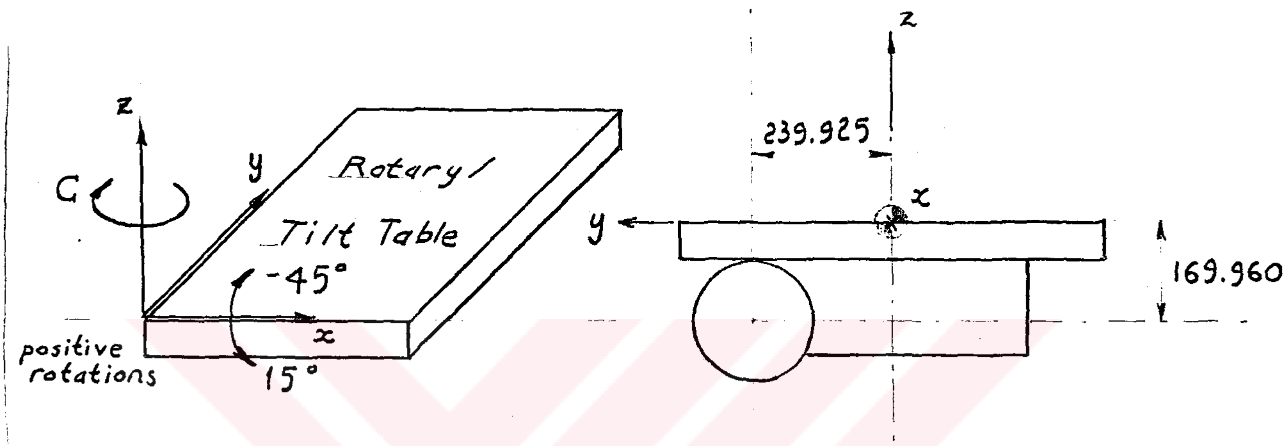


Figure 4.5 Table Offsets and Positive Directions

4.3.3 First Trials for 5- axis Machining

To check the created postprocessor, first known tool orientations are inputted and the values C and B axes are compared with the desired. However to verify x, y, and z registers a test production is required. For this a ruled surface is created in ICEM, using five axis swarf milling utility.

Two test cuts are made, the tap files for each run are included in Appendix D. The surface machining tolerances in the second run is increased up to the limit permitted by ICEM, so that the uncontinuity in the C- axis register between blocks N 35. and N 40 is reduced, and a satisfactory 5- axis machining is performed. Another remedy for this discontinuity is to separate the surfaces into pieces, then there will be no discontinuity between blocks. The result of this high change in C- axis can be performed in the demo workpiece.

The tolerances in the two trials are:

	CUT 1	CUT 2
Ruff intol	0.02	0.0089
Ruff outol	0.02	0.0010
Fin intol	0.003	0.0001
Fin outol	0.003	0.0001
Surf tol	0.02	0.0089
Angle Difference	≈ 50°	≈ 19°

4.4 Process Planning

The specifications of the milling machine are presented in Appendix E. During the whole processes ball- end milling cutters with right hand cut, helix angle 20°, two flutes, straight shank and tolerance of cutting radius is $R \pm 0.02\,mm$ are used with diameters 12 mm, 6 mm, and 4 mm. Figure 4.6

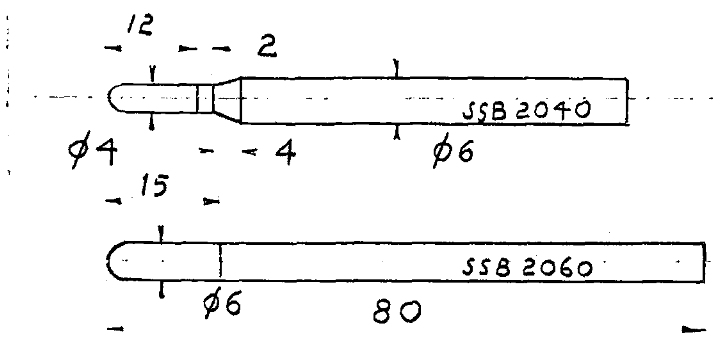


Figure 4.6 Milling Cutters

In the simulation, tool holder must also be considered. 19 - 15 mm holder length is enough for both 4 and 6 mm diameter tools.

Recommended cutting parameters:

D4	3200 rpm	14 mm/min feed
D6	2100 rpm	160 mm/min

The drawings of starting unmachined workpieces are presented in Appendix F. The workpiece is mounted at the centre of the table using a turret wise Figure 4.7. In this figure initial three- axis machined surfaces are indicated.

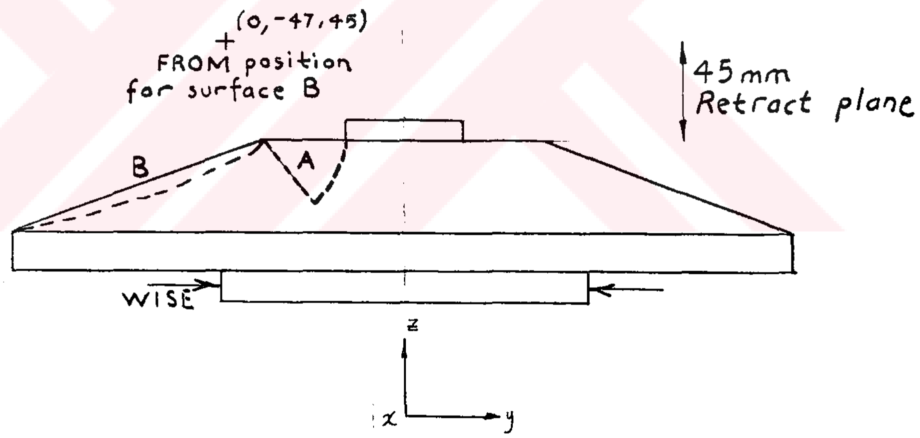


Figure 4.7 Three- Axis Machined Surfaces

Pressure and suction surfaces are separated into parts , not to interfere tool with other blades or hub. First the suction surface of the blade is machined, then the tool is moved to mill the pressure surface of the mirror blade (180^{0} apart). Because the tilting angle is -45^{0}, it is not possible to machine the same blade. While milling the pressure and suction surfaces, the adjacent vaneless space is also machined. After this cycle is finished the workpiece is rotated to machine other second surfaces. As there are six blades in impeller D this cycle is repeated six times using the following G- Codes.

```
N10 ........
 :
 :
N400 G0 C0
N410 C60 G54 C0
N420 L5 N10 N410
N430 G0 Z100 M30
```

G54 : Set actual position

L : Program repetition command

Impeller S required straightforward 3- axis machining. For this reason the cutting time is reduced considerably. Blades are defined as containment curves, first a rough pass is made to empty the vaneless space, and then using the 4 mm diameter tool finish cut is accomplished

CHAPTER V

PERFORMANCE EVALUATION

5.1 Pump Tests

Pump test procedures and rules are described in detail in standards DIN 1944 and API 610. These tests can be classified depending on the application as

- Acceptance tests, between pump marker and purchaser
- Periodical field tests
- Model tests

In the standards three quality classes are defined as precision, engineering grade 1, and engineering grade 2. For medium outputs (0.5 - 10 MW) as it is the case for both **Impellers** S and D, engineering grade 1 is suitable [22].

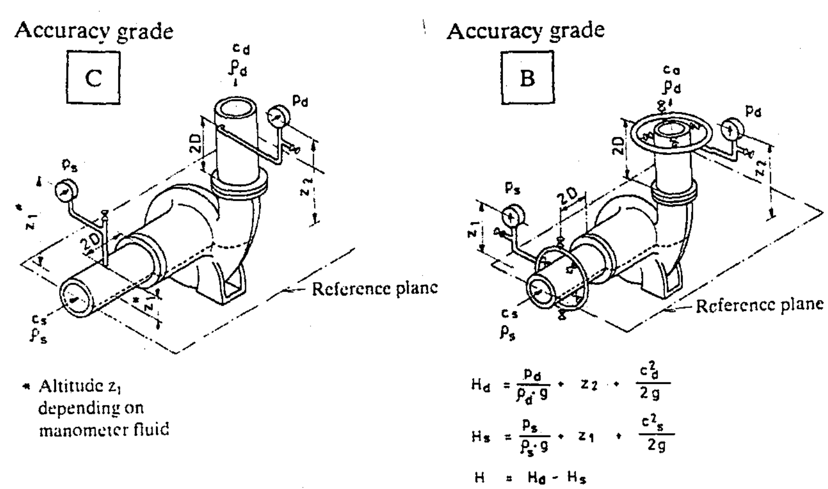


Figure 5.1 Measuring Rig For Determining The Pressure Head [22]

According to ISO standard admissible total uncertainty for measuring instruments for middle accuracy grade (grade 1) are:

Flowrate	2 %
Head	1.5 %
Power	1.5 %
Efficiency	2.8 %
Speed	0.5 %
Inlet Pressure	3 %

5.2 Test Setup

The produced impellers are mounted to the pump test bench at Fluid Mechanics Laboratory of Mechanical Engineering Department of METU. The scetch of the set- up is presented in Figure 5.2.

For the casing of impellers (See Appendix H), the volute of a conventional centrifugal pump with identical impeller diameter is used. The finally assembled pump is driven using a 15 kW electric motor. Setling chamber of set- up was designed for large flowrates up to 500 m^3/ hr, thus the inlet flow disturbances are kept at minimum.

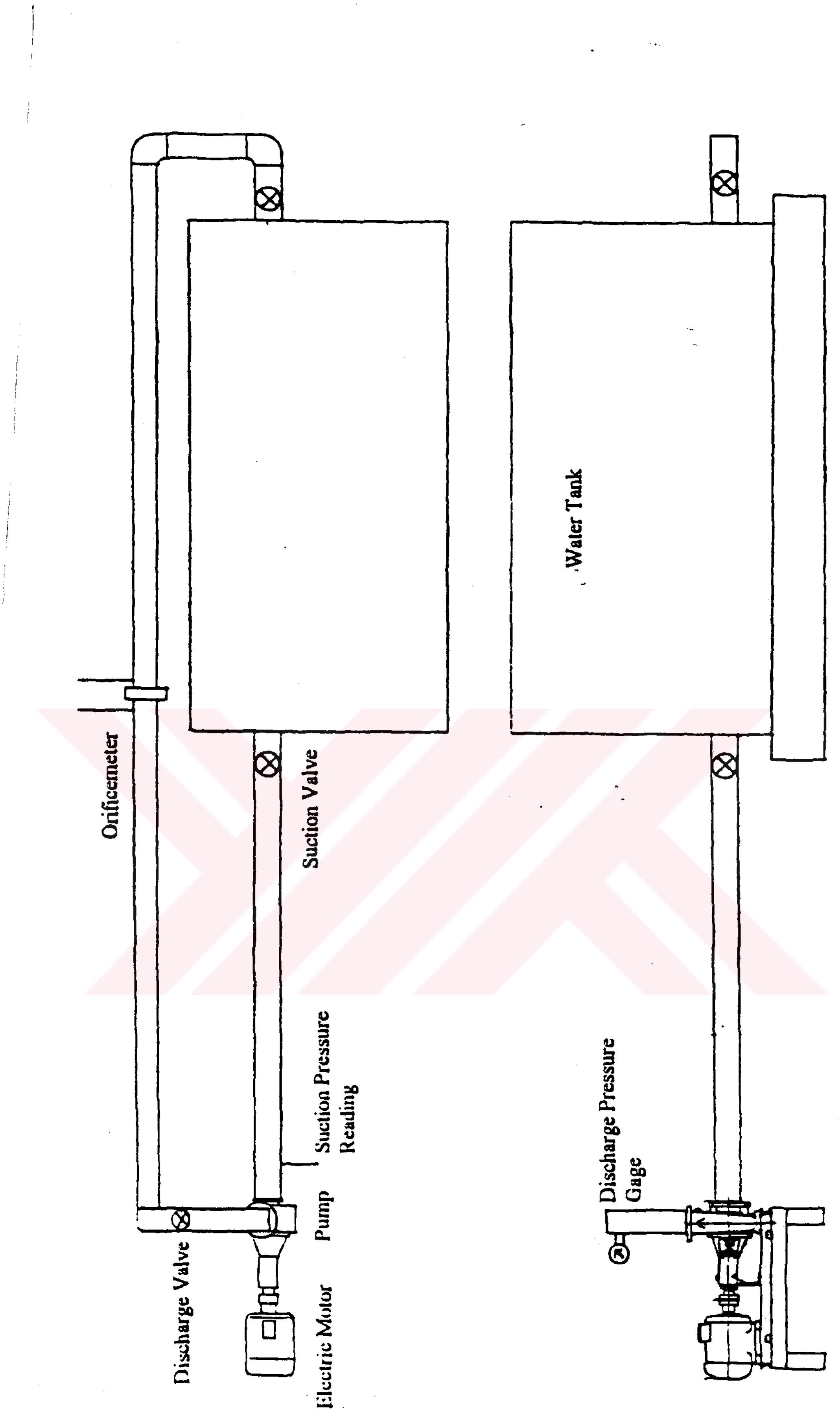


Figure 5.2 Experimental Setup

5.3 Instrumentation

5.3.1 Flow Measurement

An orificemeter is used to determine the flowrate, which is designed according to the British standards (BS 1042). The orificemeter constant which is given below, is also checked using a calibrated tank and a stopwatch. Besides four tappings around the pipe are used to give a good average pressure across the cross section.

5.3.2 Head Measurement

Discharge pressure is measured using a calibrated Bourdon gage.

For the suction, U- tube manometer is used to measure the inlet pressure. The tapping location depends on the nature of the pump inlet, and determined according to the values given in standards.

To measure a realistic static pressure at pumps with axial inlet it is also required to take care of the prerotation build up by the impeller during low flowrates.

5.3.3 Power Measurement

Power at motor terminals is measured using a wattmeter. It is connected to a single phase but, power change at other phases are also checked. The power required by the pump can be found by multiplying the power used by the pump and driving system with the efficiency of the driving unit.

$$P_1 = P_N/\eta \tag{5.1}$$

5.3.4 Rotational Speed

During the experiment the shaft speed is measured using a stroboflash

5.4 Test Results

The model impellers are tested. The test data and results are tabulated in Appendix J The performance parameters of the impelles are calculaded using the following equations.

$$P_{gage\,calib} = 1.03226\,P_{gage} + 0.226 \quad \text{bar} \tag{5.2}$$

$$P_{disch\,arg\,e}\,(P_d) = P_{gage\,calib}\,103 \quad \text{kPa} \tag{5.3}$$

$$P_{suction}\,(P_s) = -13.6\ 9.81\left(h_s - h_{initial}\right)/100 \quad \text{kPa} \tag{5.4}$$

$$Q = 0.000672\sqrt{\Delta h_{oriffice}} \quad m^3/s \tag{5.5}$$

$$v_i = Q/A_i \quad m/s \tag{5.6}$$

$$v_e = Q/A_e \quad m/s \tag{5.7}$$

$$H_i = \frac{P_s}{9.81} + \frac{v_i^2}{2\ 9.81} + Z_{in} \quad m \tag{5.8}$$

$$H_o = \frac{P_d}{9.81} + \frac{v_e^2}{2\ 9.81} + Z_o \quad m \tag{5.9}$$

$$\text{Pump Head} = H_o - H_i \tag{5.10}$$

$$P_{fluid} = 9.81\,(\text{Pump Head})\,Q \quad kW \tag{5.10}$$

$$P_{shaft} = \left(P_{wattmeter}\ \text{Power factor}\right)\eta_{motor} \tag{5.11}$$

$$\eta_{overall} = \frac{P_{fluid}}{P_{shaft}} \tag{5.12}$$

The measured results, Q, H, P determined at shaft speed, N that is not the same with the design speed, N_d are converted to the corresponding values at design speed, (parameters with index u) using the following equations.

$$Q_u = Q(N_d / N) \tag{5.13}$$

$$H_u = H(N_d / N)^2 \tag{5.14}$$

$$P_u = P(N_d / N)^3 \tag{5.15}$$

CHAPTER VI

DISCUSSIONS CONCLUSIONS and RECOMMENDATIONS FOR FUTURE WORK

The main purpose of this thesis is to apply modern manufacturing methods to fluid machinery. A centrifugal pump impeller is selected since it covers other turbomachine geometry with relatively cheap and simple test set up and procedures. In parallel the experience gained in this study can be applied to other turbomachines, such as radial turbines or compressors. The current design methods are reviewed and the one that is developed in Mechanical Engineering Department of METU is selected. Since this computer aided design code has not been completely tested. To force the production limits of CAD/CAM Center, this code is runned several times to have a 3D blade geometry that worths 5-axis CNC milling.

Finally two prototype pumps are produced with specific speeds 0.499 and 0.392. Their design flow rates are kept fixed with pump head varying (40 m and 29 m for impellers S and D respectively). Even this variation in specific speed changed the geometry considerably.

The crucial parameter in pump design is efficiency, even one or two point increase results in high energy savings. The test results showed that the design procedure is satisfactory. For both pumps the efficiency value that is predicted by CPID code is attained. Moreover other characteristic values such as head and flow rate are higher than expected. It must be noted that for both pumps the peak efficiency is reached at the design flowrate.

Impeller D

Design	Test Results
Head 29 m	34 m
Flowrate 0.0139 m^3/s	0.014 m^3/s
Power 6.27 kW	8 kW
Efficiency 0.63	0.62

Impeller S

Design	Test Results
Head 40 m	48 m
Flowrate 0.0139 m^3/s	0.014 m^3/s
Power 8.65 kW	13 kW
Efficiency 0.63	0.56

Impeller S can be compared with the pump produced by Standart Pompa which is a double curvature bladed impeller. The test results of this pump are presented by Bilgen[23].

Impeller produced by Standart Pompa

Test Results

Head 58 m

Flowrate 0.0105 m^3/s

Efficiency 0.55

However the geometry of the surfaces of impeller S is simpler than the Standart pump.

A larger diameter volute is used for impeller D during testing. This is one of the reasons for obtaining a lower efficiency than that of impeller S. Besides for the impeller D the angle between blade and shroud ought to be smaller than 90^{o}.

The radius of the tool changes the actual design geometry considerably. As the tool radius decreases, the blockage of the flow is also decreased. However the surface quality also decreases, due to this fact during milling operation tool changes are required. Milling cutter marks left on the surface after the finish cut, which is preferred to be parallel to the blades.

Machining time mainly depends on the diameter and number of blades. Five- axis interpolation between two NC blocks took longer than three-axis interpolation. Machining of Impellers took 22 hours for impeller D and 42 hours for impeller S. These times will be much lower if a CNC Lathe is used to machine shroud surfaces.

The ability of CAD design environment such ICEM to color model surfaces differently and display of surface nets helps the designer in visualization of the surface, moreover the environment supplies the tools to identify the problems in shape, blend areas, analysis and surface modeling in an economic way. Production of impellers by milling is not economically superior for conventional pumps that are cast, but the patterns can be produced accurately and cheap, with an easy trial and error work

Since accurate and identical blade passages can be obtained by CNC milling, hydraulically balanced impellers can be produced by cutting the blades, this provides higher rotational speeds. For impellers produced in low quantities, generally the diameter is large for such pumps, milling is more economical than casting.

Impeller material polyamide was not worked well, mainly in finishing operations, also during excessive clamping the workpieces were deformed. Other materials should be tried such as brass bronze or their derivatives. If adhesive bonding is still preferable, then high strength plastics such as Delrin can be applied.

This thesis is a natural step in the continuing pump research in the Fluid Mechanics Laboratory of the Mechanical Engineering Department of METU which was initiated by the works of Hancıoğlu [19] and Talayhan [16]. In order to refine the pump design and CAM procedures the followings are recommended.

- CAM of other components such as volute and inlet can also be studied.

- The cavitation characteristics of the produced pumps can be investigated, since cavitation is a limit in the useful operation range of the pump.

- Since the method followed in this thesis is very suitable for trial and error work, design modifications on any component can be realized and tested very efficiently.

- The produced impellers can be compared with the similar pumps of various manufacturers.

- Transparent impellers or other components can be produced for the flow field determination, using the laser Doppler anemometer in the fluid mechanics laboratory.

- The traditional casting process of pumps, which requires hand finishing, experience and time even for approximate results, can be transferred to a CAM environment. This study is preferable if it is the joint effort of industry and University.

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APPENDICES

APPENDIX A

DESIGN REPORTS OF BOTH IMPELLERS

```
**************************************************************************
                               DESIGN  REPORT
**************************************************************************
Time    : 01:28:09                         Date of design    : 01-24-1995

Type of Impeller : Single Curvature Bladed Impeller

Specific speed        = 0.392

Number of stages      = 1
Head per stage        =  40.00   m
Capacity of the pump  = 0.0139   m^3/sec
Speed                 = 2800     rpm
Power required        =     8.65 kW

          ----------Efficiency Values----------

Volumetric efficiency = 0.980       Hydraulic efficiency   = 0.656
Mechanical efficiency = 0.980       Overall efficiency     = 0.630

          ----------Dimensional Parameters----------

Shaft diameter = 0.0204 m             Hub diameter = 0.0285 m

Inlet shroud diameter = 0.0770 m
Inlet blade diameter  = 0.0817 m      Outlet blade diameter = 0.2201 m
Inlet breadth         = 0.0179 m      Outlet breadth        = 0.0061 m
Inlet blade angle     = 22.70 ↑       Outlet blade angle    = 33.00 ↑
                                      Outlet absolute angle =  7.86 ↑

Number of blades = 7
Blade thickness  = 0.003 m

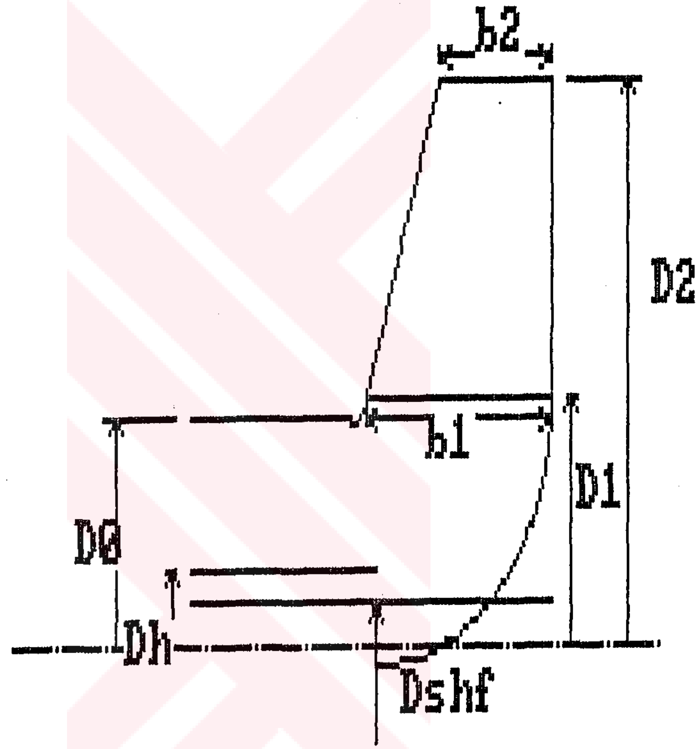
Angle of overlap       = 55.82 ↑

          ----------Cavitation Parameters----------

Suction specific speed = 2.834

NPSH                     =   2.86 m

**************************************************************************
CPI Output
**************************************************************************
```

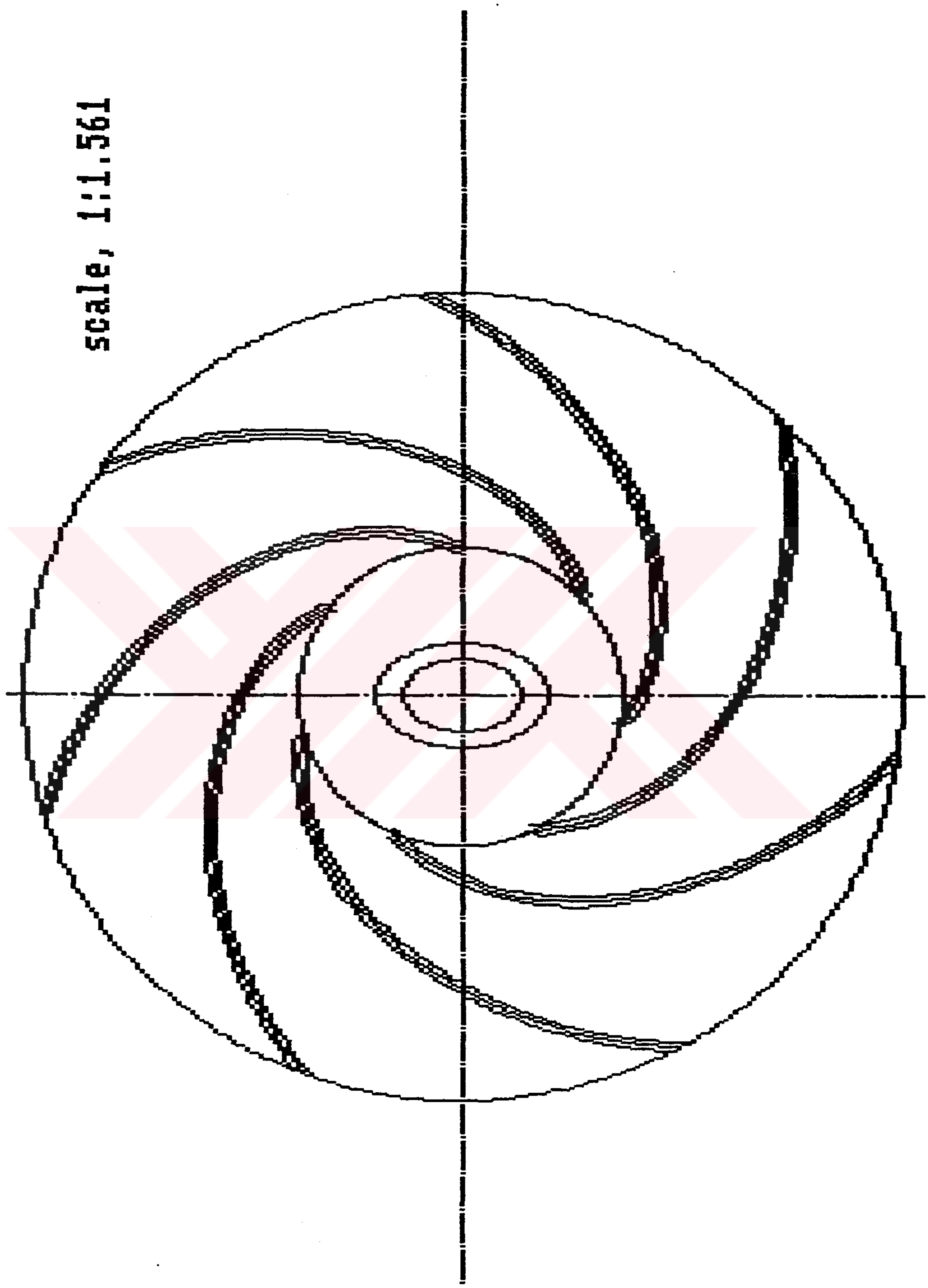


b1=0.018 m
D1=0.082 m

b2=0.006 m
D2=0.220 m

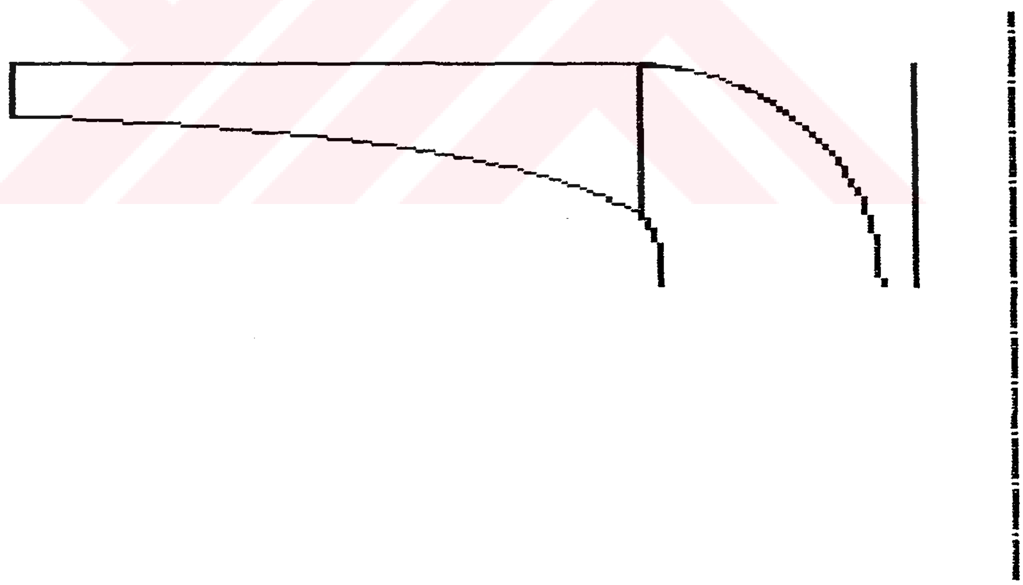
D0=0.077 m
Dh=0.029 m
Dshf=0.020 m

β1=22.70 °
β2=33.00 °


scale, 1:1.561

APPENDIX A

scale, 1:0.947



APPENDIX A

```
*****************************************************************************
                              DESIGN  REPORT
*****************************************************************************
Time    : 16:17:10                        Date of design    : 02-13-1994

Type of Impeller : Double Curvature Bladed Impeller
Specific speed        = 0.499

Number of stages      = 1
Head per stage        =  29.00  m
Capacity of the pump  = 0.0139  m^3/sec
Speed                 = 2800    rpm
Power required        =    6.27 kW

          ----------Efficiency Values----------

Volumetric efficiency = 0.980      Hydraulic efficiency   = 0.656
Mechanical efficiency = 0.980      Overall efficiency     = 0.630

          ----------Dimensional Parameters----------

Shaft diameter = 0.0183 m                 Hub diameter = 0.0256 m

Inlet shroud diameter    = 0.0836 m      Outlet blade diameter = 0.1877 m
Inlet blade hub diameter = 0.0538 m      Outlet breadth        = 0.0075 m

Inlet (hub) blade angle    = 30.47 ↑     Outlet blade angle    = 32.00 ↑
Inlet (shroud) blade angle = 20.73 ↑     Outlet absolute angle =  8.87 ↑

Number of blades = 6
Blade thickness  = 0.003 m

Angle of overlap = 49.57 ↑

          ----------Cavitation Parameters----------

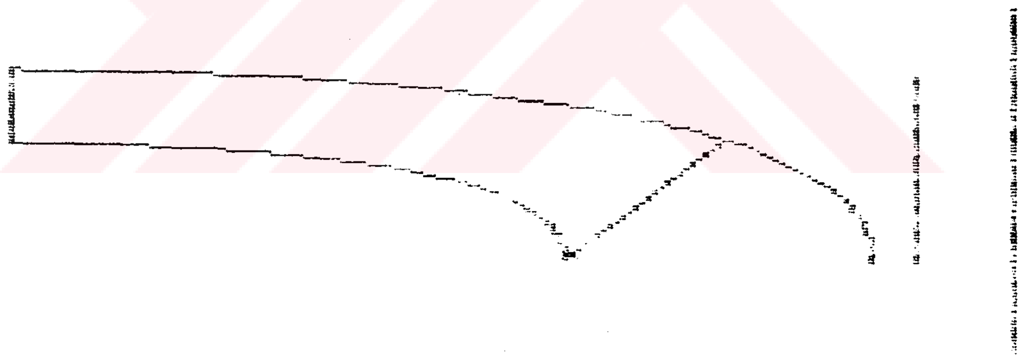
Suction specific speed = 2.872

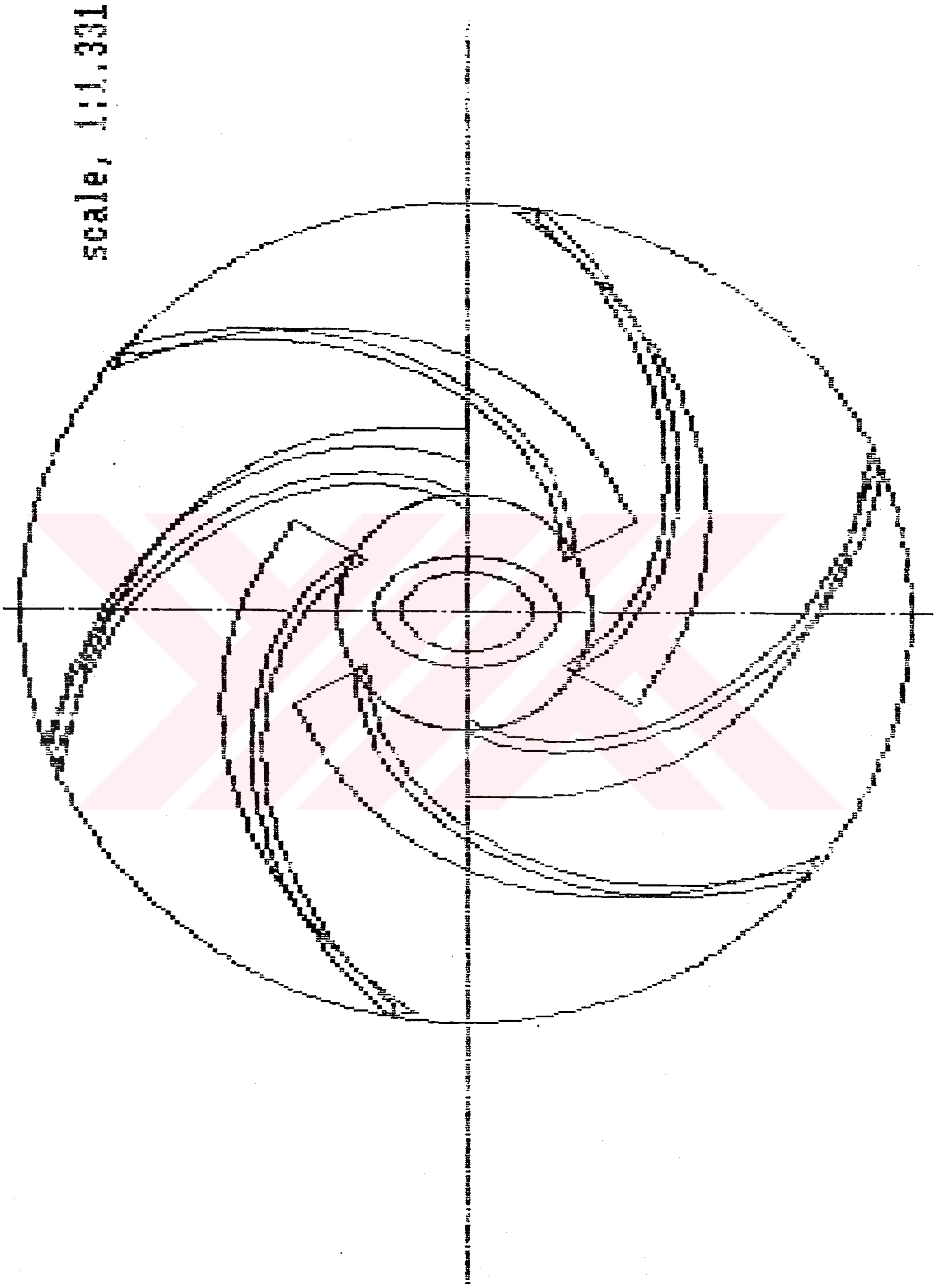
NPSH                   =   2.81 m

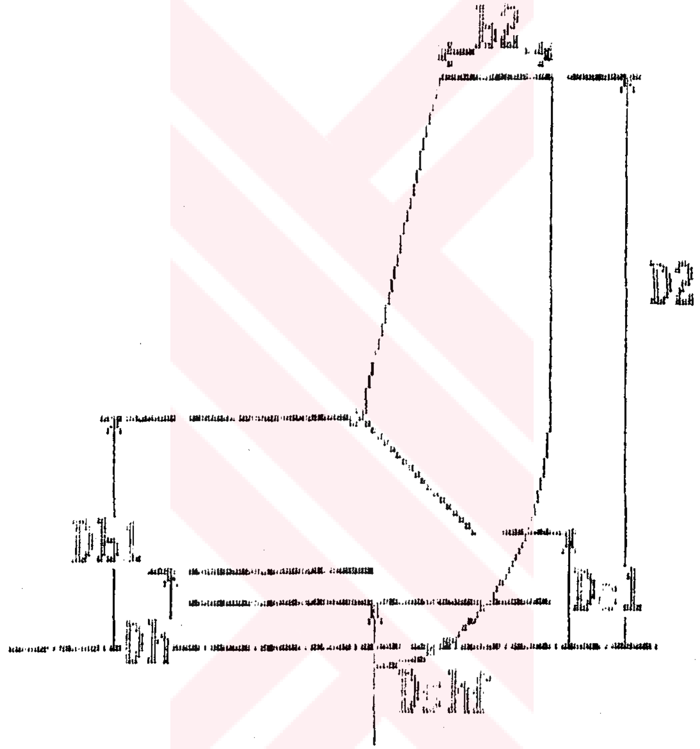
*****************************************************************************
CPI Output
*****************************************************************************
```

APPENDIX A

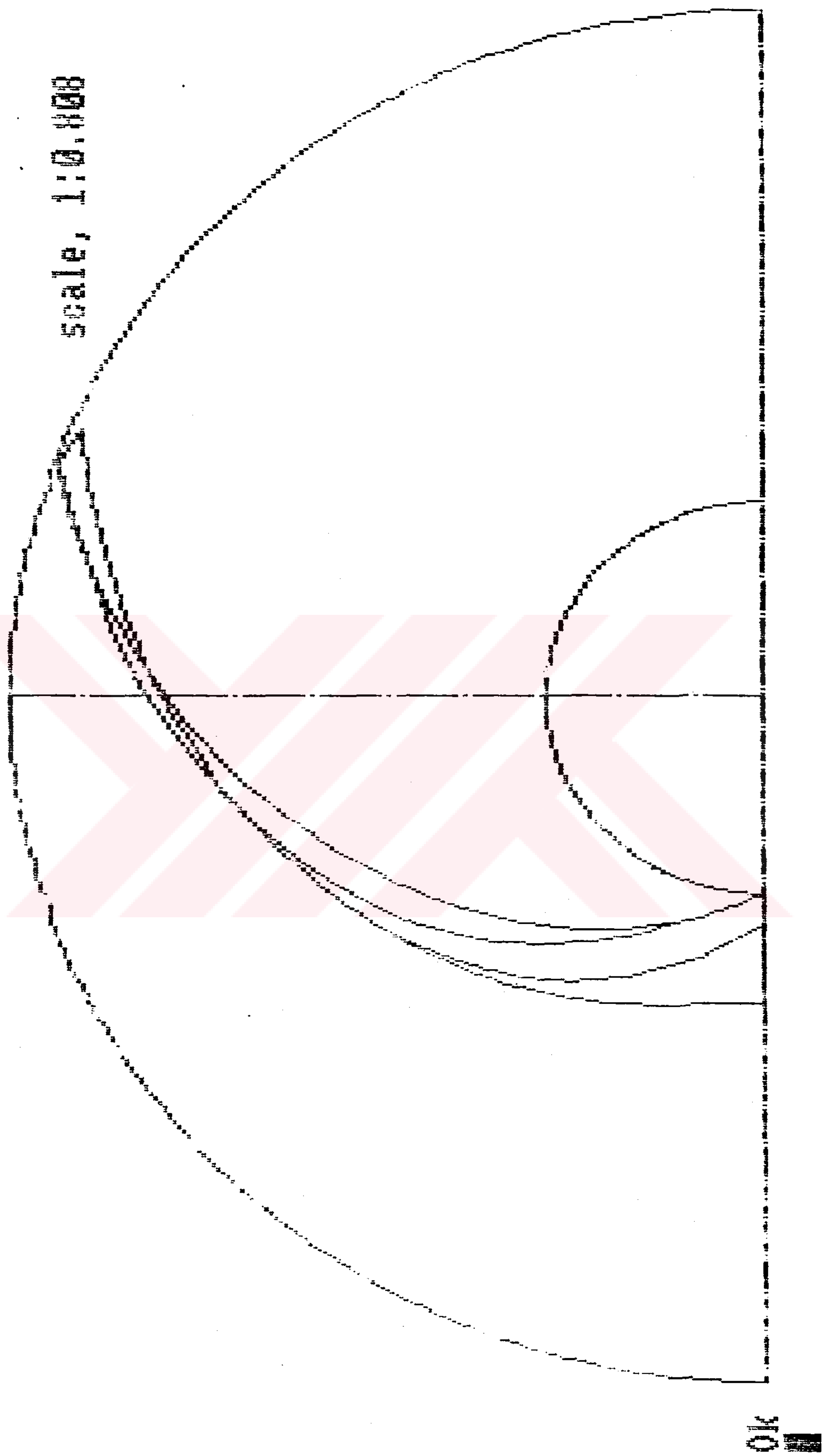
Scale, 1:0.808

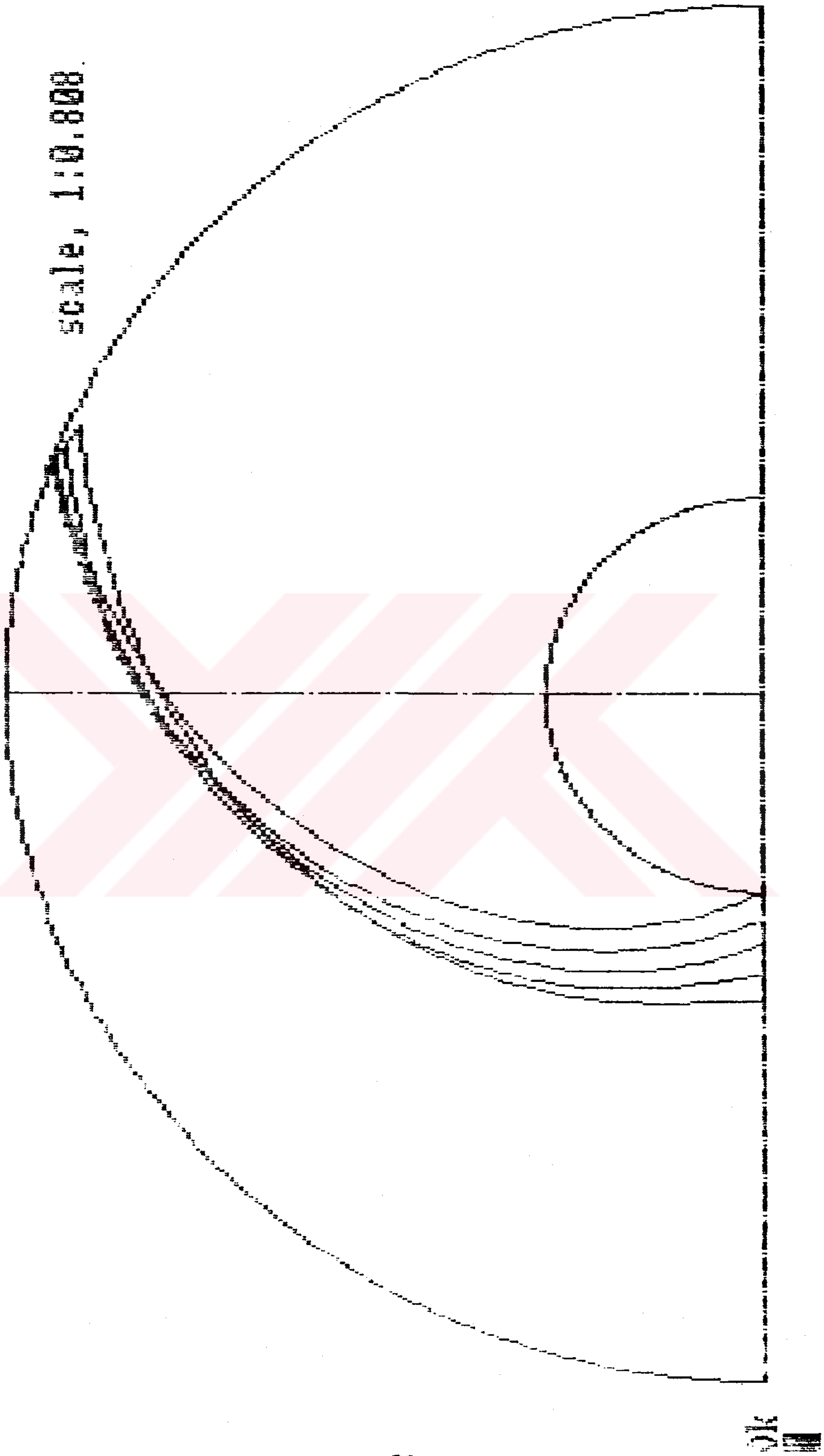



scale, 1:1.331

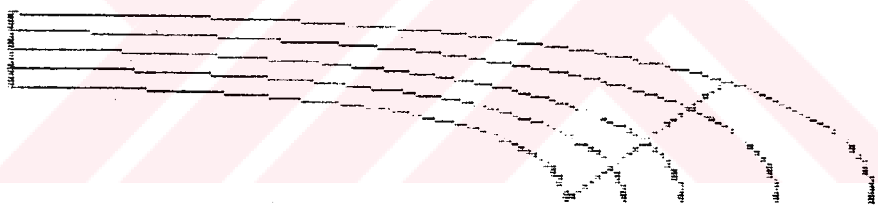


Db1=0.104 m	b2=0.008 m	Dh=0.026 m	βb1=20.73 °
Dc1=0.054 m	D2=0.138 m	Dshf=0.018 m	βc1=30.47 °
			β2= 32.00 °

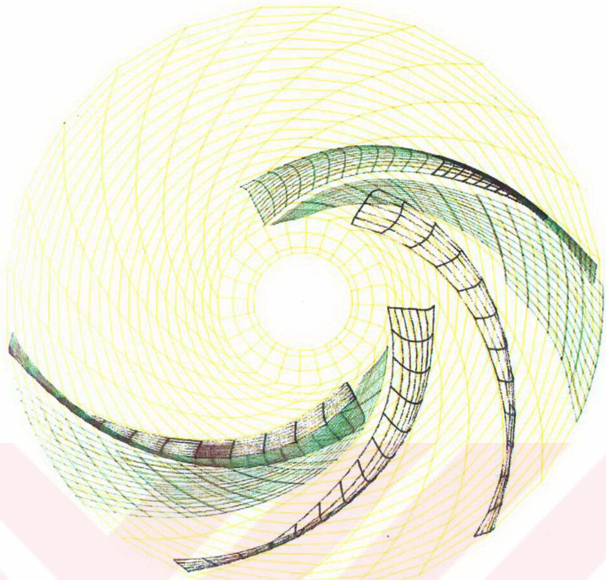

Scale, 1:0.008
Ok

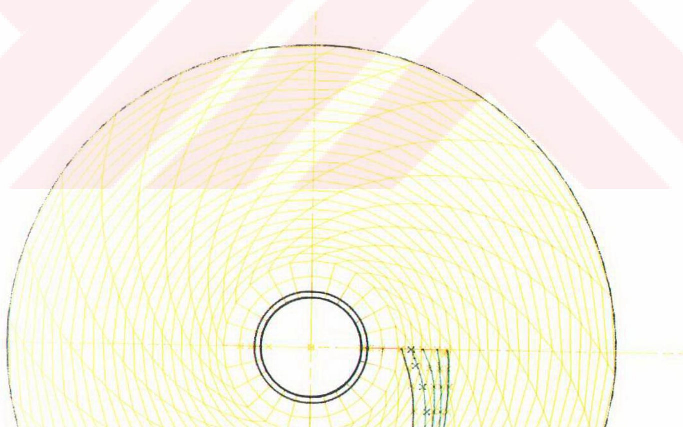

scale, 1:0.808

scale, 1:0.008




Scale, 1:0.000



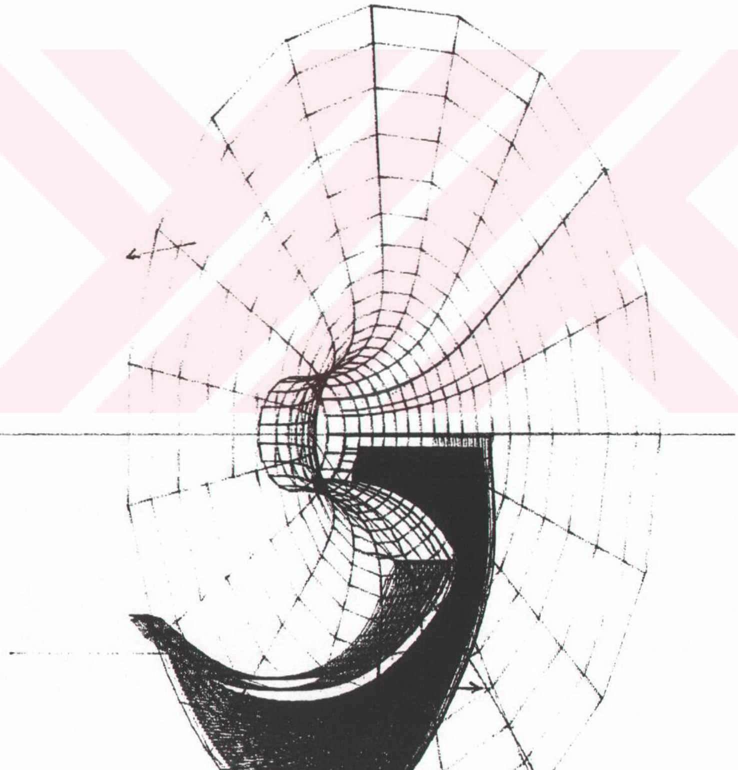


APPENDIX B

ICEM PLOTS OF PRODUCED PUMPS

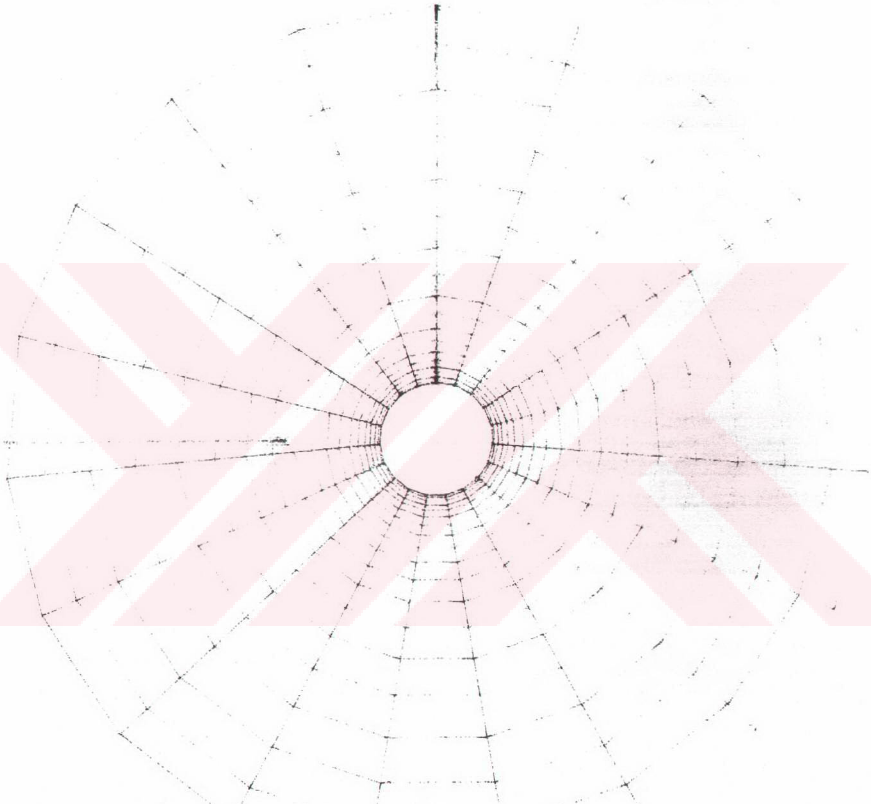
From Data Points to Toolpaths

Impeller S



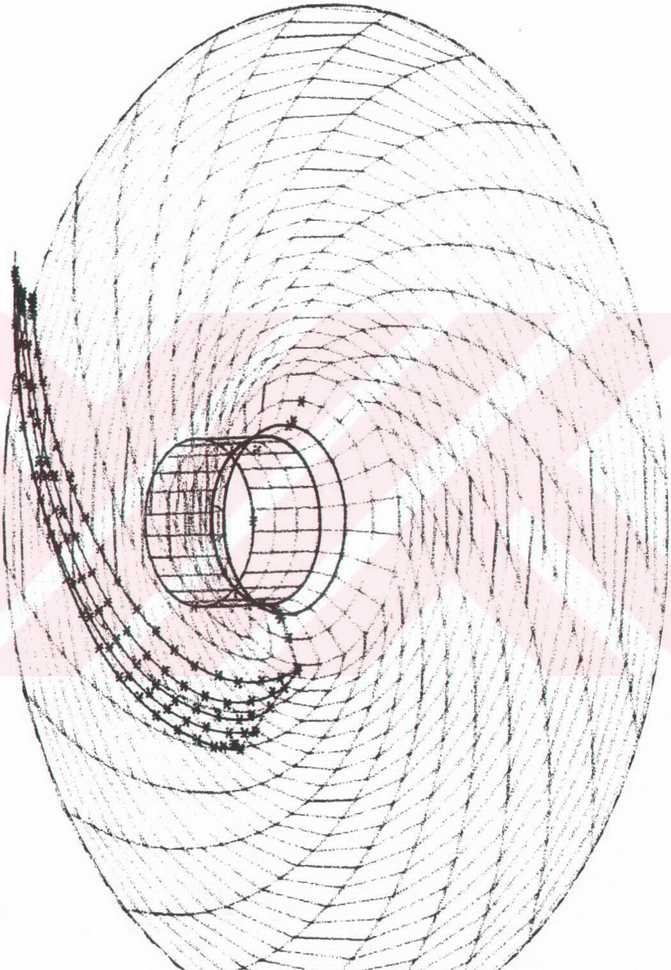
APPENDIX B

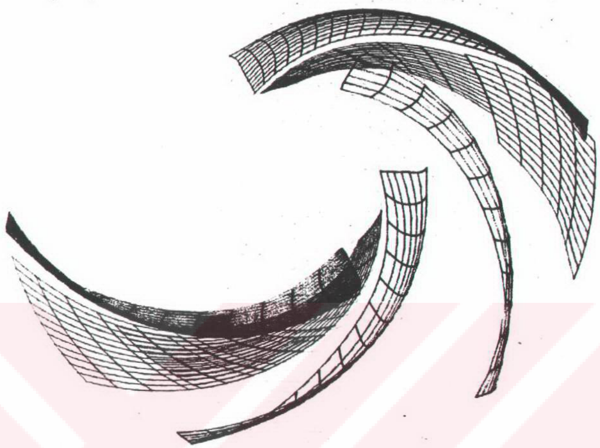
Impeller S

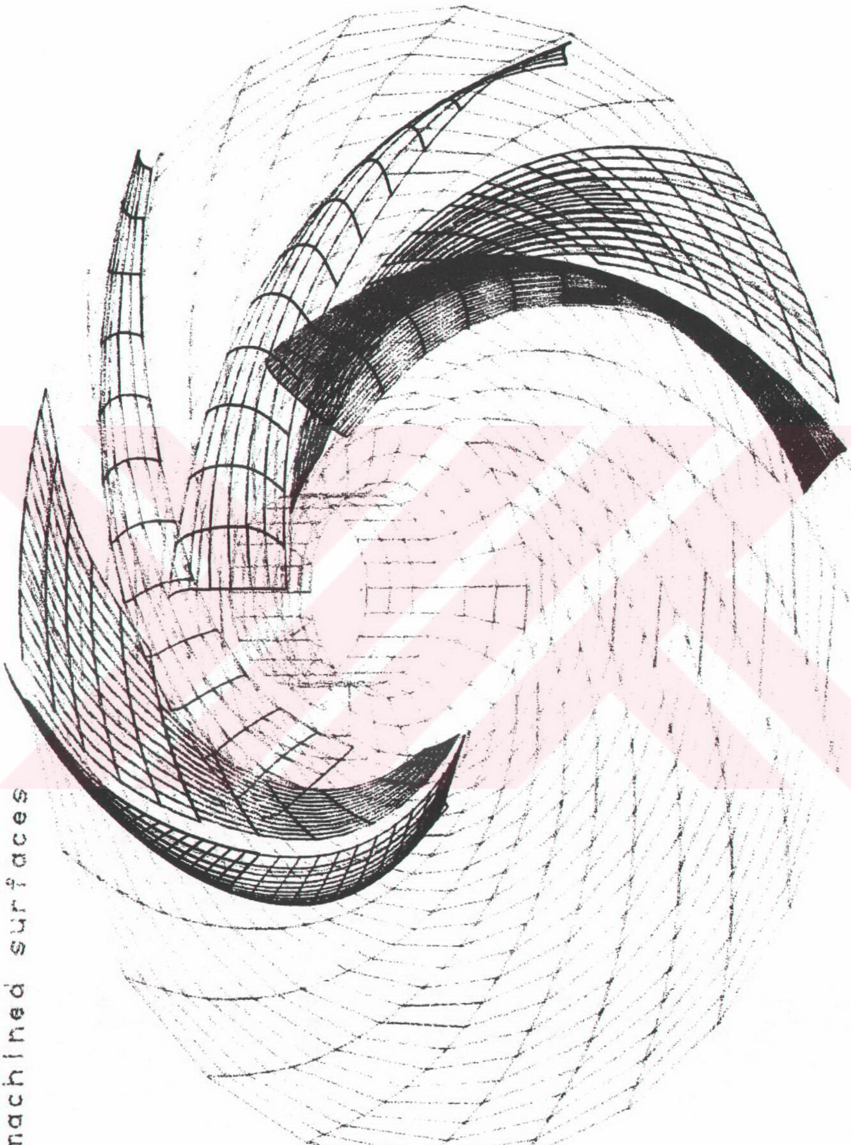


APPENDIX B

Impeller-D







machined surfaces

APPENDIX C

LIST FILE of FIVE- AXIS POSTPROCESSOR

POST-PROCESSOR KEREM1,1

General Description

General Information:

```
 1.00  Post-processor name: .......................................... KEREM1
 2.00  Post-processor I.D. number: [# GE 1 and LE 99] ...................... 1
 3.00  Machine type: [Edm,Lathe,Mill] .................................... Mill
40.00  Does the machine have a Z axis: [Yes,No] .......................... Yes
41.00  Does the machine have secondary linear axes: [Yes,No] .............. No
42.00  Does the machine have rotary tables: [Yes,No] ..................... Yes
42.10  Lowest rotary table axis: [A',B',C'] ............................... A'
42.20  Next rotary table axis: [B',C',NA] ................................. C'
42.30  Highest rotary table axis: [B',NA] ................................. NA
43.00  Does the machine have rotary heads: [Yes,No] ....................... No
60.00  Machine manufacturer: ............................................ deckel
61.00  Machine identification: ......................................... fp5cc/t
62.00  Control manufacturer: ........................................... grundig
63.00  Control identification: ........................................ dialog11
```

Display Format:

```
 1.00  Post-processor title: .......................................    kerem
 2.00  Modification level: [NA,value] ..................................... 1.
 3.11  Display X axis: [No,0-6] ........................................... No
 3.12  Display Y axis: [No,0-6] ........................................... No
 3.13  Display Z axis: [No,0-6] ........................................... No
 3.21  Display A' axis: [No,Yes,Signed] ................................... No
 3.23  Display C' axis: [No,Yes,Signed] ................................... No
 4.00  Display tool velocity: [No,0-6] .................................... No
 5.00  Display spindle speed: [No,Yes,Signed] ............................. No
 6.00  Display total elapsed time: [Yes,No] ............................... No
 7.00  Display CL record number: [Yes,No] ................................. No
 8.00  Display ISN: [Yes,No] .............................................. No
 9.10  Section time summary printed: [Yes,No] ............................. No
 9.20  Tooling summary printed: [Yes,No] .................................. No
10.20  Verification listing output in 80 columns: [Yes,No] ................ No
```

APPENDIX C

```
1ICAM Technologies          CAM-POST QUEST Version 10.0-008          3-Oct-1994 15:19
 (c) Copyright 1984                                                          Page 2
                              POST-PROCESSOR KEREM1,1

 Operation Mode:

    1.00  Post-processor units: [IN,FT,CM,MM,value] .......................... MM
    2.00  Control units code: [NA,G0-999,M0-999] ............................. NA
    3.00  Machine positioning: [Absolute,Incremental,Both] ............ Absolute
    6.00  Multiple planes: [Yes,No] ......................................... Yes
    6.01  XY-plane (G) code: [0-999] ........................................ 17
    6.02  ZX-plane (G) code: [0-999] ........................................ 18
    6.03  YZ-plane (G) code: [0-999] ........................................ 19
    6.04  Default plane: [NA,XY,ZX,YZ] ...................................... XY
    6.10  Multiple plane code alone on block: [Yes,No] ...................... No
1ICAM Technologies          CAM-POST QUEST Version 10.0-008          3-Oct-1994 15:19
 (c) Copyright 1984                                                          Page 3
                              POST-PROCESSOR KEREM1,1

                               Control Description


 G/M code assignments:

    1.00  (G) code register: ........................................... 2) Gs2
    1.10  Number of (G) codes per block: [# GE 1 and LE 9] ................... 1
    2.00  (M) code register: ........................................... 3) Ms2
    2.10  Number of (M) codes per block: [# GE 1 and LE 9] ................... 1


 Linear interpolation:

    1.00  Linear interpolation uses (G) code: [Yes,No] ..................... Yes
    4.00  Linear interpolation (G) code: [0-999] ............................. 1
    4.10  (G) code modal: [Yes,No] ......................................... Yes
    5.00  All axes feed together: [Yes,No] ................................. Yes


 High speed positioning:

    1.00  High speed positioning available: [Yes,No] ....................... Yes
    2.00  High speed positioning requires a (G) code: [Yes,No] ............. Yes
    2.10  High speed positioning (G) code: [0-999] ........................... 0
    2.20  (G) code modal: [Yes,No] ......................................... Yes
    3.00  High speed positioning also requires a feedrate code: [Yes,No] ..... No
    5.00  All axes rapid together: [Yes,No] ................................ Yes


 Circular and Helical interpolation:

    1.00  Circular interpolation method: [NA,Offset,Center,Radius] ....... Center
    2.10  CLW (G) code: [0-999] .............................................. 2
    2.20  CCLW (G) code: [0-999] ............................................. 3
    3.00  Direction codes modal: [Yes,No] .................................. Yes
    4.00  Multiple planes: [Yes,No] ........................................ Yes
```

```
 20.00  Controller uses two center registers: [Yes,No] .................... Yes
 21.00  PRIMARY center register: .................................... 4) Is3.3s
 22.00  SECONDARY center register: .................................. 5) Js3.3s
 24.00  Resolution of the circle center registers: [# GE 0.001] ......... 0.001
 25.00  Maximum offset value: [# GE 0.001] ............................ 999.999
 32.00  Maximum radius: [# GE 0.001] .................................. 999.999
 33.00  Maximum arc: [90-360,Quadrant] ............................... Quadrant
 40.00  Helical interpolation method: [NA,Axis,Signed,Unsigned] ............ NA
1ICAM Technologies        CAM-POST QUEST Version 10.0-008       3-Oct-1994 15:19
 (c) Copyright 1984                                                       Page 4
                         POST-PROCESSOR KEREM1,1

                           Machine Description

Linear axes:

101.00  X-axis register: ............................................ 6) Xs3.3s
102.00  Resolution: [# GE 0.001 and LT 999.999] ......................... 0.001
103.00  Maximum stored value: [# GE 0.002 and LE 999.999] ............. 999.999
104.00  X-axis sign convention: [Reverse,Normal] ....................... Normal
105.00  X-axis travel check: [No,Range,Total] .............................. No
108.00  Maximum X-axis feedrate: [# GT 0.] ............................... 6000.
109.00  Rapid X-axis positioning speed: [# GE 6000.] ..................... 6000.
201.00  Y-axis register: ............................................ 7) Ys3.3s
202.00  Resolution: [# GE 0.001 and LT 999.999] ......................... 0.001
203.00  Maximum stored value: [# GE 0.002 and LE 999.999] ............. 999.999
204.00  Y-axis sign convention: [Reverse,Normal] ....................... Normal
205.00  Y-axis travel check: [No,Range,Total] .............................. No
208.00  Maximum Y-axis feedrate: [# GT 0.] ............................... 6000.
209.00  Rapid Y-axis positioning speed: [# GE 6000.] ..................... 6000.
301.00  Z-axis register: ............................................ 8) Zs3.3s
302.00  Resolution: [# GE 0.001 and LT 999.999] ......................... 0.001
303.00  Maximum stored value: [# GE 0.002 and LE 999.999] ............. 999.999
304.00  Z-axis sign convention: [Reverse,Normal] ....................... Normal
305.00  Z-axis travel check: [No,Range,Total] .............................. No
308.00  Maximum Z-axis feedrate: [# GT 0.] ............................... 6000.
309.00  Rapid Z-axis positioning speed: [# GE 6000.] ..................... 6000.
400.00  Minimum linear output move: [NA,#] ................................. NA
410.00  Linear axes modal: [Yes,No] ....................................... Yes

Rotary axes:

  1.00  A'-axis Rotary control: [Continuous,Position,Index] ........ Continuous
  1.01  Direction of rotation: [CLW,CCLW,Both] ........................... Both
  1.02  A'-axis register: ........................................... 9) Bs3.3s
  1.03  Resolution: [# GT 0.] ........................................... 0.001
  1.04  Rotary axis unit system: [Degrees,#] ......................... Degrees
  1.05  Rotary axis shift value: [#] ........................................ 0.
  1.06  Maximum output with respect to 360: [Less,Equal,More] ............ Less
  1.07  Positioning method: [Absolute,Incremental,Both] .............. Absolute
  1.08  Position specification: [Full,Half] .............................. Full
  1.09  Combined rapid move: [Yes,No] ..................................... Yes
  1.10  Controlled speed during rapid positioning: [Yes,No] ............... Yes
  1.11  DPM controllable: [Yes,No] ......................................... No
```

APPENDIX C

```
1.12  A'-axis Tolerance: [# GT 0. and LE 0.0005] ..................... 0.0005
1.13  Maximum stored value: [# GE 0.001] ................................. 45.
1.14  A'-axis sign convention: [Reverse,Normal] ..................... Reverse
1.15  A'-axis travel check: [No,Range,Total] ............................ No
1.16  Feedrate control: [Both,Feedrate,Rapid] ......................... Both
1.17  Minimum degrees per minute: [NA,#] ................................ NA
1.18  Maximum degrees per minute: [# GE 0.001] ....................... 1000.
1.19  Rapid positioning speed: [# GE 1000.] .......................... 1000.
1.20  Minimum rotary move: [NA,#] ....................................... NA
1.21  X-offset value of A'-axis center: [#] ............................. 0.
1.22  Y-offset value of A'-axis center: [#] ......................... 239.925
```



```
1.23  Z-offset value of A'-axis center: [#] ......................... -169.96
2.00  C'-axis Rotary control: [Continuous,Position,Index] ........ Continuous
2.01  Direction of rotation: [CLW,CCLW,Both] .......................... Both
2.02  C'-axis register: ........................................ 10) Cs3.3s
2.03  Resolution: [# GT 0.] .......................................... 0.001
2.04  Rotary axis unit system: [Degrees,#] .......................... Degrees
2.05  Rotary axis shift value: [#] ...................................... 0.
2.06  Maximum output with respect to 360: [Less,Equal,More] ........... More
2.07  Positioning method: [Absolute,Incremental,Both] .............. Absolute
2.08  Position specification: [Full,Half] ............................. Full
2.09  Combined rapid move: [Yes,No] .................................... Yes
2.10  Controlled speed during rapid positioning: [Yes,No] .............. Yes
2.11  DPM controllable: [Yes,No] ........................................ No
2.12  C'-axis Tolerance: [# GT 0. and LE 0.0005] ..................... 0.0005
2.13  Maximum stored value: [# GE 0.001] ........................... 9999.999
2.14  C'-axis sign convention: [Reverse,Normal] ...................... Normal
2.15  C'-axis travel check: [No,Range,Total] ............................ No
2.16  Feedrate control: [Both,Feedrate,Rapid] ......................... Both
2.17  Minimum degrees per minute: [NA,#] ................................ NA
2.18  Maximum degrees per minute: [# GE 0.001] ....................... 1000.
2.19  Rapid positioning speed: [# GE 1000.] .......................... 1000.
2.20  Minimum rotary move: [NA,#] ....................................... NA
2.21  X-offset value of C'-axis center: [#] ............................. 0.
2.22  Y-offset value of C'-axis center: [#] ............................. 0.
2.23  Z-offset value of C'-axis center: [#] ............................. 0.
4.00  Rotary axes modal: [Yes,No] ...................................... Yes
```

Home position and Reference point:

```
1.00  Home position type: [No,Fixed,Reference] .......................... No
2.00  X -axis default starting position: [#] ............................ 0.
2.01  Y -axis default starting position: [#] ............................ 0.
2.02  Z -axis default starting position: [#] ............................ 0.
2.10  A'-axis default starting position: [#] ............................ 0.
2.11  C'-axis default starting position: [#] ............................ 0.
3.00  Number of GOHOME motion blocks: [# GE 0 and LE 4] .................. 1
3.10  X -axis GOHOME motion block: [# GE 0 and LE 1] ..................... 1
3.11  Y -axis GOHOME motion block: [# GE 0 and LE 1] ..................... 1
3.12  Z -axis GOHOME motion block: [# GE 0 and LE 1] ..................... 1
3.20  A'-axis GOHOME motion block: [# GE 0 and LE 1] ..................... 1
```

APPENDIX C

```
   3.21  C'-axis GOHOME motion block: [# GE 0 and LE 1] ...................... 1
   7.00  Type of stop output following GOHOME: [None,OPSTOP,STOP] ......... STOP
   8.00  FROM statement processing: [Ignore,From,Goto] .................... Goto
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                               POST-PROCESSOR KEREM1,1

                               Automated Canned Cycles


General Cycle Information:

   1.00  G81-G89 canned cycles supported: [Yes,No] ......................... No
   5.00  Default CYCLE statement clearance: [# GE 0.] ...................... 3.
   6.10  Square off positioning moves in cycle: [Yes,No] .................. Yes
   6.30  Square off first positioning move following CYCLE/OFF: [Yes,No] ... Yes
  10.60  Default CYCLE statement dwell: [# GT 0.] .......................... 1.


Canned Cycles:

   1.00  DRILL cycle simulated: [Yes,No] ................................... Yes
   2.00  FACE cycle simulated: [Yes,No] .................................... Yes
   3.00  TAP cycle simulated: [Yes,No] ..................................... Yes
   4.00  Reverse TAP cycle simulated: [Yes,No] ............................. Yes
   5.00  BORE cycle simulated: [Yes,No] .................................... Yes
   6.00  BORE with DWELL cycle simulated: [Yes,No] ......................... Yes
   7.00  BORE with ORIENT cycle simulated: [Yes,No] ........................ Yes
   7.30  Default CYCLE statement orient angle: [# GE 0. and LT 360.] ....... 0.
   7.80  Default CYCLE statement orient clearance: [# GT 0.] ............... 0.3
   8.00  REAM cycle simulated: [Yes,No] .................................... Yes
   9.00  REAM with DWELL cycle simulated: [Yes,No] ......................... Yes
  10.00  DEEP cycle simulated: [Yes,No] .................................... Yes
  10.20  Default DEEP secondary clearance: [# GT 0.] ....................... 1.5
  11.00  BRKCHP cycle simulated: [Yes,No] .................................. Yes
  12.70  Default CYCLE statement step: [# GT 0.] ........................... 3.
  13.70  Minimum step: [# GT 0.] ........................................... 0.3
  14.40  Default BRKCHP secondary clearance: [# GT 0.] ..................... 3.
  15.00  THRU cycle simulated: [Yes,No] .................................... Yes
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                               POST-PROCESSOR KEREM1,1

                            Optional Post-processor Words


The AIR Command:

   1.00  Air device available: [Yes,No] .................................... No


The BREAK Command:

   1.00  Tape break checking desired: [Yes,No] ............................. No
```

APPENDIX C

```
The CLAMP Command:

  1.00  Physical clamp/unclamp capability: [Yes,No] ...................... No


The COOLNT Command:

  1.00  Coolant tape controllable: [Yes,No] .............................. No


The CUTCOM Command:

101.00  LENGTH compensation available: [Yes,No] .......................... No
201.00  DIAMETER compensation available: [Yes,No] ........................ No
301.00  FIXTURE compensation available: [Yes,No] ......................... No


The DELAY Command:

  1.00  DELAY facility available: [Yes,No] ............................... No
******  To simulate some Canned Cycles, DELAY is required


The DISPLY Command:

  1.00  CRT display available: [Yes,No] .................................. No


The END Command:

  1.00  END (M) code: [0-999] ............................................. 2
  2.00  Spindle turned off by control: [Yes,No] .......................... No
  2.10  SPINDL/OFF required before END: [Yes,No] ......................... No
  3.00  Coolant turned off by control: [Yes,No] .......................... No
  3.10  COOLNT/OFF required before END: [Yes,No] ......................... No


The FEDRAT Command:

  1.00  Feedrate tape controlled: [Yes,No] ............................... No
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                               POST-PROCESSOR KEREM1,1


The INSERT Command:

  1.00  Prefix OPSKIP character: [Yes,No] ................................ No
  1.10  Sequence number included: [Yes,No] ............................... No
  2.00  End of block appended: [Yes,No] .................................. No
  3.00  Blanks removed: [Yes,No] ......................................... No


The LOADTL Command:

  1.00  COOLNT/OFF generated by Post: [Yes,No] ........................... No
```

```
  1.10   SPINDL/OFF generated by Post: [Yes,No] ............................ No
  1.20   SPINDL/ORIENT generated by Post: [angle,No] ....................... No
  1.30   CUTCOM/OFF generated by Post: [Yes,No] ............................ No
  3.00   TOOL change location: [No,Home,Special,Both] ...................... No
  5.00   Does your machine have an automatic tool changer (ATC)? [Yes,No] ... No
  5.05   Manual tool change (M) code: [NA,0-999] ............................ 6
  9.90   ADJUST default: [Now,Next] ...................................... Next
 10.00   Head attachments (holders): [Yes,No] .............................. No

The OPSKIP Command:

  1.00   Optional skip available: [Yes,No] ................................. No

The OPSTOP Command:

  1.00   Optional stop available: [Yes,No] ................................. No
  1.10   Output STOP (M) code: [Yes,No] .................................... No

The POSTN Command:

  1.00   Preset positioning available: [Yes,No] ............................ No

The RAPID Command:

  1.00   RAPID command modal: [Yes,No] ..................................... No

The RETRCT Command:

  1.00   Different feed requested: [Yes,No] ................................ No

The REWIND Command:

  1.00   REWIND (M) code: [0-999] .......................................... 30
  2.00   Spindle turned off by control: [Yes,No] ........................... No
  2.10   SPINDL/OFF required before REWIND: [Yes,No] ....................... No
  3.00   Coolant turned off by control: [Yes,No] ........................... No
  3.10   COOLNT/OFF required before REWIND: [Yes,No] ....................... No
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                          POST-PROCESSOR KEREM1,1

The SEQNO Command:

  1.00   Sequence numbering required: [Yes,No] ............................. Yes
  2.00   Code required on every block: [Yes,No] ............................ Yes
  3.00   Sequence number register: ...................................... 1) Ns4
  4.00   Minimum increment required: [# GT 0.] .............................. 5.
  5.00   Minimum value: [#] ................................................ 10.
  6.00   Maximum value: [# GE 10.] ........................................ 9995.
```

7.00 Default method of SEQNO: [Regular,Auto] .... Regular
7.01 Sequence numbers starting on first block: [Yes,No] .... Yes
7.02 Initial sequence number: [# GE 10. and LE 9995.] .... 10.
7.03 Default increment: [# GE 5.] .... 5.

The SPINDL Command:

1.00 Spindle tape controllable: [Yes,No] .... Yes
2.00 Speed code method: [No,Direct,Table,Calculated] .... Direct
2.30 Spindle speed register: .... 11) Ss4
3.00 Spindle controlled by (M) codes: [Yes,No] .... Yes
3.10 SPINDL/ON,CLW code: [NA,0-999] 3
3.20 SPINDL/ON,CCLW code: [NA,0-999] 4
3.29 Presence of speed code changes speed: [Yes,No] .... No
3.30 SPINDL/OFF code: [NA,0-999] 5
3.40 SPINDL/LOCK code: [NA,0-999] .... NA
3.50 SPINDL/NEUTRL code: [NA,0-999] .... NA
3.60 SPINDL/ORIENT code: [NA,0-999] .... NA
****** BORE - Automated canned cycle needs SPINDL/ORIENT
5.00 Controllable gears available: [Yes,No] .... No
6.00 Spindle RPM resolution: [# GT 0. and LT 9999.] .... 1.
6.01 Minimum RPM: [# GT 0. and LT 9999.] .... 1.
6.02 Maximum RPM: [# GT 1. and LE 9999.] .... 6300.

The STOP Command:

1.00 STOP (M) code: [0-999] 0
2.00 Spindle turned off by control: [Yes,No] .... No
2.10 SPINDL/OFF required before STOP: [Yes,No] .... No
2.20 SPINDL/ON required after STOP: [Yes,No] .... No
3.00 Coolant turned off by control: [Yes,No] .... No
3.10 COOLNT/OFF required before STOP: [Yes,No] .... No
3.20 COOLNT/ON required after STOP: [Yes,No] .... No

The TMARK Command:

1.00 TMARK symbol: [NA,Sequence,Rewind] .... NA

The TRANS Command:

1.00 TRANS values are cumulative: [Yes,No] .... No

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POST-PROCESSOR KEREM1,1

Post-processor Macros

Startup/Shutdown Macros:

1.00 User defined machine startup macro: [Yes,No] .... No
2.00 User defined machine shutdown macro: [Yes,No] .... No

5.00 Motion startup macro: [Yes,No] .... No
6.00 Motion shutdown macro: [Yes,No] .... No
7.00 User defined LOADTL startup macro: [Yes,No] .... No
8.00 User defined LOADTL shutdown macro: [Yes,No] .... No

User Defined Syntax Macros:

No user defined post-processor macros exist.

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POST-PROCESSOR KEREM1,1

Register Assignment Summary

Index	Name	Punch Format	"." Req	Omit Lead	Omit Trail	"+" Req	Register Descriptor
1	N	4.0	No	Yes	No	No	Ns4
2	G	2.0	No	Yes	No	No	Gs2
3	M	2.0	No	Yes	No	No	Ms2
4	I	3.3	Yes	Yes	Yes	No	Is3.3s
5	J	3.3	Yes	Yes	Yes	No	Js3.3s
6	X	3.3	Yes	Yes	Yes	No	Xs3.3s
7	Y	3.3	Yes	Yes	Yes	No	Ys3.3s
8	Z	3.3	Yes	Yes	Yes	No	Zs3.3s
9	B	3.3	Yes	Yes	Yes	No	Bs3.3s
10	C	3.3	Yes	Yes	Yes	No	Cs3.3s
11	S	4.0	No	Yes	No	No	Ss4

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POST-PROCESSOR KEREM1,1

"G" Code Summary

Code Description

0 .... High speed positioning mode
1 .... Linear interpolation mode
2 .... CLW circular interpolation
3 .... CCLW circular interpolation
17 .... Circular interpolation, Cutter compensation, Cycles in XY-plane

18 .... Circular interpolation, Cutter compensation, Cycles in ZX-plane
19 .... Circular interpolation, Cutter compensation, Cycles in YZ-plane

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POST-PROCESSOR KEREM1,1

"M" Code Summary

Code Description

0 .... STOP
2 .... END
3 .... Clockwise spindle rotation
4 .... Counter-clockwise spindle rotation
5 .... Stop spindle rotation

6 .... Manual tool change (M) code
30 .... REWIND

APPENDIX D

TWO CLFILES FOR FIVE- AXIS MILLING OF THE SAME RULED SURFACE

APPENDIX D

```
%1999    (M-D11-000900- -3.10.94-BLADE DENEME1)
?
0820

%1999*T    ( - -000030- - - )
T1 I/M:M R3 L0 ()
?
070C

%1999*%    ( - -0008D0- -3.10.94-BLADE DENEME1)
N1 G17 T1
N2 S500 M3; F500
N3 G0 X92 Y-100
N4 Z25
N10G1X91.004Y276.457Z199.638B-40.624C89.191
N15X81.984Y234.54Z196.354B-33.11C88.629
N20X71.972Y187.011Z187.342B-24.402C86.717
N25X62.251Y151.101Z175.515B-17.34C82.993
N30X45.069Y121.051Z159.728B-10.293C72.81
N35X-14.095Y100.635Z146.052B-4.866C31.646 } 70° Discontinuity in C- axis Register
N40X-72.982Y43.293Z159.074B-6.894C-38.838 }
N45X-66.769Y48.271Z183.013B-12.499C-57.7
N50X-59.45Y72.675Z203.001B-17.945C-63.412
N55X-53.144Y99.629Z218.121B-22.772C-65.614
N60X-47.444Y125.19Z229.105B-26.925C-66.418
N65X-42.1Y148.207Z236.879B-30.447C-66.519
N70X-36.97Y168.45Z242.261B-33.41C-66.21
N75X-31.967Y186.032Z245.884B-35.888C-65.637
N80X-27.026Y201.237Z248.227B-37.955C-64.879
N85X-20.86Y217.357Z249.869B-40.055C-63.74
N90X-14.621Y230.803Z250.505B-41.714C-62.44
N95X-8.226Y242.088Z250.443B-43.018C-61.013
N100X-1.595Y251.635Z249.891B-44.035C-59.484
N105X6.221Y260.706Z248.862B-44.902C-57.663
N110X6.252Y260.716Z243.458
N115X-1.18Y252.138Z244.784B-44.085C-59.395
N120X-8.253Y241.989Z245.715B-43.006C-61.029
N125X-15.058Y229.852Z246.077B-41.599C-62.545
N130X-20.043Y219.143Z245.826B-40.28C-63.588
N135X-26.202Y203.374Z244.62B-38.239C-64.749
N140X-30.82Y189.503Z242.821B-36.367C-65.487
N145X-36.66Y169.259Z239.043B-33.528C-66.19
N150X-41.147Y151.718Z234.688B-30.973C-66.491
N155X-46.981Y126.766Z226.699B-27.178C-66.442
N160X-51.618Y105.964Z218.261B-23.839C-65.9
N165X-57.946Y78.33Z203.904B-19.027C-64.062
N170X-65.264Y52.054Z184.469B-13.53C-59.222
N175X-72.733Y40.771Z160.302B-7.699C-43.712
N180X-27.721Y94.894Z143.347B-4.605C21.437
N185X42.367Y118.935Z155.778B-9.673C71.075
N190X61.41Y149.008Z172.196B-16.892C82.628
N195X73.722Y195.284Z186.82B-25.941C87.2
N200X83.153Y240.616Z194.307B-34.193C88.758
N205X90.935Y276.504Z196.637B-40.624C89.191
N210X90.863Y276.55Z193.637
N215X81.831Y234.639Z190.901B-33.11C88.629
```

APPENDIX D

```
N220X71.804Y187.109Z182.286B-24.402C86.717
N225X62.064Y151.187Z170.645B-17.34C82.993
N230X44.857Y121.096Z154.944B-10.293C72.81
N235X-14.286Y100.512Z141.255B-4.866C31.646
N240X-72.91Y43.068Z154.173B-6.894C-38.838
N245X-66.609Y48.092Z177.927B-12.499C-57.7
N250X-59.258Y72.533Z197.662B-17.945C-63.412
N255X-52.939Y99.52Z212.473B-22.772C-65.614
N260X-47.24Y125.112Z223.104B-26.925C-66.418
N265X-41.905Y148.157Z230.493B-30.447C-66.519
N270X-36.791Y168.423Z235.461B-33.41C-66.21
N275X-31.806Y186.022Z238.651B-35.888C-65.637
N280X-25.657Y204.707Z240.859B-38.415C-64.666
N285X-19.505Y220.256Z241.684B-40.419C-63.491
N290X-13.259Y233.238Z241.56B-42.001C-62.164
N295X-6.838Y244.149Z240.773B-43.243C-60.715
N300X-.163Y253.389Z239.515B-44.209C-59.167
N305X6.283Y260.727Z238.054B-44.902C-57.663
N310X6.315Y260.738Z232.649
N315X-1.106Y252.161Z234.655B-44.085C-59.395
N320X-8.166Y242.011Z236.251B-43.006C-61.029
N325X-14.954Y229.871Z237.264B-41.599C-62.545
N330X-21.565Y215.232Z237.436B-39.782C-63.915
N335X-26.47Y202.228Z236.781B-38.086C-64.82
N340X-32.613Y183.041Z234.609B-35.475C-65.756
N345X-37.291Y166.17Z231.605B-33.088C-66.262
N350X-43.318Y141.752Z225.502B-29.489C-66.541
N355X-48.061Y120.932Z218.598B-26.272C-66.343
N360X-54.441Y92.306Z206.185B-21.549C-65.21
N365X-59.772Y70.039Z193.423B-17.474C-63.092
N370X-67.486Y45.701Z172.679B-11.811C-56.506
N375X-72.119Y47.398Z148.238B-6.152C-32.681
N380X3.449Y105.721Z140.244B-5.502C44.376
N385X49.724Y126.515Z156.076B-11.738C76.044
N390X64.648Y159.637Z171.418B-19.062C84.212
N395X75.905Y206.398Z183.978B-27.976C87.727
N400X85.072Y250.661Z189.602B-35.977C88.932
N405X90.786Y276.596Z190.636B-40.624C89.191

?
7465
```

APPENDIX D

```
%1999   (M-D11-000900- -4.10.94-BLADE DENEME2)
?
0820

%1999*T   ( - -000030- - - )
T1 I/M:M R3 L0 ()
?
070C

%1999*%   ( - -0008D0- -4.10.94-BLADE DENEME2)
N1 G17 T1
N2 S500 M3; F500
N3 G0 X92 Y280
N4 Z300
N10G1X91.004Y276.457Z199.638B-40.624C89.191
N25X88.193Y263.97Z199.045B-38.386C89.099
N30X86.065Y254.117Z198.358B-36.622C88.984
N35X83.367Y241.252Z197.141B-34.316C88.771
N40X80.606Y227.82Z195.455B-31.899C88.462
N45X78.476Y217.433Z193.837B-30.018C88.15
N50X75.712Y204.144Z191.34B-27.589C87.636
N55X72.789Y190.643Z188.267B-25.084C86.941
N60X70.45Y180.462Z185.561B-23.161C86.263
N65X67.274Y167.824Z181.683B-20.717C85.16
N70X63.689Y155.463Z177.252B-18.241C83.664
N75X60.602Y146.523Z173.58B-16.374C82.177
N80X56.007Y135.993Z168.613B-14.048C79.674
N85X50.097Y126.502Z163.31B-11.756C76.078
N90X44.23Y120.32Z159.205B-10.084C72.252
N95X33.88Y114.011Z154.126B-8.102C65.223
N100X17.555Y109.033Z149.53B-6.341C53.953
N105X-8.568Y102.466Z146.347B-5.022C35.646
N110X-41.754Y86.685Z146.111B-4.508C9.748    } 20° Discontinuity in C- axis Register
N115X-60.691Y69.114Z148.474B-4.794C-9.974   }
N120X-71.122Y51.136Z153.784B-5.79C-28.725
N125X-72.994Y42.204Z160.398B-7.18C-40.737
N130X-71.807Y40.106Z167.407B-8.744C-48.362
N135X-69.722Y42.146Z174.37B-10.373C-53.398
N140X-67.447Y46.62Z181.076B-12.012C-56.872
N145X-65.203Y52.551Z187.428B-13.633C-59.359
N150X-63.58Y57.598Z191.932B-14.827C-60.78
N155X-61.633Y64.354Z197.233B-16.285C-62.173
N160X-59.77Y71.416Z202.171B-17.701C-63.249
N165X-57.983Y78.634Z206.749B-19.071C-64.087
N170X-56.263Y85.906Z210.979B-20.393C-64.741
N175X-54.599Y93.16Z214.88B-21.667C-65.253
N180X-52.985Y100.341Z218.465B-22.892C-65.649
N185X-51.412Y107.398Z221.751B-24.067C-65.953
N190X-49.875Y114.318Z224.763B-25.195C-66.181
N195X-48.37Y121.064Z227.511B-26.274C-66.344
N200X-46.892Y127.637Z230.02B-27.308C-66.453
N205X-45.438Y134.013Z232.304B-28.296C-66.517
N210X-44.005Y140.197Z234.381B-29.241C-66.54
N215X-42.589Y146.176Z236.266B-30.143C-66.53
N220X-41.19Y151.951Z237.974B-31.004C-66.489
N225X-39.804Y157.528Z239.52B-31.826C-66.422
```

APPENDIX D

```
N230X-38.581Y162.326Z240.771B-32.526C-66.342
N235X-37.062Y168.101Z242.179B-33.36C-66.219
N240X-35.556Y173.641Z243.432B-34.151C-66.072
N245X-34.059Y178.952Z244.542B-34.901C-65.904
N250X-32.569Y184.034Z245.521B-35.611C-65.718
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APPENDIX D

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APPENDIX D

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?
7465
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APPENDIX E

SPECIFICATIONS OF THE MILLING MACHINE USED

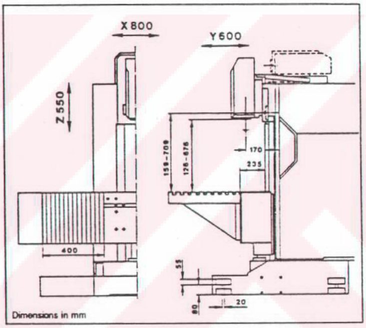
Working range FP5CC/T

X axis ________ 800 mm (32")
with NC universal table (Version 5) ________ 700 mm (28")

Y axis ________ 600 mm (24")

Z axis ________ 550 mm (22")

Non-metric values are approximations.



Technical data FP5CC/T

Feed drive

AC synchronous motors
X axis ________ 13 Nm
Y axis ________ 13 Nm
Z axis ________ 21 Nm

Feed rates steplessly programmable

metric ____ 2 to 10000 mm/min
inches ____ 0.08 to 388 in/min

Rapid traverse

metric ________ 10000 mm/min
inches ________ 388 in/min

Measuring system

Direct measuring system

Resolution ________ 0.001 mm
4th axis ________ 0.001°

Input increments

metric ________ 0.001 mm
inches ________ 0.0001 in

Table slide

1 guide slot

Width ________ 14^{H7} mm (0.55")

Tapped holes for table accessories ________ M 12
(metric thread 12 mm dia)

Max laod on table slide ____ 1000 kg (2200 lb)

Tool mounting

Tools clamped by cup spring assembly, hydraulic release.
Spindle taper: ST 40
(standard taper No. 40)
for tool shanks to DIN 69871-A
with draw-in pin DIN 69872-A

Optional:
System Ott w/clamping groove

Tool changer for vertical and horizontal spindle

Max. tool dia ____ 100 mm (4")
- if neighboring positions are vacant ____ 160 mm (6")

Max. tool length from spindle nose ________ 300 mm (12")

Max. tool weight __ 10 kg (22 lb)

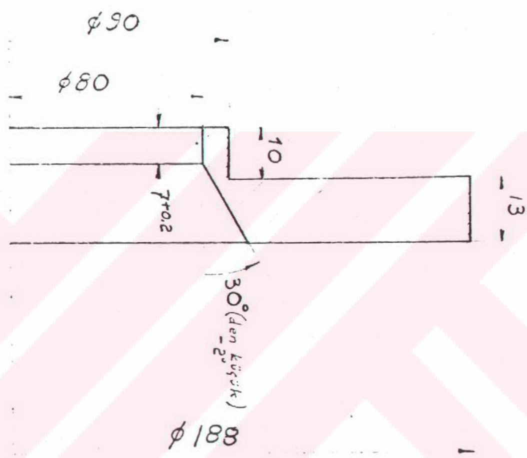
No. of tools ________ 26

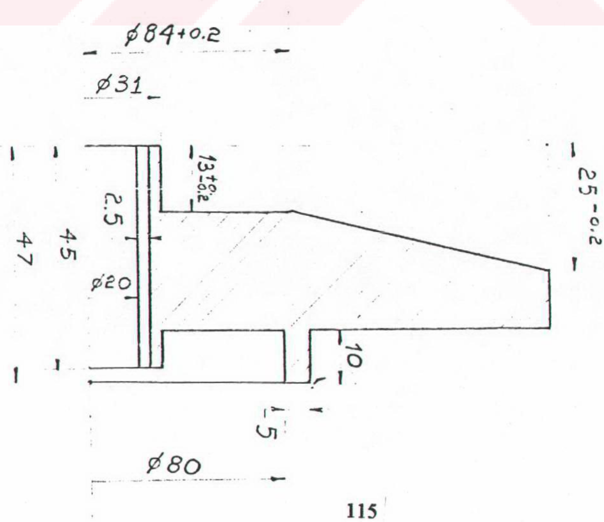
1-9

APPENDIX F

WORKPIECES BEFORE MILLING OPERATIONS

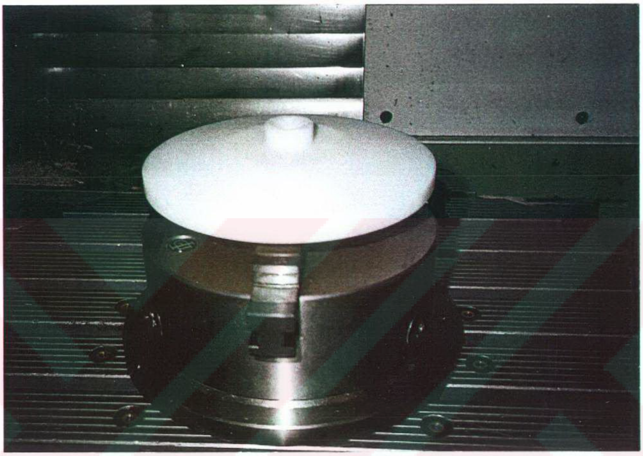
Impeller D

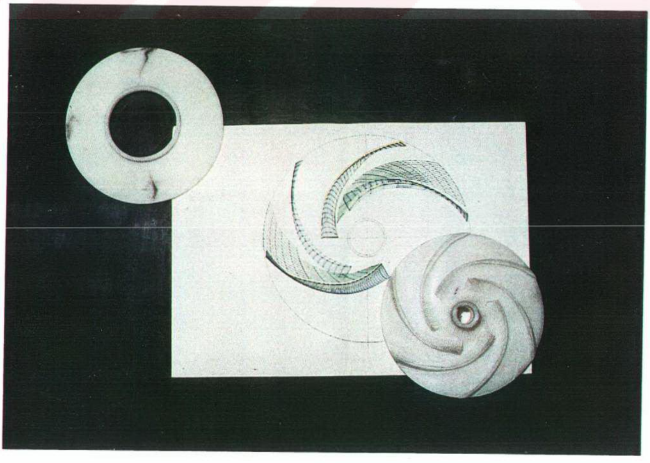


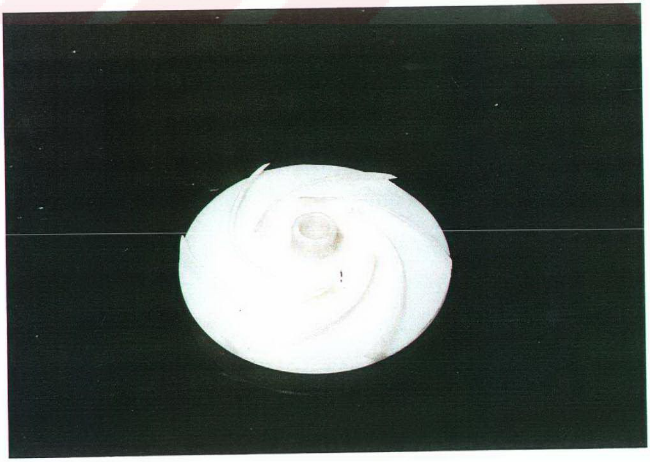


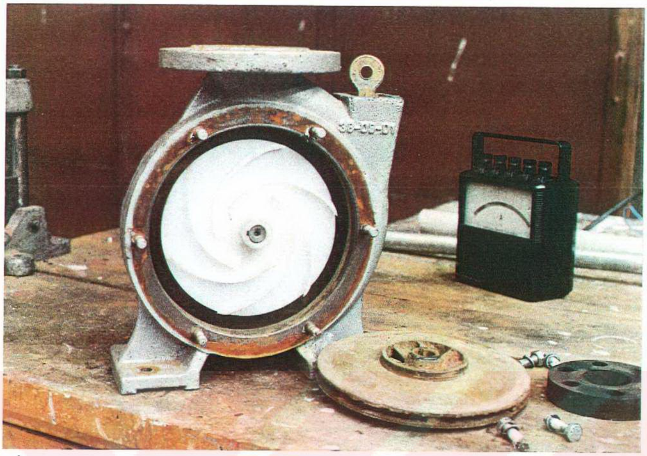
APPENDIX G

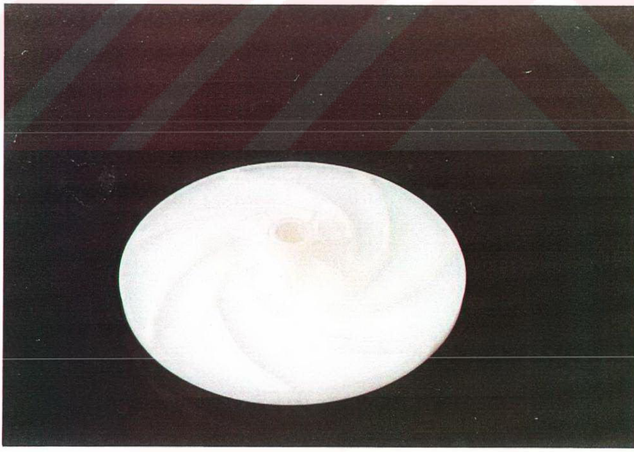
PHOTOGRAPHS

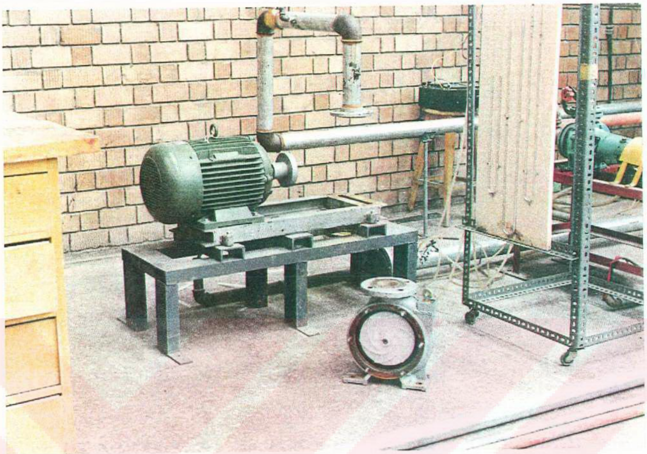






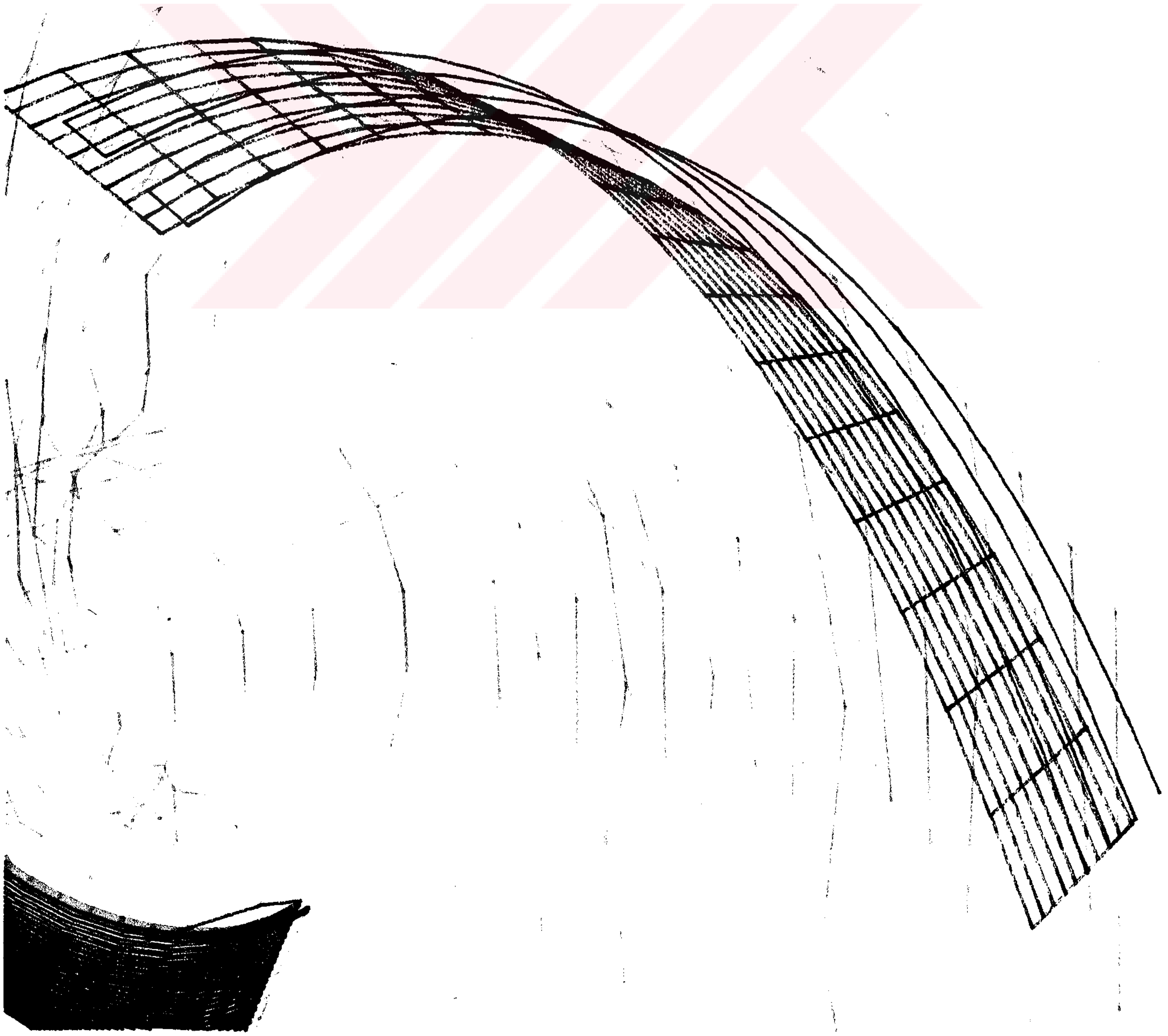






APPENDIX III

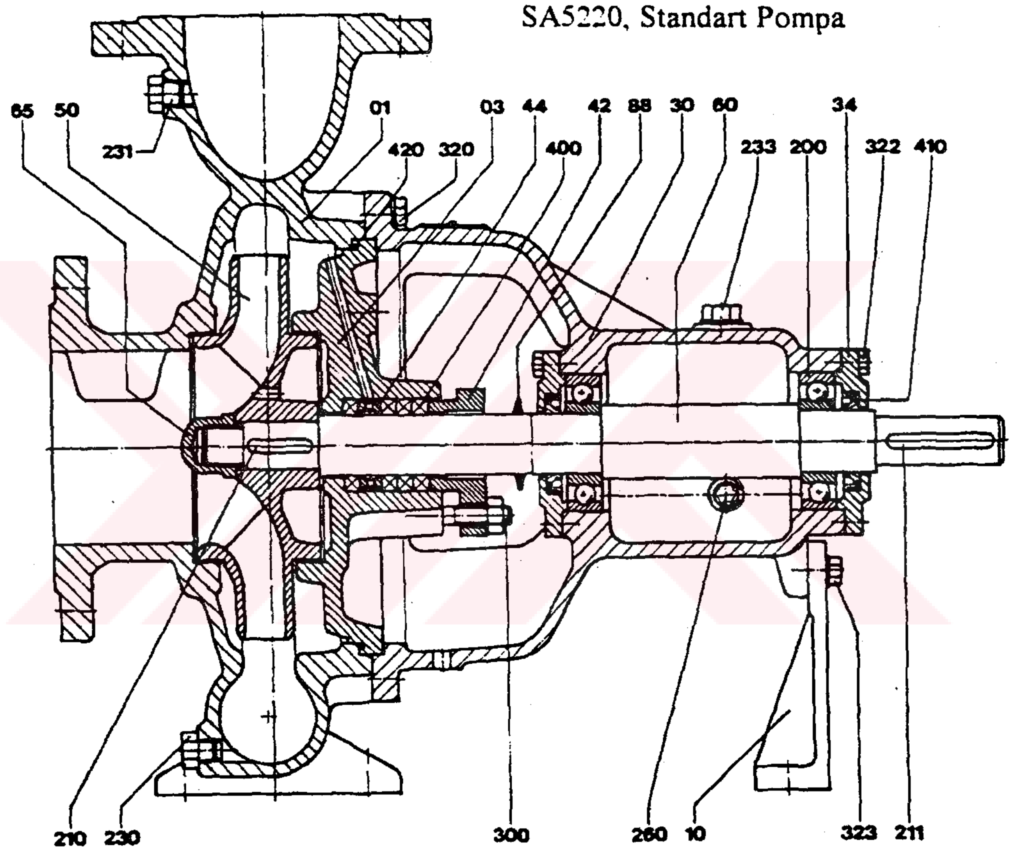
TOOLPATH AND FIVE- AXIS SWARF MILLED RULED SURFACE



APPENDIX H

CASING OF IMPELLERS

SA5220, Standart Pompa



01 - Volute casing	65 - Impeller nut	300 - Gland stud and nut
03 - Stuffing box cover	88 - Deflector	320 - H.Cap screw (casing)
10 - Frame foot	200 - Ball bearing	322 - H.Cap screw (Bea. cover)
30 - Bearing housing	210 - Impeller key	323 - H.Cap screw (frame foot
34 - Bearing cover (oil lub.)	211 - Coupling key	400 - Stuffing box packing
42 - Stuffing box gland	230 - Air plug	410 - Oil seal
44 - Lantern ring	231 - Drain plug	420 - O-ring (casing)
50 - Impeller	233 - Oil filling plug	
60 - Pump shaft	260 - Oil eye	

APPENDIX J

TEST DATA AND RESULTS

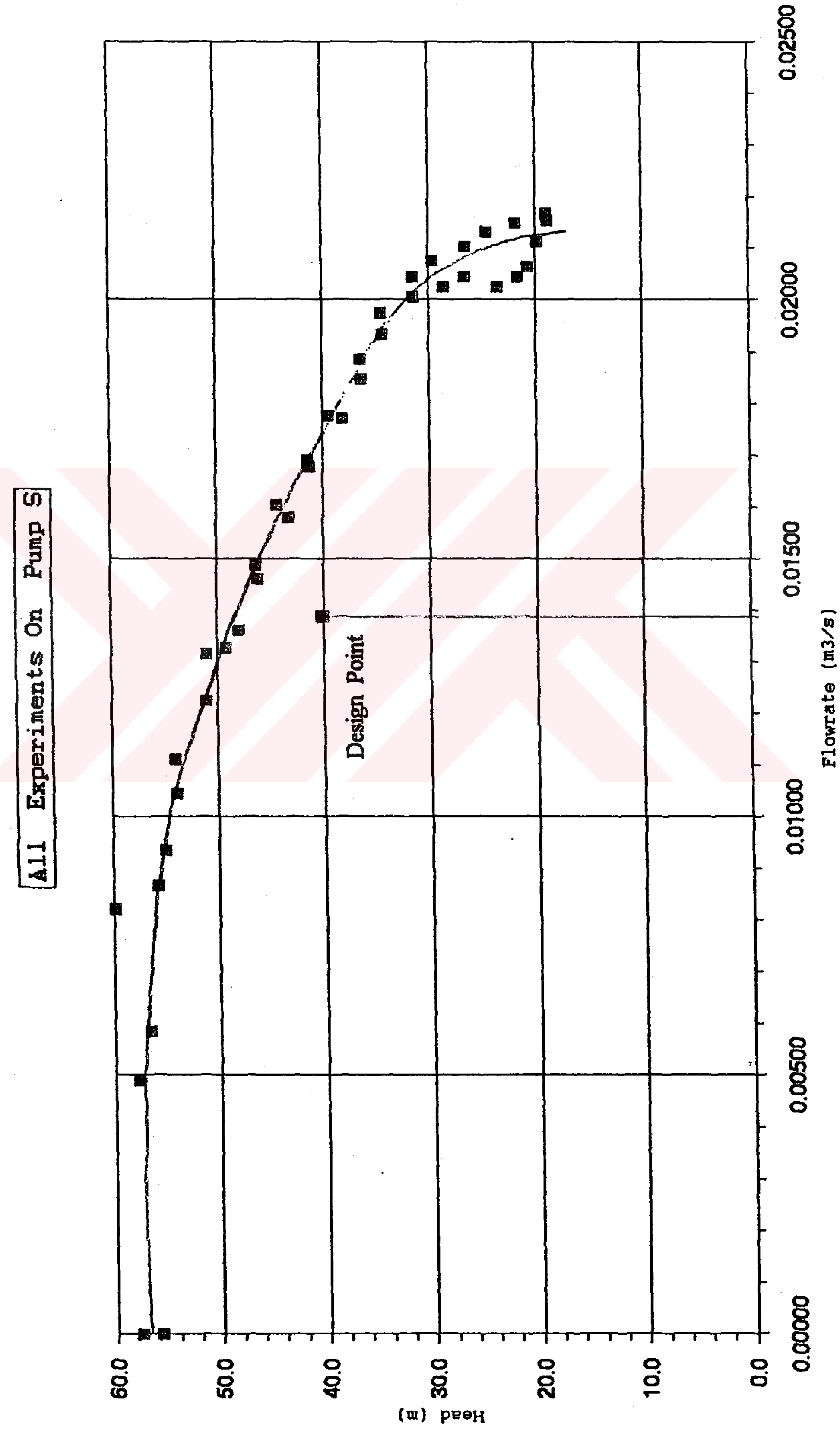
Impeller S

Test Data and Results of Impeller S

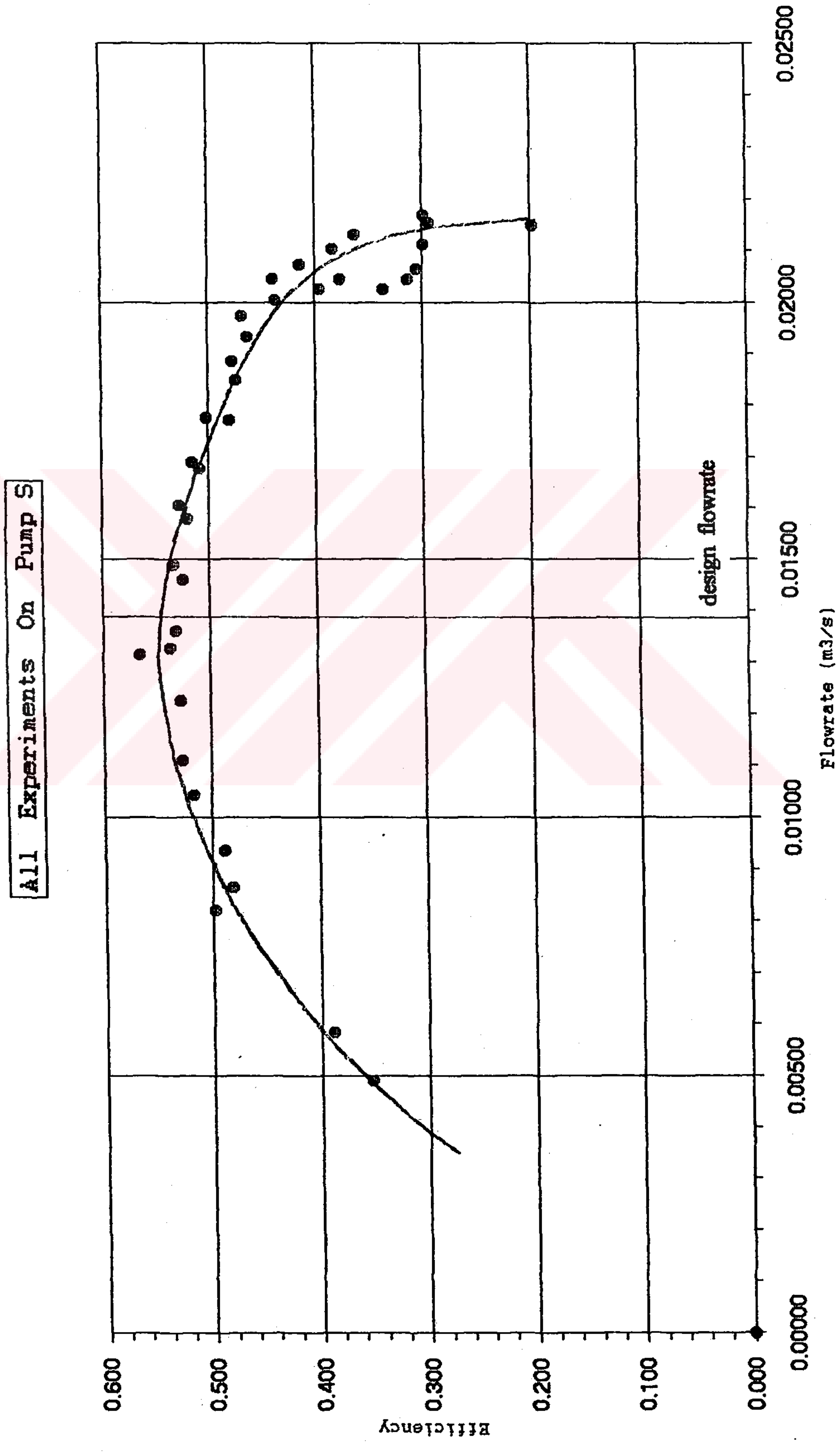
SINGLE CURVATUE PUMP TEST					Date: Feb, 7 - 8, 1995				
					Time: 14:10 - 17:30				
					Notes: All Experiments				
hs initial	h ori initial	P atm	Temp	Z in	Z out	D inlet	D outlet	Power Factor	N
mmHg	mmHg	mmHg	C	cm	cm	mm	mm		rpm
72	32	675	15	60.5	133	69.6	56.9	6	2966-2974

Power Wattmeter	hs	Del H	P gage	P gage calib	Pd	Ps	Vi	Vo	Q	Hi	Ho	Pump Head	Power Fluid	Efficiency	Motor Power	Qu	Hu	Pu
(kW)	mmHg	mm	bar	bar *	kPa	kPa	m/s	m/s	m3/s	m	m	m	kW	0.00	kW	m3/s	m	kW
1.1	82	-32	5.5	5.9	608.0	-1.3	0.00	0.00	0.00000	0.5	63.3	62.8	0.00	0.000	6.6	0.00000	55.8	5.5
1.68	72	28	5.7	6.1	629.3	0.0	1.37	2.05	0.00521	0.7	65.7	65.0	3.32	0.352	10.08	0.00491	57.7	8.4
2.06	70	136	5.9	6.3	650.6	0.3	2.29	3.43	0.00871	0.9	68.2	67.3	5.75	0.498	12.36	0.00821	59.8	10.3
2.2	60	186	5.4	5.8	597.4	1.6	2.61	3.90	0.00992	1.1	63.0	61.9	6.02	0.488	13.2	0.00935	55.0	11.0
2.38	48	276	5.3	5.7	586.8	3.2	3.10	4.64	0.01178	1.4	62.2	60.8	7.04	0.527	14.28	0.01112	54.0	12.0
2.48	36	342	5	5.4	554.9	4.8	3.42	5.11	0.01300	1.7	59.2	57.5	7.33	0.527	14.88	0.01225	51.1	12.5
2.54	27	408	4.8	5.2	533.6	6.0	3.70	5.54	0.01410	1.9	57.3	55.4	7.66	0.538	15.24	0.01329	49.2	12.8
2.7	10	520	4.5	4.9	501.7	8.3	4.16	6.21	0.01579	2.3	54.4	52.1	8.07	0.533	16.2	0.01488	46.3	13.6
2.81	-13	610	4.3	4.7	480.4	11.3	4.48	6.70	0.01703	2.8	52.6	49.8	8.32	0.528	16.86	0.01605	44.2	14.1
2.84	-20	680	4	4.4	448.5	12.3	4.71	7.05	0.01793	3.0	49.6	46.6	8.20	0.515	17.04	0.01690	41.4	14.3
2.92	-37	765	3.8	4.1	427.3	14.5	4.96	7.41	0.01885	3.3	47.7	44.3	8.20	0.501	17.52	0.01777	39.4	14.7
3	-65	855	3.5	3.8	395.4	18.3	5.26	7.87	0.02001	3.9	44.8	40.9	8.03	0.478	18	0.01887	36.3	15.1
3.04	-72	940	3.3	3.6	374.1	19.2	5.51	8.24	0.02095	4.1	42.9	38.8	7.98	0.468	18.24	0.01975	34.5	15.3
3.07	-90	1010	3	3.3	342.2	21.6	5.70	8.53	0.02169	4.5	39.9	35.5	7.55	0.438	18.42	0.02045	31.5	15.4
3.1	-94	1040	2.8	3.1	321.0	22.1	5.78	8.65	0.02200	4.6	37.9	33.3	7.19	0.413	18.6	0.02074	29.6	15.6
3.04	-114	1070	2.5	2.8	289.1	24.8	5.86	8.77	0.02231	4.9	34.7	29.8	6.53	0.383	18.24	0.02103	26.5	15.3
3.02	-120	1100	2.3	2.6	267.8	25.6	5.94	8.89	0.02261	5.0	32.7	27.6	6.13	0.362	18.12	0.02132	24.6	15.2
4.96	-110	1120	2	2.3	235.9	24.3	5.99	8.97	0.02281	4.9	29.5	24.6	5.50	0.198	29.76	0.02150	21.8	24.9
2.88	-110	1140	1.7	2.0	204.0	24.3	6.05	9.05	0.02301	4.9	26.3	21.4	4.82	0.298	17.28	0.02169	19.0	14.5
2.88	-122	1125	1.7	2.0	204.0	25.9	6.01	8.99	0.02286	5.1	26.2	21.2	4.75	0.294	17.28	0.02155	18.8	14.5
2.92	-115	1080	1.8	2.1	214.6	24.9	5.89	8.81	0.02241	4.9	27.2	22.3	4.89	0.299	17.52	0.02113	19.8	14.7
2.92	-110	1030	1.9	2.2	225.3	24.3	5.76	8.61	0.02190	4.8	28.1	23.3	5.01	0.306	17.52	0.02065	20.7	14.7
2.95	-110	1010	2	2.3	235.9	24.3	5.70	8.53	0.02169	4.7	29.1	24.3	5.18	0.313	17.7	0.02045	21.6	14.8
2.97	-108	990	2.2	2.5	257.2	24.0	5.65	8.45	0.02148	4.7	31.2	26.5	5.59	0.335	17.82	0.02025	23.5	14.9
3.02	-100	1010	2.5	2.8	289.1	22.9	5.70	8.53	0.02169	4.6	34.5	29.9	6.36	0.376	18.12	0.02045	26.6	15.2
3.06	-92	990	2.7	3.0	310.3	21.9	5.65	8.45	0.02148	4.5	36.6	32.1	6.77	0.395	18.36	0.02025	28.5	15.4
3.02	-90	970	3	3.3	342.2	21.6	5.59	8.37	0.02127	4.4	39.8	35.4	7.38	0.436	18.12	0.02005	31.4	15.2
3	-80	900	3.3	3.6	374.1	20.3	5.39	8.07	0.02052	4.2	42.8	38.6	7.77	0.462	18	0.01934	34.3	15.1
2.96	-65	820	3.5	3.8	395.4	18.3	5.16	7.71	0.01962	3.8	44.7	40.8	7.86	0.474	17.76	0.01849	36.3	14.9
2.94	-63	750	3.7	4.0	416.7	18.0	4.94	7.39	0.01879	3.7	46.6	42.9	7.91	0.480	17.64	0.01772	38.1	14.8
2.84	-38	670	4	4.4	448.5	14.7	4.68	7.00	0.01780	3.2	49.6	46.3	8.09	0.508	17.04	0.01679	41.2	14.3
2.74	-20	590	4.2	4.6	469.8	12.3	4.41	6.59	0.01676	2.8	51.4	48.6	7.99	0.520	16.44	0.01580	43.2	13.8
2.68	-7	500	4.5	4.9	501.7	10.5	4.07	6.10	0.01550	2.6	54.4	51.8	7.88	0.525	16.08	0.01461	46.0	13.5
2.56	-5	430	4.7	5.1	523.0	10.3	3.80	5.68	0.01444	2.4	56.3	53.9	7.64	0.532	15.36	0.01362	47.9	12.9
2.48	15	400	5	5.4	554.9	7.6	3.67	5.49	0.01397	2.1	59.4	57.4	7.86	0.565	14.88	0.01317	50.9	12.5
2.28	45	240	5.3	5.7	586.8	3.6	2.91	4.36	0.01108	1.4	62.1	60.7	6.60	0.516	13.68	0.01045	53.9	11.5
2.1	55	155	5.5	5.9	608.0	2.3	2.42	3.61	0.00919	1.1	64.0	62.8	5.67	0.481	12.6	0.00866	55.8	10.5
1.78	57	53	5.6	6.0	618.7	2.0	1.63	2.44	0.00620	0.9	64.7	63.8	3.87	0.388	10.68	0.00584	56.6	8.9
1.06	76	-32	5.7	6.1	629.3	-0.5	0.00	0.00	0.00000	0.6	65.5	64.9	0.00	0.000	6.36	0.00000	57.7	5.3

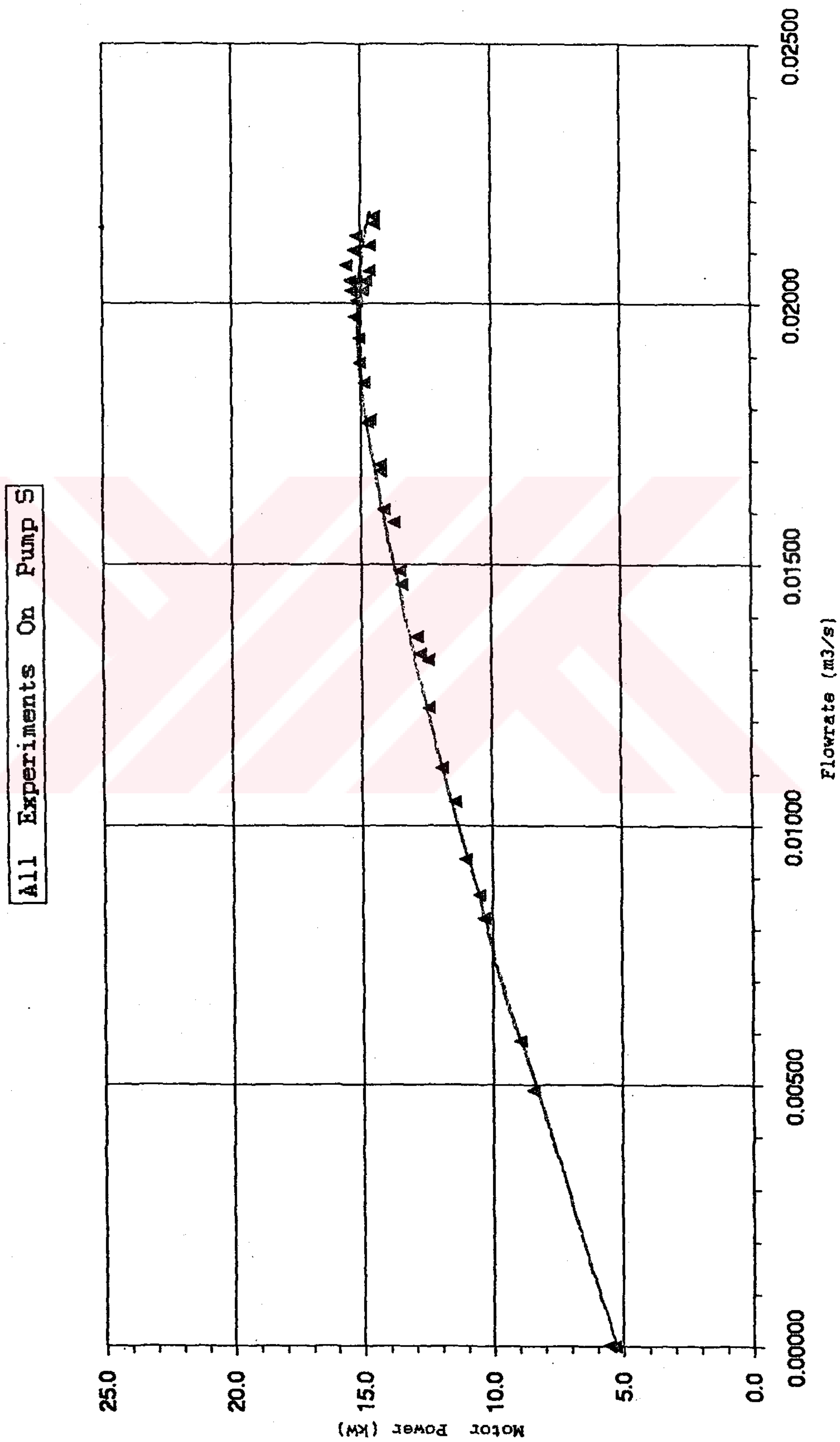
APPENDIX J


All Experiments On Pump S
Design Point
Flowrate (m3/s)
Head (m)
0.00000
0.00500
0.01000
0.01500
0.02000
0.02500
60.0
50.0
40.0
30.0
20.0
10.0
0.0

APPENDIX J


All Experiments On Pump S
design flowrate
Flowrate (m3/s)
Efficiency
0.00000
0.00500
0.01000
0.01500
0.02000
0.02500
0.000
0.100
0.200
0.300
0.400
0.500
0.600

APPENDIX J



All Experiments On Pump S
Flowrate (m3/s)
Motor Power (kW)
0.00000
0.00500
0.01000
0.01500
0.02000
0.02500
0.0
5.0
10.0
15.0
20.0
25.0

APPENDIX J

Impeller D

Test Data and Results of Impeller D

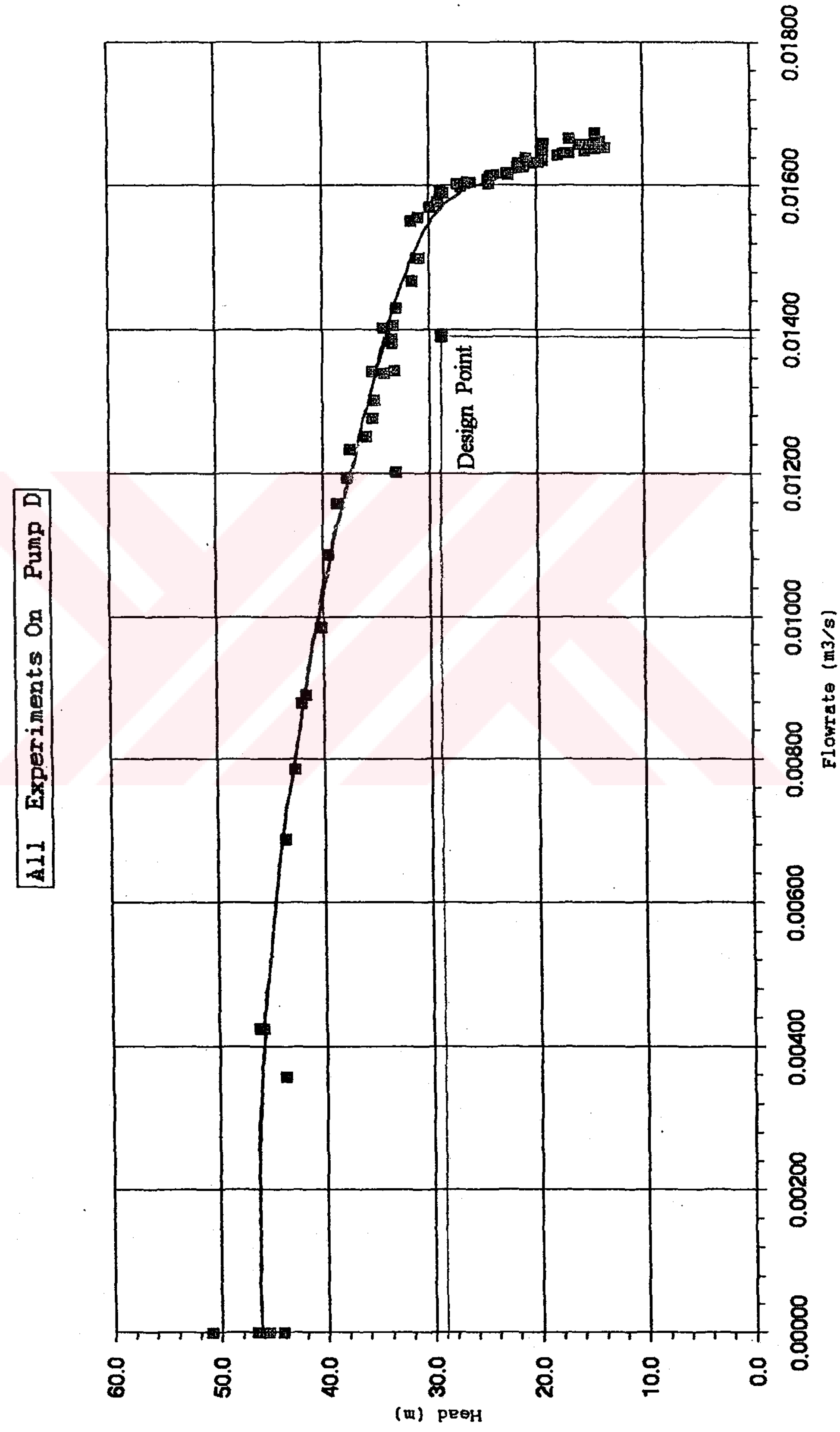
DOUBLE CURVATUE PUMP TEST

Date: Nov, 23-29, 1994
Time: 17:32 - 18:54
Notes: All Experiments

hs initial	h oi initial	P atm	Temp	Z in	Z out	D inlet	D outlet	Power Factor	N
mmHg	mmHg	mmHg	C	cm	cm	mm	mm		rpm
41	0	674	12	60.5	133	69.6	56.9	6	2966-2974

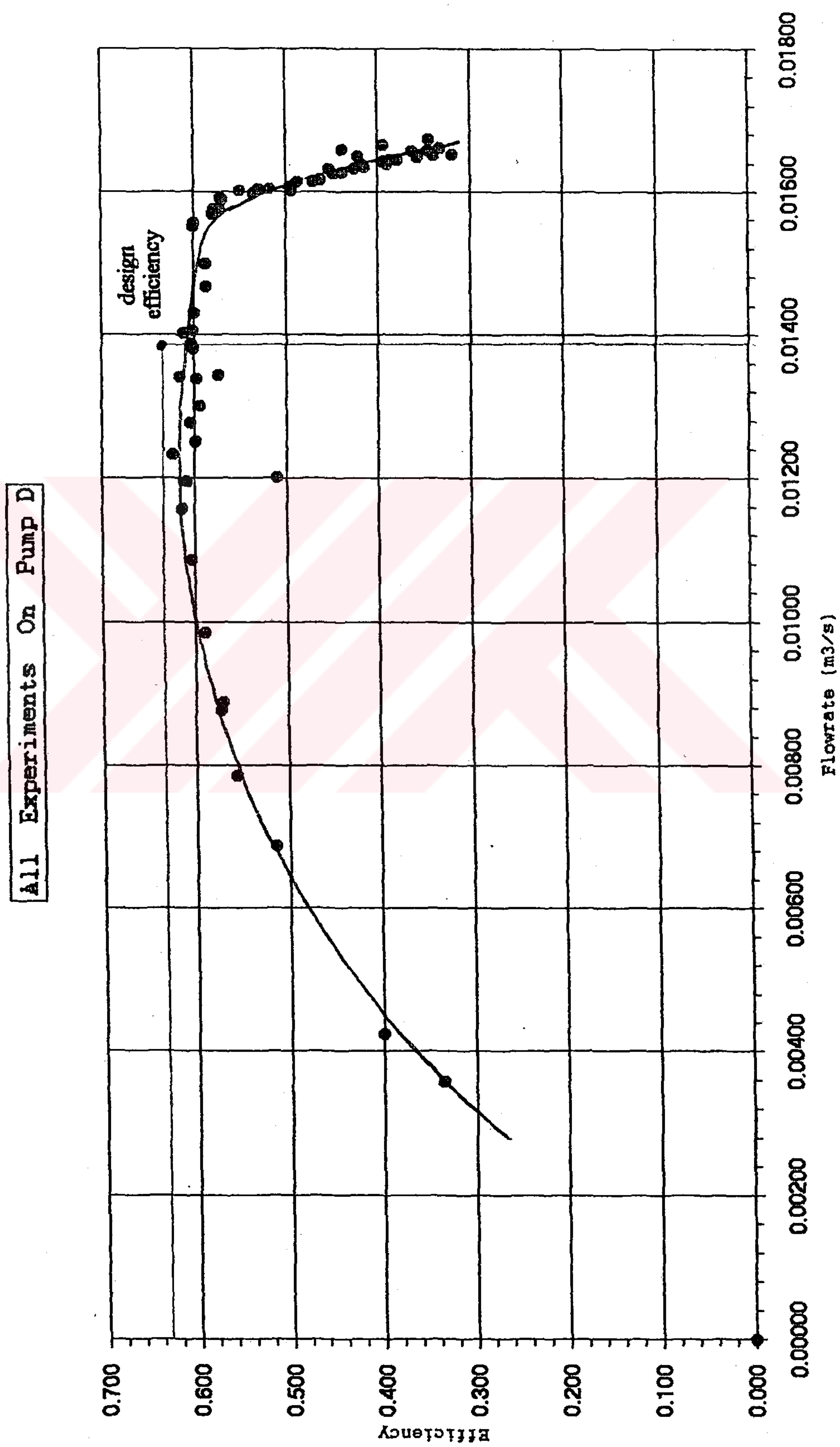
Power Wattmeter	hs	Del H	P gage	P gage calib	Pd	Ps	Vi	Vo	Q	Hi	Ho	Pump Head	Power Fluid	Efficiency	Motor Power	Qu	Hu	Pu
(kW)	mmHg	mm	bar	bar *	kPa	kPa	m/s	m/s	m3/s	m	m	m	kW	0.00	kW	m3/s	m	kW
0.72	40	0	4.45	4.8	496.4	0.1	0.00	0.00	0.00000	0.6	51.9	51.3	0.00	0.000	4.32	0.00000	45.6	3.6
0.96	45	32	4.25	4.6	476.1	-0.5	1.00	1.49	0.00380	0.6	49.9	49.3	1.84	0.335	5.76	0.00358	43.8	4.8
1.24	63	154	4.1	4.5	459.2	-2.9	2.19	3.28	0.00834	0.6	48.7	48.1	3.94	0.556	7.44	0.00786	42.8	6.2
1.325	79	192	4	4.4	448.5	-5.1	2.45	3.66	0.00931	0.4	47.7	47.3	4.32	0.571	7.95	0.00878	42.1	6.7
1.38	77	242	3.8	4.1	427.3	-4.8	2.75	4.11	0.01045	0.5	45.7	45.2	4.64	0.588	8.28	0.00986	40.2	6.9
1.495	89	334	3.6	3.9	406.0	-6.4	3.23	4.83	0.01228	0.5	43.9	43.4	5.23	0.612	8.97	0.01158	38.6	7.5
1.52	93	356	3.5	3.8	395.4	-6.9	3.33	4.99	0.01268	0.5	42.9	42.4	5.28	0.608	9.12	0.01195	37.7	7.6
1.54	96	390	3.3	3.6	374.1	-7.3	3.48	5.22	0.01327	0.5	40.9	40.4	5.26	0.597	9.24	0.01251	36.9	7.7
1.58	106	422	3.2	3.5	363.5	-8.7	3.63	5.43	0.01380	0.4	39.9	39.5	5.35	0.592	9.48	0.01301	35.1	7.9
1.57	104	447	3.1	3.4	352.9	-8.4	3.73	5.59	0.01421	0.5	38.9	38.4	5.36	0.597	9.42	0.01339	34.1	7.9
1.6	109	493	3	3.3	342.2	-9.1	3.92	5.87	0.01492	0.5	38.0	37.5	5.49	0.600	9.6	0.01407	33.3	8.0
1.62	115	537	2.8	3.1	321.0	-9.9	4.09	6.12	0.01557	0.5	36.0	35.5	5.42	0.586	9.72	0.01468	31.5	8.1
1.63	116	560	2.75	3.1	315.6	-10.0	4.18	6.25	0.01590	0.5	35.5	35.0	5.46	0.587	9.78	0.01499	31.1	8.2
1.66	124	614	2.6	2.9	299.7	-11.1	4.38	6.55	0.01665	0.5	34.1	33.6	5.49	0.578	9.96	0.01570	29.9	8.3
1.66	125	632	2.5	2.8	289.1	-11.2	4.44	6.64	0.01689	0.5	33.0	32.6	5.40	0.569	9.96	0.01593	28.9	8.3
1.66	125	637	2.3	2.6	267.8	-11.2	4.46	6.67	0.01696	0.5	30.9	30.4	5.06	0.534	9.96	0.01599	27.0	8.3
1.661	125	642	2.2	2.5	257.2	-11.2	4.48	6.70	0.01703	0.5	29.8	29.3	4.90	0.516	9.966	0.01605	26.1	8.3
1.64	125	649	2	2.3	235.9	-11.2	4.50	6.73	0.01712	0.5	27.7	27.2	4.57	0.487	9.84	0.01614	24.2	8.2
1.63	124	652	1.85	2.1	220.0	-11.1	4.51	6.75	0.01716	0.5	26.1	25.6	4.30	0.462	9.78	0.01618	22.7	8.2
1.62	123	659	1.75	2.0	209.3	-10.9	4.53	6.78	0.01726	0.5	25.0	24.5	4.14	0.447	9.72	0.01626	21.7	8.1
1.6	123	664	1.6	1.9	193.4	-10.9	4.55	6.81	0.01732	0.5	23.4	22.9	3.88	0.425	9.6	0.01633	20.3	8.0
1.57	122	667	1.5	1.8	182.7	-10.8	4.56	6.83	0.01736	0.6	22.3	21.8	3.71	0.413	9.42	0.01636	19.3	7.9
1.566	123	670	1.5	1.8	182.7	-10.9	4.57	6.84	0.01739	0.6	22.3	21.8	3.72	0.415	9.396	0.01640	19.4	7.9
1.53	121	673	1.35	1.6	166.8	-10.7	4.58	6.86	0.01743	0.6	20.7	20.1	3.44	0.394	9.18	0.01644	17.9	7.7
1.51	120	675	1.25	1.5	156.2	-10.5	4.59	6.87	0.01746	0.6	19.7	19.0	3.26	0.378	9.06	0.01646	16.9	7.6
1.47	119	678	1.1	1.4	140.2	-10.4	4.60	6.88	0.01750	0.6	18.0	17.4	2.99	0.356	8.82	0.01650	15.5	7.4
1.45	119	680	1	1.3	129.6	-10.4	4.61	6.89	0.01752	0.6	17.0	16.3	2.81	0.339	8.7	0.01652	14.5	7.3
1.437	117	681	0.9	1.2	118.9	-10.1	4.61	6.90	0.01754	0.7	15.9	15.2	2.62	0.319	8.622	0.01653	13.6	7.2
1.9	40	0	5	5.4	554.9	0.1	0.00	0.00	0.00000	0.6	57.9	57.3	0.00	0.000	11.4	0.00000	50.9	9.5
1.6	40	45	4.5	4.9	501.7	0.1	1.18	1.77	0.00451	0.7	52.6	51.9	2.30	0.251	9.6	0.00425	46.1	8.0
1.61	104	490	3.1	3.4	352.9	-8.4	3.91	5.85	0.01488	0.5	39.0	38.5	5.62	0.611	9.66	0.01402	34.2	8.1
1.6	109	360	3	3.3	342.2	-9.1	3.35	5.01	0.01275	0.3	37.5	37.2	4.66	0.510	9.6	0.01202	33.1	8.0
1.6	109	450	3	3.3	342.2	-9.1	3.75	5.61	0.01426	0.4	37.8	37.4	5.23	0.572	9.6	0.01344	33.2	8.0
0.72	42	0	4.3	4.7	480.4	-0.1	0.00	0.00	0.00000	0.6	50.3	49.7	0.00	0.000	4.32	0.00000	44.2	3.6
1.68	115	600	2.8	3.1	321.0	-9.9	4.33	6.47	0.01646	0.6	36.2	35.6	5.75	0.589	10.08	0.01552	31.6	8.4
1.61	150	660	1.65	1.9	198.7	-14.5	4.54	6.79	0.01726	0.2	23.9	23.8	4.02	0.437	9.66	0.01628	21.1	8.1
1.8	165	670	1.6	1.9	193.4	-16.5	4.57	6.84	0.01739	0.0	23.4	23.4	4.00	0.389	10.8	0.01640	20.8	9.0
1.52	121	675	1.3	1.6	161.5	-10.7	4.59	6.87	0.01746	0.6	20.2	19.6	3.36	0.367	9.12	0.01646	17.4	7.6
1.48	163	685	1	1.3	129.6	-16.3	4.62	6.92	0.01759	0.0	17.0	16.9	2.92	0.346	8.88	0.01658	15.0	7.4
1.5	160	685	1.1	1.4	140.2	-15.9	4.62	6.92	0.01759	0.1	18.1	18.0	3.10	0.362	9	0.01658	16.0	7.5
1.44	160	688	0.9	1.2	118.9	-15.9	4.63	6.93	0.01763	0.1	15.9	15.8	2.74	0.333	8.64	0.01662	14.1	7.2
1.56	155	665	1.5	1.8	182.7	-15.2	4.55	6.81	0.01733	0.1	22.3	22.2	3.78	0.424	9.36	0.01634	19.7	7.8
1.59	150	650	1.8	2.1	214.6	-14.5	4.50	6.74	0.01713	0.2	25.5	25.4	4.26	0.469	9.54	0.01615	22.5	8.0
1.63	150	645	2	2.3	235.9	-14.5	4.49	6.71	0.01707	0.1	27.7	27.5	4.61	0.495	9.78	0.01609	24.4	8.2
1.58	125	480	3	3.3	342.2	-11.2	3.87	5.79	0.01472	0.2	37.9	37.7	5.44	0.603	9.48	0.01388	33.5	7.9
1.62	134	560	2.7	3.0	310.3	-12.4	4.18	6.25	0.01590	0.2	35.0	34.7	5.42	0.585	9.72	0.01499	30.8	8.1
1.635	145	620	2.5	2.8	289.1	-13.9	4.40	6.58	0.01673	0.2	33.0	32.8	5.39	0.577	9.81	0.01577	29.2	8.2
1.642	156	640	2.3	2.6	267.8	-15.3	4.47	6.69	0.01700	0.1	30.9	30.8	5.14	0.548	9.852	0.01603	27.4	8.2
1.626	145	640	2	2.3	235.9	-13.9	4.47	6.69	0.01700	0.2	27.7	27.4	4.58	0.493	9.756	0.01603	24.4	8.2
1.65	142	620	2.5	2.8	289.1	-13.5	4.40	6.58	0.01673	0.2	33.0	32.8	5.38	0.571	9.9	0.01577	29.1	8.3
1.58	126	475	3	3.3	342.2	-11.3	3.85	5.76	0.01465	0.2	37.9	37.7	5.42	0.600	9.48	0.01381	33.5	7.9
1.53	128	406	3.2	3.5	363.5	-11.3	3.56	5.32	0.01354	0.1	39.8	39.7	5.28	0.604	9.18	0.01277	35.3	7.7
1.45	118	698	1	1.3	129.6	-10.3	4.67	6.98	0.01775	0.7	17.0	16.4	2.85	0.344	8.7	0.01674	14.5	7.3
1.47	117	692	1.25	1.5	156.2	-10.1	4.65	6.95	0.01768	0.7	19.7	19.0	3.30	0.393	8.82	0.01667	16.9	7.4
1.5	115	686	1.5	1.8	182.7	-9.9	4.63	6.92	0.01760	0.7	22.4	21.7	3.76	0.437	9	0.01659	19.3	7.5
1.55	114	679	1.5	1.8	182.7	-9.7	4.60	6.89	0.01751	0.7	22.4	21.7	3.72	0.421	9.3	0.01651	19.3	7.8
1.6	111	664	1.75	2.0	209.3	-9.3	4.55	6.81	0.01732	0.7	25.0	24.3	4.13	0.452	9.6	0.01633	21.6	8.0
1.63	108	650	2	2.3	235.9	-8.9	4.50	6.74	0.01713	0.7	27.7	27.0	4.53	0.487	9.78	0.01615	23.9	8.2
1.64	106	642	2.25	2.5	262.5	-8.7	4.48	6.70	0.01703	0.7	30.4	29.6	4.95	0.526	9.84	0.01605	26.3	8.2
1.647	103	630	2.5	2.8	289.1	-8.3	4.43	6.63	0.01687	0.8	33.0	32.3	5.34	0.567	9.882	0.01590	28.7	8.3
1.652	99	604	2.75	3.1	315.6	-7.7	4.34	6.49	0.01652	0.8	35.7	34.9	5.65	0.599	9.912	0.01557	31.0	8.3
1.62	84	510	3	3.3	342.2	-5.7	3.99	5.97	0.01518	0.8	38.0	37.2	5.54	0.598	9.72	0.01431	33.0	8.1
1.577	76	449	3.25	3.6	368.8	-4.7	3.74	5.60	0.01424	0.8	40.5	39.7	5.54	0.615	9.462	0.01342	35.2	7.9
1.52	66	378	3.5	3.8	395.4	-3.3	3.44	5.14	0.01308	0.9	43.0	42.1	5.41	0.622	9.12	0.01233	37.4	7.6
1.46	53	294	3.75	4.1	422.0	-1.6	3.03	4.53	0.01152	0.9	45.4	44.5	5.03	0.603	8.76	0.01086	39.5	7.3
1.33	39	197	4	4.4	448.5	0.3	2.48	3.71	0.00943	0.9	47.8	46.8	4.33	0.570	7.98	0.00889	41.6	6.7
1.2	26	118	4.25	4.6	475.1	1.7	1.92	2.87	0.00730	1.0	50.2	49.2	3.52	0.514	7.2	0.00688	43.7	6.0
1	17	45	4.5	4.9	501.7	3.2	1.18	1.77	0.00451	1.0	52.6	51.6	2.26	0.400	6	0.00425	45.9	5.0
0.73	8	0	4.6	5.0	612.3	4.4	0.00	0.00	0.00000	1.1	53.6	52.5	0.00	0.000	4.38	0.00000	46.6	3.7

APPENDIX J

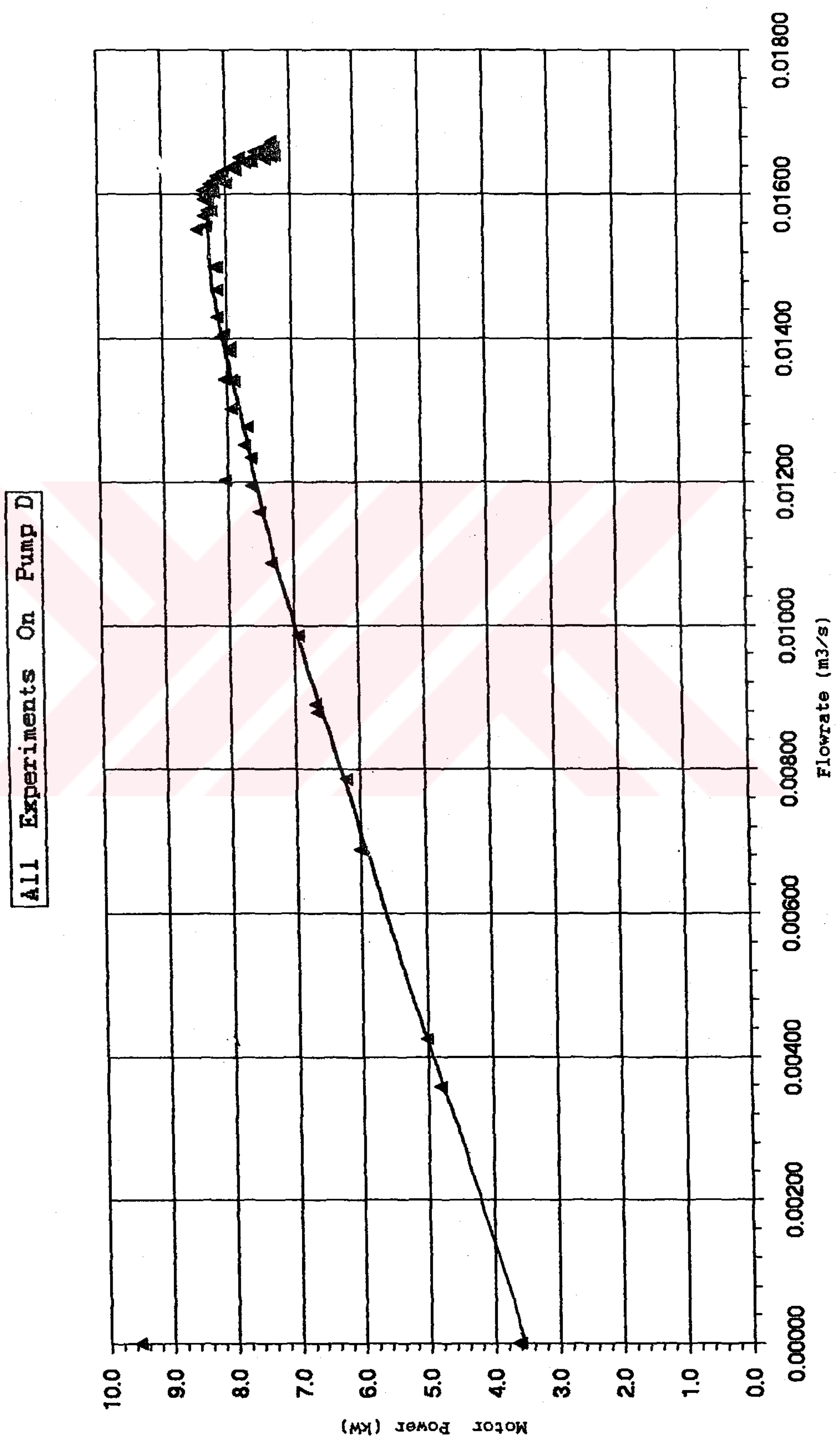


All Experiments On Pump D
Design Point
Head (m)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Flowrate (m3/s)
0.00000
0.00200
0.00400
0.00600
0.00800
0.01000
0.01200
0.01400
0.01600
0.01800

APPENDIX J


All Experiments On Pump D
design efficiency
Efficiency
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Flowrate (m3/s)
0.00000
0.00200
0.00400
0.00600
0.00800
0.01000
0.01200
0.01400
0.01600
0.01800

APPENDIX J


All Experiments On Pump D
Flowrate (m3/s)
Motor Power (kW)
0.00000
0.00200
0.00400
0.00600
0.00800
0.01000
0.01200
0.01400
0.01600
0.01800
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

APPENDIX K

USER MANUAL

To have the prototype impellers one must start by running the Centrifugal Pump Impeller Design Program (CPID). The CPID code uses drive A: and operates on PC. After the serial number is typed correctly, proceed by following the instructions. The instructions in the programme guides the designer efficiently and tricks are explained by Talayhan in his thesis [16].

To obtain geometric data of the impeller two methods are available:

a) Open the CPID outputs on the DRHALO graphics programme

- Obtain the view editing menu in design programme (CPID)
- Select option "P", type the letter for the desired figure.
- Insert graphics disk which must be blank
- Press Alt+PrtScr when message OK. appear.
- The selected drawings will be saved as DRHALO files. (DRHALO1000) These files can be manipulated using DRHALO facilities.
- With the cursor co-ordinates of streamlines or pattern crosssections can be read.
- Input these points to the ICEM design environment.

b) Using directly the plot files of CPID

To model the impeller surface on ICEM, either pattern crosssections curves with their z values or streamlines in both meridonial and blades views are needed.

After the view editing menu is run CPID code produces three extra files:

BLCRS.DAT, Co-ordinates of the points on hub shroud lines and various blade streamlines at meridonial view.

PATTERN.DAT, Co-ordinates of the points on hub, shroud lines and blade streamlines at blade view.

PATCS1, Pattern crosssections on blade view. (The z heights is obtained by plotting a meridonial view)

It is possible using ICEM ' s INPUT/ OUTPUT function to import all the data files to the design environment, however since few points produce smooth and easily manipulatible curves, some of these points must be deleted.

After importing data points to ICEM. Generate surface curves (either pattern crosssections or surface streamlines). Using these curves obtain B- Spline surfaces. Before starting to the toolpath simulation, all detail drawings must be complete, the tools to be used should be decided, and tool holder geometry should be specified. Then;

- Create toolpaths
- Create CLTAPE and CLPRINT in ICEM
- Convert these files into the form which can be processed by the postprocessor. Use ICEMCLT software.
- Start "camgener"

- Input the postprocessor name and cld file name
- Direct the resulting files with the tap extensions to the milling machine controller. Use software happycam.
- For the shapes and dimensions of stock workpieces see Appendix F.