DIPLOMARBEIT von
cand. aer. NIKOLOPOULOS Konstantinos
Matr. Nr. 1350924

Ausgefuehrt an den

Universitaet von Stuttgart- Institut fuer Aero- & Gasdynamik (IAG)

und

Nationale Technische Universitaet von Athen - Labor fuer thermische Turbomachinen (LTT)

BETREUER: Dr.-Ing. Ekkerhardt SCHMIDT

MAI 2000

SUBJECT OF THE DIPLOMA THESIS

„Preliminary Design of a Radial Flow Compressor“

The aim of this work is to develop a method, if possible fully automatic, in order to obtain the basic geometry of a radial compressor.

A meridional flow solver will be used as the basis for the design procedure. Using this solver and changing successively the hub and tip wall shapes, as well as the blade shape, the specific aim will be to obtain as close as possible a specified suction side velocity distribution. The tip section will be considered.

In order to obtain this result, the hub and tip meridional lines will be approximated by Bezier curves. The shape of the mean blade surface will be provided by the tip line from each point of which a straight line will be issued towards the hub with a prescribed peripheral lean angle in respect to the radial direction. The thickness distribution will be given as well. Inlet conditions and rotating speed will be also specified.

Each time the corresponding Bezier curve will be deformed, until the goal set is reached as close as possible. At the end of each line modification a smoothing procedure will follow, in order to adapt the line to preset standards, keeping it though as close as possible to the computation results. For instance, inflection points will be avoided for the line representing the tip meridional wall.

The three successive correction procedures will be applied first independently. The resulting changes will be studied and proposals for shortening computational time and rendering the computational procedure automatic will be advanced on the basis of the experience acquired.

Prof. Dr-Ing. Ekk. Schmidt *Prof. Dr K.D. Papailiou*

I wish to herewith thank *Prof. Ekk. Schmidt* for being my supervisor and for supporting me in preparing this thesis at all stages and *Prof. K.D. Papailiou* not only for giving me the possibility of using all the facilities of his laboratory but also for providing me with his deep knowledge and guidance throughout the project. I must also mention *M.Eng. P. Kioussis* for helping me in all practical aspects in an almost daily basis and last but not least my parents for their support during my study years.

TABLE OF CONTENTS

SCOPE OF THE THESIS

The aim of the present diploma thesis is to develop a semi-automatic method for determining the basic geometry of a radial or mixed-flow compressor or turbine. The basis of the flow calculation used is the well known meridional flow theory. We have used a meridional flow solver developed entirely at the Laboratory of Thermal Turbomachines (LTT) at NTUA. The geometry of the turbomachine or channel is approximated and varied by using Bézier curves. They are generated by a custom made program for generating lines using the Bézier equations and the De Casteljau‘ s algorhythm. By combining the flow solver and the Bézier Curve generator we tried to optimize the geometry of the channel in order to achieve desired pressure distributions on the blade.

Special attention has been given to finding a simple and fast method for getting results that will then be treated as basis for more detailled investigations by taking more parameters into the flow solver or by using other solvers.

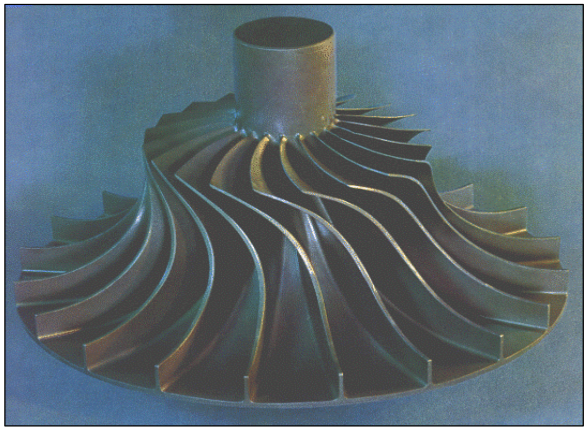
As practical example we have used a mixed-flow compressor, part of the TETLEI 2-gas turbine project that has been extensively calculated at LTT in the past in order to have a good reference.
TETLEI (Turbine Electric Taxi for Low Environmental Impact) was a vehicle with a series hybrid powertrain (made up from a gas turbine and an electric motor), and a traction battery. TETLEI had two modes of operation: Zero Emissions Vehicle (ZEV) mode (using the batteries and motor) and Hybrid Electric mode (using the engine as a generator to drive the motors and charge the batteries as required).

Finally more refinements of the method are being presented and the problems encountered are thoroughly analyzed and possible solutions discussed.

INTRODUCTION

Modern flow analysis and calculations by using advanced computing techniques and devices are today commonplace in the world of turbomachines and mechanical engineering in general. The basic philosophy of approaching an optimum design by making assumptions and testing simple cases first is still applicable. In the „direct-“ or design-method of achieving desired flow characteristics we are varieting the geometry. We are almost always confronted with geometrical or other physical constraints.

One of the most interesting examples for designing is the mixed-flow turbomachine (a radial one being a special case of a mixed-flow one). It is used in all modern turbochargers and produces high pressure ratios in only one stage. It is compact, reliable and can be designed to serve various purposes. One of the drawbacks is its complex shape. It is relatively difficult to manufacture and even more difficult to perform a real 3D calculation on it. Thus it serves as a good example for finding a good methodology of getting reliable results that are later used for more complex methods of calculation and design.
A typical radial turbocharger disc is shown beneath:



In the present thesis we like to gain insight into the basic tendencies of the meridional flow by viewing the parametric solution from the correspondent change of the geometry. We have the possibility of changing more than one parameters- e.g. geometric and inlet data, the solver complexity (with or without viscous effects etc) and other built-in variables of the solver (smoothing, assumptions on the pressure distributions, numerical solution methods used etc.). In our case we will obtain solutions by retaining the basic inlet data and the same solver (inviscid, numerical methods always the same). For more detailed data on the assumptions taken for our analysis please refer to CHAPTER 5 – GENERAL ASSUMPTIONS

Our main ‘variables‘ will be the form of the hub and the beta-distribution of the blade since we know from experience and viscous solvers that changing the tip form can easily cause separations. Apart from that manufacturing a complex shaped profile of a case for the tip (cascade) is sometimes impossible whereas the profile of the hub poses no problem. The distribution of the beta-angles is the second serious parameter that will be taken into account.

Equations used:

RADIAL AND MIXED FLOW TURBOMACHINES

All internal flow devices are governed by the *NAVIER-STOKES* equations. As known they are a set of nonlinear partial differential equations that are elliptic in space for steady & incompressible flow. For reducing the computing time various assumptions are taken into account. In our case by assuming incompressible and steady flow without thermal effects we are actually taking the LAPLACE-equation as basis:

$$\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} = 0$$

It is representative of equilibrium or incompressible problems , there is no 'time' involved ($t \rightarrow \infty$)
All points instantaneously effect all other points ! ('infinite' wave speed)
We need to specify two boundary conditions in each coordinate direction but no no initial conditions are required.

MERIDIONAL THEORY

The „Meridional Theory“ is solving a quasi-2D flow problem instead of the real 3D prolem by taking into account the so-called S1-S2 surfaces as first developed by *WU* in the 1950s and *VAVRA* almost at the same time and the radial equilibrium equation. For more details please refer to the following CHAPTER 1 – THE MERIDIONAL THEORY

BÉZIER CURVES

Curves can be described in various ways (parametric, nonparametric, through equations etc. One such description is the one proposed by Bezier. Bezier curves are named after the French mathematician Pierre Bezier, who developed them at first for use in the automobile industry in the 1950‘s. These curves are described or defined by using an algorhythm and they are quite easily visualized and computed. That is the main reason that almost all computers are using today the Bezier curves as their graphics basis. A short introduction into the Bezier Curves is presented in

SYMBOLS AND ABBREVIATIONS USED

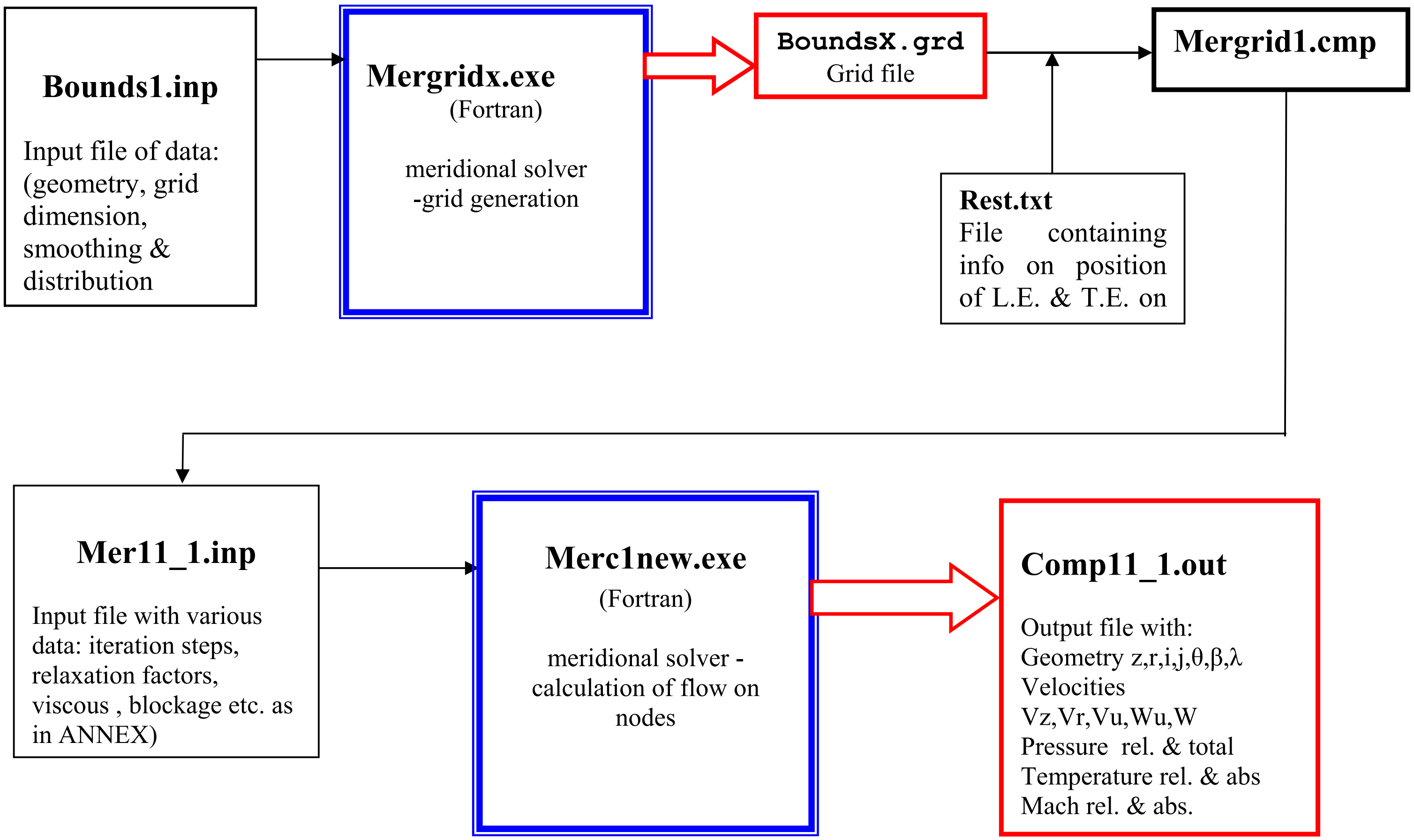
SYMBOL/ ABBR.		
b_i	$\in E^3$	Point (Bezier curve)
LE	-	Leading Edge
Ma	-	Mach Number= velocity/speed of sound
n,r, i	$\in N$	Variable
PS	-	Pressure side
SS	-	Suction side
t , u , a	$\in R$	Variable
TE	-	Trailing Edge
α	radians	Alpha angle
β	radians	Beta angle
θ	radians	Theta angle

CHAPTER 1 – THE MERIDIONAL THEORY

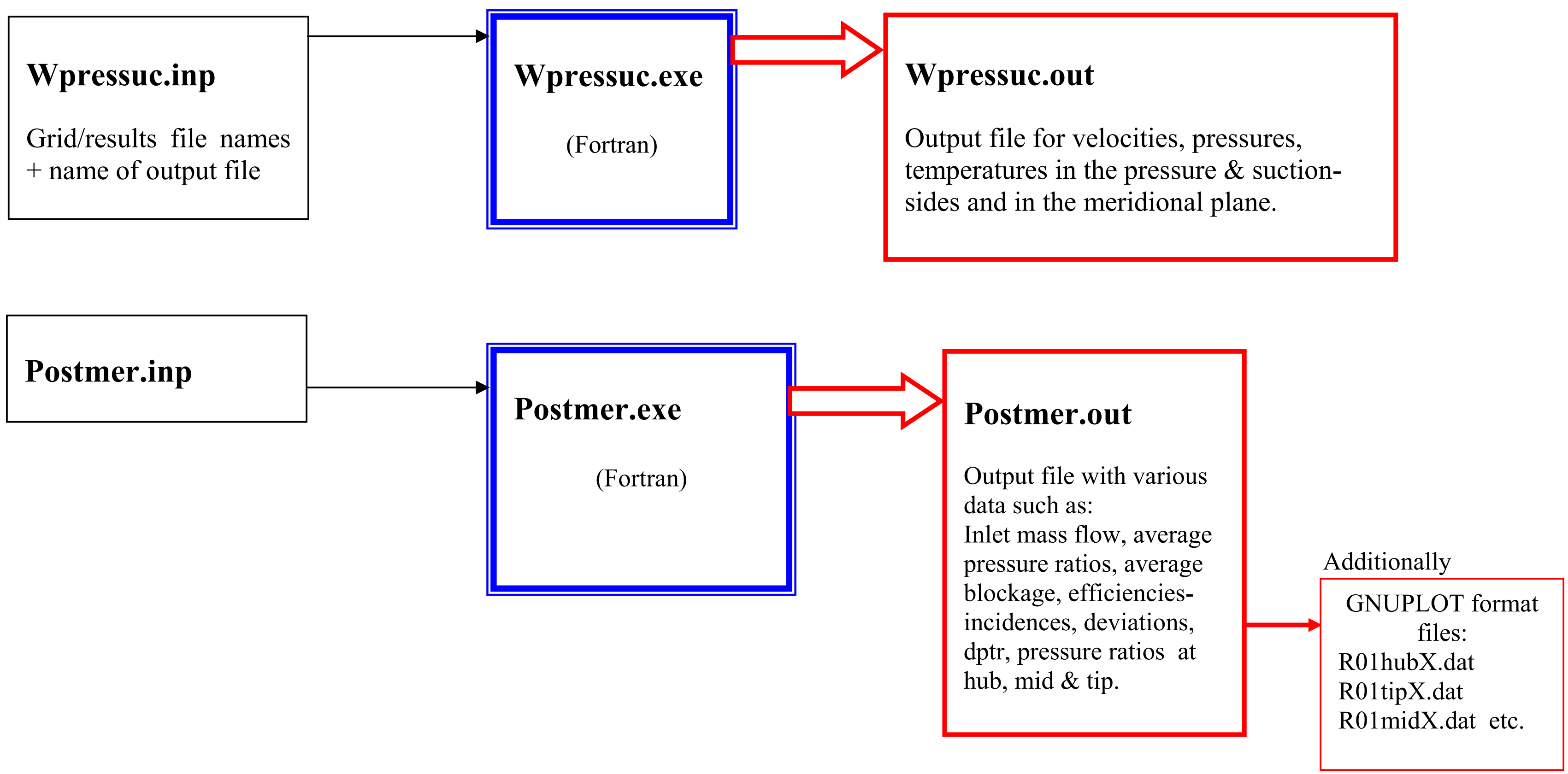
CHAPTER 2- THE MERIDIONAL SOLVER USED

A modular program has been used as basis for getting results for various flow characteristics. Its basis theory has been depicted in th previous chapter. Though the solver itself was not subject of this diploma thesis it is important to present the main characteristcs and input-output that has been used. A generic flowchart of the meridional solver and the post processing package can be viewed in the following two pages.
More specifically:
The main program of the meridional solver is written in FORTRAN and has been converted into an executable file (binary) so that it can be „ran" directly without the use of a FORTRAN compiler . It consistsmainly of the data input, a grid generator, the meridional solver itself and various integrated numerical routines (smoothing, eror control etc) . The postprocessor is used for the graphical output (usually for the Gnuplot- format) as well as the file processing and calculating the desired velocity/pressure distributions at the tip side of the blade. Both postprocessors are written in FORTRAN and also converted to executable binary files.
Both the above are 'called' by a BATCH-file that „calls" all necessary input files and the relevant subprograms in order to run more than one cases automatically and fast without manual input each time.
We only have to change the input files, i.e. the distributions in our case and we have results in a few minutes „runtime". In further investigations more refinements can be taken into account by varying other variables (for example the smoothing, the number of interpolations or the total ressure loss assumptions)

MERIDIONAL SOLVER FLOWCHART



POSTPROCESSING FLOWCHART



CHAPTER 3- THE BÉZIER CURVES THEORY

GENERAL

The theory of parametric surfaces (and curves) was well known in differential geometry but applications in design was not very extensive before the 1950s. The use of the parametric curves with the emerging of computing devices led in the 1960s to the Computer Aided Geometric Design. One can say that a major milestone was the theory of the Bézier curves/Surfaces and the so called Coons patches. Later the B-Spline methods extended the Bézier theory to what is today's standard in computer graphics and design.

The Bézier curves and surfaces were developed independently by two european Engineers, P. de Casteljau (Citröen) and P. Bézier (Rénault). They developed a mathematical curve formulation which is very easily adapted to a computer system and very useful for modeling and design in general. The Bézier curves are curves that can be designed by a simple subdivision method (divide-and-conquer) or recursive and this was how they were first defined by De Casteljau. They are also (mathematically) analytically defined (quadratic, cubic or higher degree) usually using the so called Bernstein polynomials as shown beneath.
They are numerically very stable so that they form the ideal geometry standard for representing piecewise polynomial curves. A Bézier curve is "stretched" or controlled by the position of points, which are hereafter called "control points" of the Bézier curve.

The De Casteljau Algorhythm

A simple recursive formula can be used to generate a polynomial curve of arbutrary degree n. The so called "de Casteljau algorhythm" generates each point of a Bezier curve from a repeated linear interpolation.

With $b_0,b_1,b_2,\ldots..,b_n \in E^3$ and $t \in R$

Set

$$b_i^r(t) = (1-t)b_i^{r-1}(t) + tb_{i+1}^{r-1}(t)$$

and

$$b_i^0(t) = b_i$$

with $r=1,2,\ldots..,n$ and $i=0,1,\ldots.,n-r$

The Bezier Curve is then formed by the points :

$$b_0^n(t)$$

The vertices b_i are the the control points and the polygon formed with these vertices $b_0,b_1,\ldots..,b_n$ is called the control polygon of the Bezier curve $\mathbf{b^n}$.

In our case we have developed a Bezier Curve Generator using a Bezier curve of the third degree (n=3). In this case the de Casteljau algorhythm yields:

n=3
r=1,2,3
i = 0,…,3-r
t $\in$ R $\wedge$ [0,1]

$$b_0^1(t) = (1-t)b_0^0(t) + tb_1^0(t)$$

$$b_1^1(t) = (1-t)b_1^0(t) + tb_2^0(t)$$

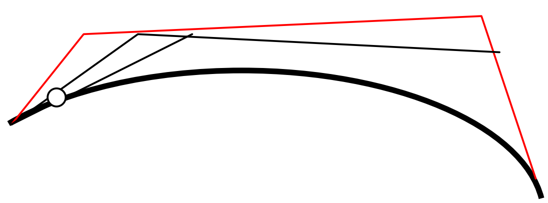
$$b_2^1(t) = (1-t)b_2^0(t) + tb_3^0(t)$$

$$b_0^2(t) = (1-t)b_0^1(t) + tb_1^1(t)$$

$$b_1^2(t) = (1-t)b_1^1(t) + tb_2^1(t)$$

$$b_0^3(t) = (1-t)b_0^2(t) + tb_1^2(t)$$

Thus we can calculate any point of the Bezier Curve by calculating for a given t starting from the control points b_0,b_1 and b_2 and proceeding to new control points, between which we take a new intersection at t and so on. Finally for n=3 and if we do so for all t's between 0 and 1 we get a Bezier Curve (actually a 3rd degree polynomial) with starting point at b_0 and ending point at b_3
As shown in the diagram beneath:



The Bernstein Form of the Bézier Curve

One explicit representation for a Bezier Curve is given with the help of the Bernstein Polynomials. These are defined by

$$B_i^n(t) = \binom{n}{i} t^i (1-t)^{n-i}$$

With

$$\binom{n}{i} = \frac{n!}{i!(n! - i!)}$$

The Bernstein polynomials are nonnegative over t = 0 to 1 and the *intermediate* "de Casteljau" points can be expressed by Bernstein polynomials of the degree r :

$$b_i^r(t) = \sum_{j=0}^{r} b_{i+j} B_j^t(t)$$

i $\in$ {0,n-r}

For the case r=n we get the points on the Bezier Curve, thus:

i=0 $\wedge$ r=n $\Rightarrow$

$$b_0^n(t) = \sum_{j=0}^{n} b_j B_j^n(t) = \sum_{j=0}^{n} b_j \binom{n}{j} t^j (1-t)^j$$

In our case again for n=r=3 we obtain:

$$b_0^3(t) = \sum_{j=0}^{3} b_j B_j^3(t) = \sum_{j=0}^{3} b_j \binom{3}{j} t^j (1-t)^j$$

$$= b_1 \binom{3}{1} t(1-t)^1 + b_2 \binom{3}{2} t^2 (1-t)^2 + b_3 \binom{3}{3} t^3 (1-t)^3$$

$$= 3b_1 t(1-t) + 3b_2 t^2 (1-t)^2 + b_3 t^3 (1-t)^3$$

Properties of the Bezier Curves

Bezier curves possess some very useful properties. Most important of these are the affine invariance, invariance under affine parameter transformations, the convex hull property and the endpoint interpolation.
Affine tranformation is important because the curve can easily be rotated, scaled etc. Bezier curves are invariant against affine transformations- this is very important because applying an affine transformation to a computed curve or applying the transformation on the control polygon and then calculate the curve has the same results. An affine transforamation is for example a rotation by 23 degrees. We can rotate the control points only and then calculate the new curve instead of calculating the whole curve and then rotate all the points of the curve.
Affine parameter transformations are important because we do not have to calculate a Bezier curve for an interval [0,1]. We can extend all our calculations to any interval [a,b] while for easiness we can use the form interval [0,1] by introducing a local parameter t=(u-a)/(b-a).

$$\sum_{i=0}^{n} b_i B_i^n(t) = \sum_{i=0}^{n} b_i B_i^n \left(\frac{u-a}{b-a}\right)$$

The Bezier curve for $t \in [0,1]$ lies in the convex hull of the control polygon. That will be very useful in our case since it assists immensely to the visualization and the correct "guessing"of the curve to be derived since we modify the control polygon in order to obtain a new curve each time!
The Bezier curve passes through b_0 and b_n . That is always very useful since we know the starting and end points and since these are fixed control points.

Other properties include:

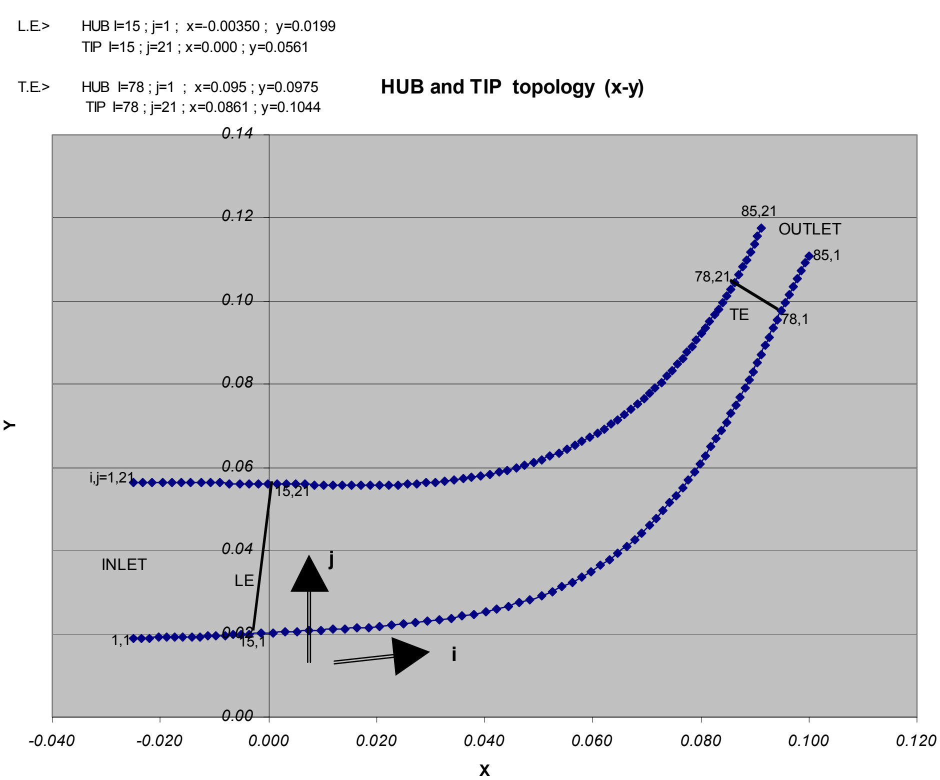
The derivative of the Bezier curve is another Bezier curve, obtained by differentiating the original control polygon. It is called a hodograph. All derivatives of a Bezier Curve can also be calculated by using the "de Casteljau algorhythm".
Bernstein polynomials are symmetric with respect to t and (1-t) which means that the order of the Bezier points does not matter – b_o, b_1 …. b_n is the same as using b_n, b_{n-1}, …. b_o
Pseudo-local control is also useful in visualization. If we move only one of the control points then the curve is mostly affected where t=i/n (because the Bernstein -polynomials have their maximum there).

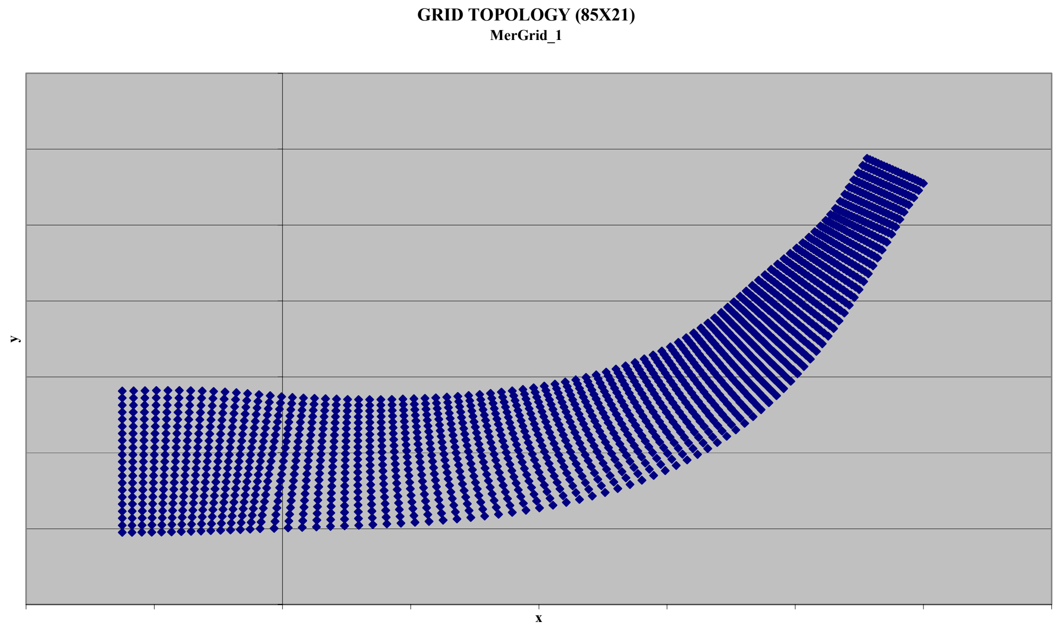
CHAPTER 4- THE BÉZIER CURVES GENERATOR

A separate program in FORTRAN is used for the calculation of any desired BÉZIER-curve. That program approximates the initial geometry and by varying the coefficients another BÉZIER-curve is generated that is then used as a new hub- or tip- or beta-distribution. That would not be practical if it would not be graphically illustrated somehow. That is the purpose of a small VISUAL BASIC module that displays the initial BÉZIER curve and their control points- when running the module it is possible to move any control point so that a new curve is generated and displayed in real-time. The new curve is then used as input for the meridional flow solver and so on.

CHAPTER 5 – GENERAL ASSUMPTIONS AND DATA OF REFERENCE CASE INVESTIGATED

The geometry of inlet, outlet, blade and all inlet data (RPM, Temperature, velocity distribution etc.) are given (ANNEX A- TETLEI 2, FLOW & BOUNDARIES DATA).
The meridional solver is used for determining the flow at a grid that lies in a meridional plane and thus with an assumption the flow data is calculated on the blades (SS and PS).




GRID TOPOLOGY (85X21)
MerGrid_1
y
x

CHAPTER 6- RESULTS OF COMPUTATIONS

Various sets of calculations have been produced. We will present at first parametric solutions acquired by changing the geometry of specific regions:

No.	HUB or TIP	BLADE AREA concerned	No. of diagrams	Designation Notes
1	HUB	Forward (near LE)	3	HUB_FORWARD X
2	HUB	Middle	3	HUB_MIDDLE X
3	HUB	End (near TE)	3	HUB_END X
4	TIP	Forward (near LE)	3	TIP_FORWARD X
5	TIP	Middle	3	TIP_MIDDLE X
6	TIP	End (near TE)	3	TIP_END X

* LE= Leading Edge TE=Trailing Edge X=variable number

Then combinations of geometric changes have been examined. A total of 10 diagrams are presented in this Chapter (representing a selection of interesting or „good“ results). The designation is more arbitrary for these cases (are numbered as presented).

CHAPTER 8 - CONCLUSION

- Further documentation on solver, if required,
- Documentation on the VISUAL BASIC module (Bézier),
- Results of independent variations are to be analyzed and presented,
- Refinements on geometry assumptions will be entered after results will be studied,
  any significant problems uptodate or possible weaknesses in the future are to be denoted and their impact is to be estimated
- If possible some degree of automation or at least a user-friendly input-output shall be developed,
- Proposals for further developments shall be suggested,
- Final documentation and plots.

ANNEXES

ANNEX A- TETLEI 2, FLOW & BOUNDARIES DATA

Flow and gemetric data (constant throughout this thesis)

Total number of blades: 11

Design rotational speed of compressor: 48000 RPM

$\gamma = c_p/c_v = 1.395$

Rg = 287.5 (Gas constant)

INLET MASS FLOW 1.302016761069339

OUTLET MASS FLOW 1.303727865080600

MASS AVERAGE PRESS RATIO = 5.236

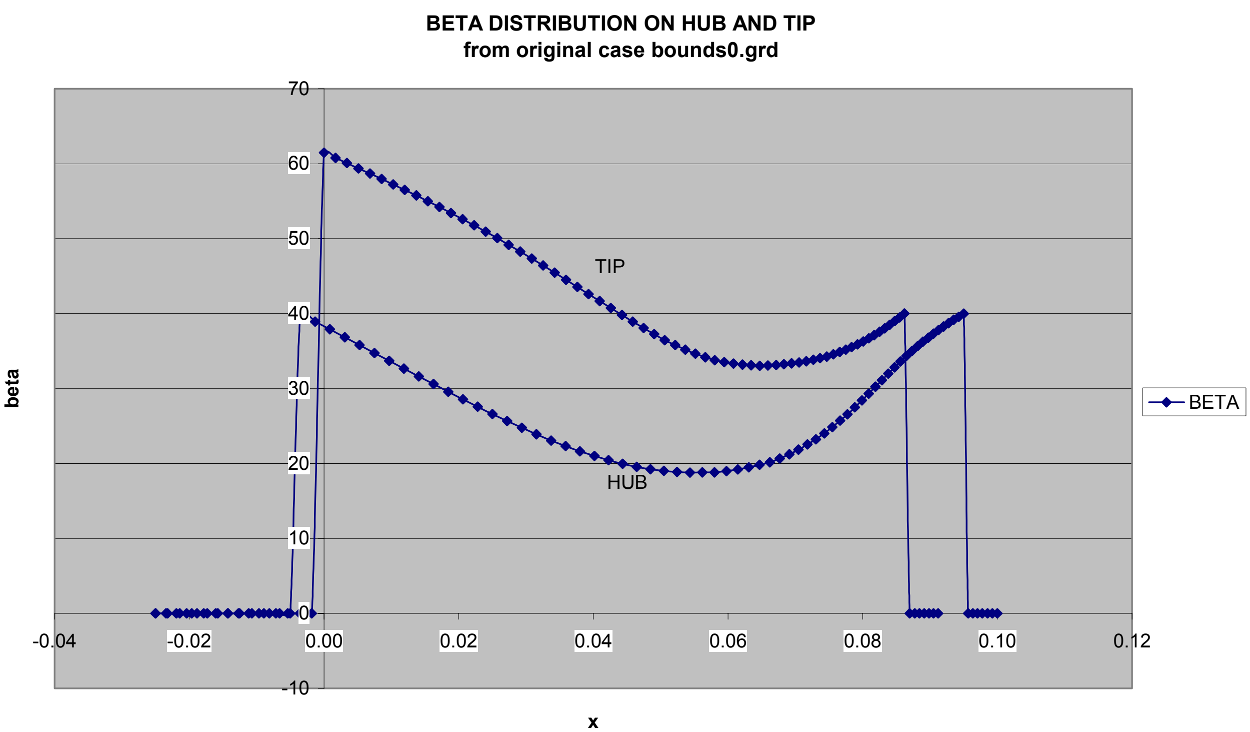
MASS AVERAGE BLOCKAGE = 0.1640

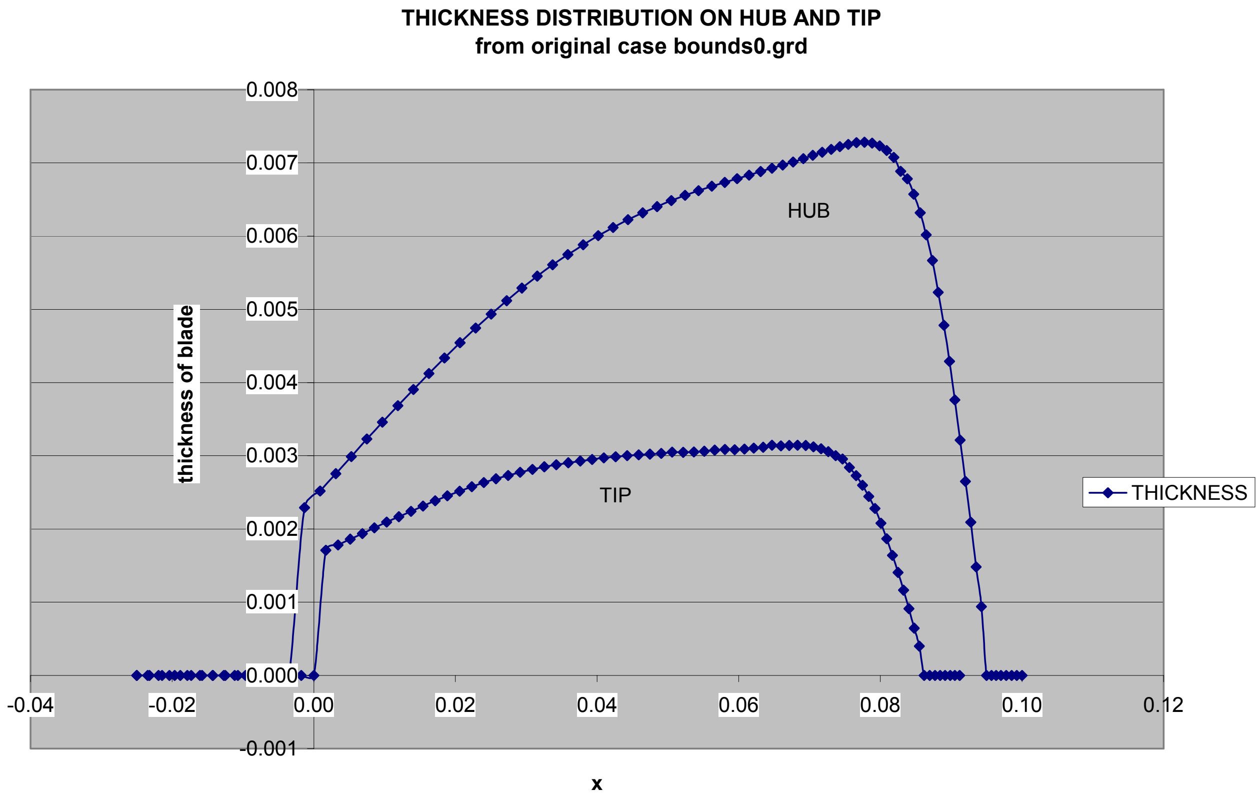
	HUB	MID	TIP
EFFICIENCY :	0.8800	0.8884	0.8986

	HUB	MID	TIP
INCIDENCE :	1.3609596	3.7706195	3.1440602
INC AF. BL. :	-9.263925	-3.052856	-.8278779
Deviation :	9.9999622	9.9999762	9.9999659
Delta BETA :	0.0051026	10.700456	21.476405
PITCH to CHORD :	0.5659700	10.700456	0.6918320
LOSS δP_{tr} : .	0.550E+05	0.550E+05	0.550E+05
Pressure ratio :	5.1973427	5.3371469	5.5138096

__________Blade Row Number_________ { 1 }

Axial Length.............…………..	0.099
Inlet Tip Radius........…………..	0.056
Inlet Hub/Tip Ratio........………	0.356
Outlet Mean Diameter......…….	0.201
Outlet tip radius..........………...	0.104
Inlet rel. Mach at Tip......……...	0.883
Inlet Tip Blade Angle......……...	61.476
Outlet Mean Blade Angle....……	40.211
Outlet Mean Abs. Flow Angle…	-76.752
Lamda at Tip-T.E..........………	66.575




THICKNESS DISTRIBUTION ON HUB AND TIP
from original case bounds0.grd
thickness of blade
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
-0.001
-0.04
-0.02
0.00
0.02
0.04
0.06
0.08
0.10
0.12
x
HUB
TIP
THICKNESS

ANNEX B- MERIDIONAL SOLVER DOCUMENTATION

mergrid.exe + bounds.inp file

		POSSIBLE VALUES	DATA USED in BOUNDS.INP	NOTES
1	Type of parameter for B-splines		2	
	Enhanced CL	0		
	Eq. Distance	1		
	CL (chord length)	2		
	Centri pedal	3		
2	Smoothing	Y=1	1	
3	Enter subfix for output file	" "	bounds1	produces *.grd,*.lpc,*.crv
4	Desired grid dimension (<300X300)	(x,y)	85 21	
5	Type the Data file name	"…."	bounds1.cmp	
6	Smooth Hub (using Sbr SG13) subroutine	Y=1	0	
7	Smooth Tip (using Sbr SG13)	Y=1	0	
8	Isodistribute into the j-direction		1	INVISCID
	the points on LE,TE & isostations lines	Y=1		
	OR log distribution near Hub AND Tip	Y=0		
	OR geom. distribution near Hub OR Tip	Y=2		
9	Smooth INLET (using Sbr SG13)	Y=1	0	
10	Smooth OUTLET (using Sbr SG13)	Y=1	0	
11	For blade No (1) - LE / smooth LE or TE (using Sbr SG13)	Y=1	0	
12	For blade No (1) - TE / smooth LE or TE (using Sbr SG13)	Y=1	0	
13			2	
	Linear internal node distribution mode	Y=1		
	Simple Laplacian Grid	Y=2		
	Thomas Middlecoff method	Y=3		* in case of stretching use (3)
14	Continue finding intersections more accurately using B-Splines	Y=1	0	

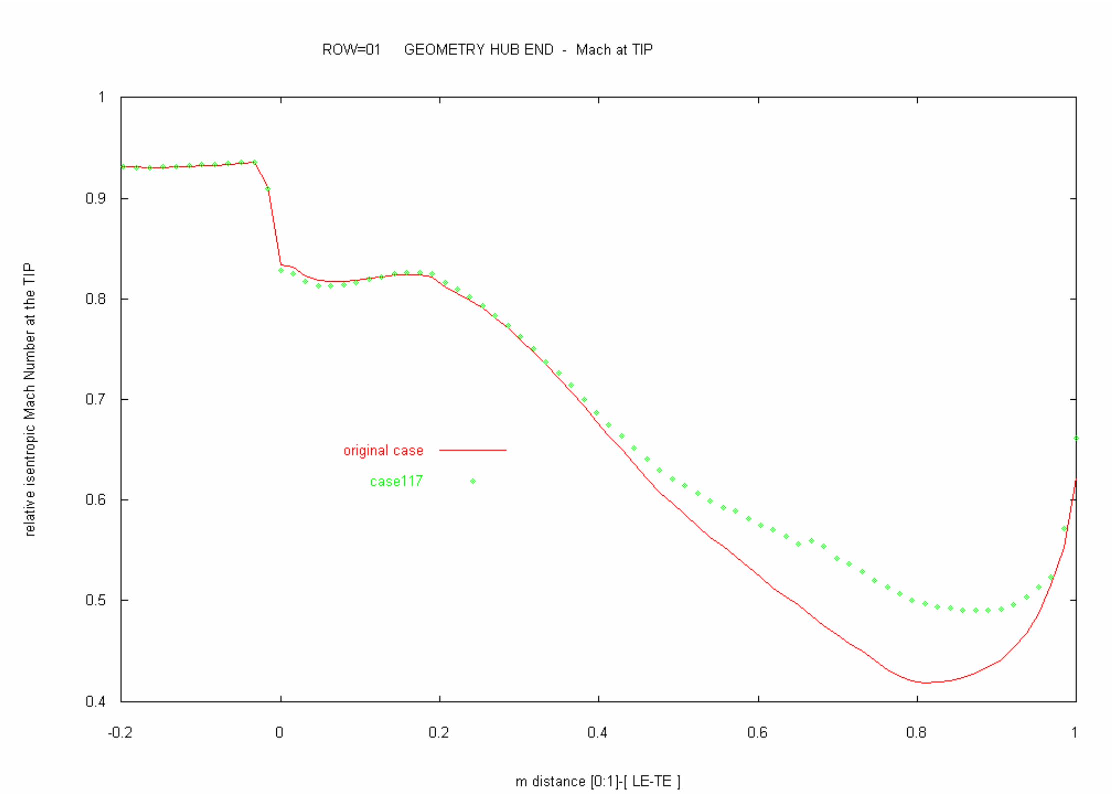
15	FREE SPACE Enter no of points of the SPACE no (1)	(x)	15	
16	FREE SPACE Isodistribute into i-direction ***		1	
17	BLADE SPACE Enter no of points of the SPACE no (1)	(x)	63	
18	BLADE SPACE Isodistribute into i-direction ***		1	
19	FREE SPACE Enter no of points of the SPACE no (2)	(x)	7	
20	FREE SPACE Isodistribute into i-direction		1	
21	Calculate curvatures on iso-i & iso-j directions	Y=1	0	
22	Do you want to interpolate from a given table of a previous grid with given theta and thickness to find the values of theta and thickness on the grid	Y=1	1	
23	Enter file containing z,r,thickness - include after itblade,jtblade the following: np1,np1 (points of the NURBS) i.e. 300,300 and izerle,izerte=0 for thickness=0 at LE & TE for BLADE no (1)	"……"	bounds1.geo	
24	Include splitter blade	Y=1	0	
25	Enter output file name for blade No 1	"….."	bounds.gep	grid for control
26	Enter Title name	"….."	ULEV_TAP1	

Mer11_1.inp file

STEP		POSSIBLE VALUES	NOTES	DATA USED IN mer11_1.inp
1	Enter it max (maximum iterations)	x		50
2	Input file name	" … "		mergrd1.cmp
3	Enter undrl for s (0 - 1)	x		
4	Emulate blockage (Y=1)	0,1	boundary layer	1
5	Blockage Hub to Tip (min-max)	x,y		0 2.9E-1
6	R*Vu (=2) beta (=1) theta (=0) AS INPUT	0,1,2		1
7	Enter CFL for PSI Eqs (typical CFL=1)	x	factor	1
	MT for GMRES (~4)	x	factor	4
	AMC for Upwind (i.e. ~0.85)	x	factor	0.85
8	Transfer method (1=simple ; 2= enhanced)	1 , 2	2 when separation of flow !	1
9	Stations for smoothing of RVu AND Dens distribution at LE (none=-1)	x OR -1	differential equations (transport)	1
10	Relaxation for beta new	Y appr. =1	Underrelaxation factor	1
11	Relaxation for pt new for row nr1	Y appr. =2	Underrelaxation factor	1
12	Relaxation for t*grad(s)	Y appr. =3	Underrelaxation factor	1
13	0 to stop or itmax to continue	0 OR x	deviation is forced	0
14	itmax for viscous	x		50
15	Relaxation for t*grad(s)	x		1
16	0 to stop or itmax to continue	0 OR x		0
17	Do you want to continue? (Y=1)	0,1		1
18	Blade OR entropy (1 0 OR 0 1)	as left		0 1
19	Enter underrelax factor for pt	x	pt losses	1
20	itmax for viscous	x		50
21	Relaxation for t*grad(s)	x		1
22	0 to stop or itmax to continue	0 OR x		0
23	Do you want to continue? (Y=1)	0,1		0
24	Output file name	" … "		comp11_1.out

ANNEX D- PLOTS

Case 117



BIBLIOGRAPHY

1. PAPAILIOU K.D. - „Περιληπτικές Σημειώσεις των Μαθημάτων ΘΕΡΜΙΚΩΝ ΣΤΡΟΒΙΛΟΜΗΧΑΝΩΝ I – II (Lecture Notes on Thermal Turbomachines Parts I – II)“ Athens 1985/1990

2. VAVRA M.H. – „Aero-Thermodynamics and Flow in Turbomachines“, New York 1974

3. WU Ch. - NACA Technical Note 2604 , „A general theory of 3D flow in sub- & supersonic turbomachines of axial-, radial, and mixed flow types“ , Washington 1952

4. WU Ch. , WOLFENSTEIN L. – NACA Technical Note 1795 „Application of radial-equilibrium condition to axial-flow compressor and turbine design“ , Washington 1949

OTHER REFERENCES

1. Th. WILLIAMS, C. KELLEY, A. WOO “GNUPLOT Manual for v3.5“ 1993

2. K. JOY „On–Line Geometric Modelling Notes“ UC- Davis 1996 *http://garphics.cs.ucdavis.edu/CADGNotes/CADG-Notes.html*

3. DATAPLOT Manual (online)

4. GNUPLOT Manual

5. KIOUSSIS P.– PhD Thesis NTUA/LTT „Ανάπτυξη μεθόδου ανάλυσης και υπολογισμού της ροής πολυβάθμιων, διηχητικών συμπιεστών” (Development of an analysis method for transonic flow in multistage compressors), Athens 1996

6. SIERROS G. - PhD Thesis NTUA/LTT „Συμβολή στο Σχεδιασμό Συνιστωσών Μικρών Αεριοστροβίλων για χρήση σε κινητήρες Υβριδικών οχημάτων” (Contribution to the design of small gas-turbines for use in hybrid-vehicles engines), Athens 2000