LABYRINTH SEAL PREPROCESSOR AND POST-PROCESSOR DESIGN AND PARAMETRIC STUDY

by

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ABSTRACT

Vibrations caused due to aerodynamic excitation may cause severe limitation to the performance of turbomachines. The force resulting from the non-uniform pressure distribution within the labyrinth cavity is identified as a major source of this excitation. In order to perform rotor dynamic evaluation of rotor-bearing-seal system, accurate prediction of this force is essential.

A visual basic based front-end, for a labyrinth seal analysis program, has been designed herein. In order to accurately predict the excitation force, proper modeling of labyrinth leak path is important. Thus, the front-end developed herein incorporates a leak-path geometric diagram for visual analysis of labyrinth leak path and tooth location. Furthermore, to investigate influence of various operating conditions and gas properties on excitation force (effective cross-coupling stiffness), a parametric study is performed on both the eye seal and the balance piston labyrinth seal.

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NOMENCLATURE

Symbol	Description	Units
API	American Petroleum Institute	--
C_{xx}	Direct-coupled damping	$F \cdot T/L$
C_{xy}	Cross-coupled damping	$F \cdot T/L$
K_{xx}	Direct-coupled stiffness	F/L
K_{xy}	Direct-coupled stiffness	F/L
Laby	Labyrinth Seal	--
N	Rotor Speed	Rev/T
Ncr	1st critical speed	Rev/T
P_{inlet}	Gas pressure at seal inlet	F/A
Pr	Pressure ratio.	Dim
Qe	Effective cross-coupling stiffness	F/L
Qe_{bp}	Effective cross-coupling stiffness for balance piston.	F/L
r	Shaft radius	L
sr	Gas swirl ratio at seal inlet	Dim
V_{abs}	Gas absolute velocity	L/T
ω	Frequency	Rad/T

CHAPTER 1

Introduction and Literature Review

1.1 Introduction

The Labyrinth seal is an innovation first introduced by C. A. Parsons in the early 20th century. His idea was to incorporate a torturous path between the high and low-pressure regions by using non-contacting teeth and separating chambers [15]. Labyrinth seal since then have become an integral design element in high performance turbomachinery. Main purpose of non-contacting labyrinth seals is to reduce internal leakage. While it does an excellent job in reducing the leakage, but unfortunately, due to uneven pressure distribution in labyrinth cavities, it develops a destabilizing force, capable enough to drive the rotor unstable. In order to perform stability analysis of high performance turbomachinery, it is essential to predict the magnitude of this destabilizing force. Thus, a labyrinth analysis program, DYNLAB [20], was developed in early 1980's to predict the leakage and the dynamic coefficients of labyrinth seals. Even though to date, several companies have been successfully using this program, the DYNLAB's MS-DOS based interface is gradually becoming obsolete with the recent advances in computer technology. Thus, a compatible, user-friendly and easy to use, user interface was much needed.

This research has developed an easy to use Microsoft Excel (visual basic) based pre and post-processor for the above-mentioned program. Furthermore, the front-end incorporates a leak-path geometric diagram for visual analysis of labyrinth leak path and tooth location. In addition, a parametric study is performed on eye seal and balance piston labyrinth seal shown in Figure 1-1.

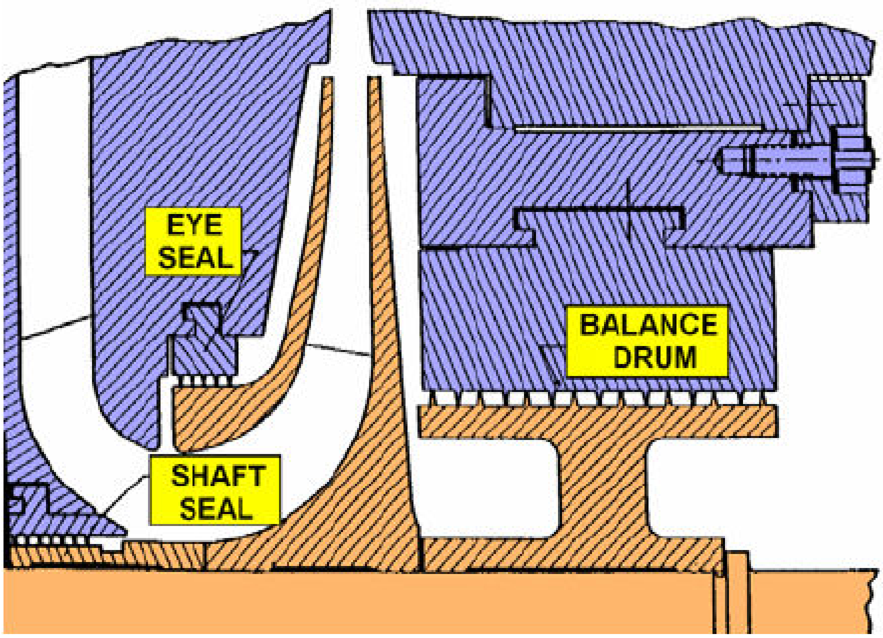


Figure 1-1 Typical compressor labyrinth configuration [14]

1.2 Literature

Alford [1] identified labyrinth seal has a destabilizing effect on rotor whirl. He considered two aerodynamic forces being the cause of the self-excitation of the rotor whirl. One is due to circumferential variation of static pressure within the labyrinth cavity and another exciting force being due to eccentricity of rotor causing circumferential variation of blade-tip clearance. Alford further explained that due to these forces, whirl occurs in direction of rotation at systems natural frequency. He concluded that by providing adequate stiffness to rotor and/or to rotor support, whirl is reduced considerably. Alford also concluded that Labyrinth seals having minimum flow at inlet are more desirable and stable then having minimum flow clearance at discharge.

Since Alford, several authors have worked on theories for calculation of labyrinth seal coefficients. Benckert and Wachter [16] presented formulas for lateral forces due to shaft rotation and inlet swirl, which they developed through experiments. Their discussion included the effects of operational conditions such as differential pressure, speed, inlet flow conditions and geometry of labyrinth seal, on the spring characteristics of labyrinth seals. They asserted the fact that lateral forces resulting out of labyrinth cavities have to be accounted for in rotor dynamics and they permit a more accurate stability analysis. Benckert further concluded that by placing swirl web (brakes) upstream of the labyrinth effectively reduces the inlet swirl and in turn reduces the lateral force sensitivity.

Iwatsubo [2] performed theoretical analysis to evaluate the instability forces of labyrinth seals in turbomachinery. He extended the fundamental equation proposed by Kostyuk [1972] to consider the variation of chamber cross section, but he neglected the area derivative in circumferential direction. Iwatsubo wrote continuity and momentum equation to define the average circumferential velocity within a labyrinth chamber. His experimental studies showed that the fluid in the labyrinth cavity forms a continuous vortex and flows in circumferential direction.

In addition, Wyssmann et. al [17] also presented a theory for calculation of stiffness and damping coefficients for centrifugal compressor labyrinth seals based on turbulent flow calculations. Unlike Iwatsubo's one-control-volume model, Wyssmann et. al [17] proposed two-control-volume model for circumferential flow in a labyrinth chamber. One control volume is for throughflow regime; the other is for the vortex region between labyrinth teeth [18 (p.344)]. Wyssmann et. al [17] studied the influence of labyrinth geometry, operating conditions, and mole weight on labyrinth cross-coupling stiffness. He concluded that labyrinth coefficients are strongly dependent on tooth height and inlet swirl velocity.

Childs and Scharrer [19] extended Iwatsubo's theories and compared it to experimental results of Benckert and Wachter [16]. The model developed gave results that were within 25% of the experimental results. This discrepancy could have been due to known uncertainty in Wachter and Benckert experimental results. Their results included only the influence of entry swirl and not the rotating shaft on cross-coupling stiffness. However, the model was only valid for see-through type of labyrinth seal since the model fared very poorly in comparison with interlocking and grooved seal data.

Kirk [20] developed a labyrinth analysis program, DYNLAB, based on theories of Iwatsubo and Scharrer with several important extensions and modifications in the derivation of the perturbation equations. Furthermore, he compared the results of DYNLAB to full-load shop test data and Childs' [19] computer program results. The static seal comparison was in excellent agreement for both tooth on stator and full labyrinth design [20]. In addition, the comparisons for full labyrinth at rotor speed of 9540 rpm showed good agreement if the perturbation is non-synchronous.

In an effort to improve and validate predictions of Bulk-Flow approaches, theories of Iwatsubo, Childs and Scharrer, and Kirk, Moore [12] utilized three-dimensional computational fluid dynamics to model the Labyrinth seal flow path by solving the Reynolds Averaged Navier Stokes equations. His study utilized a CFD code—SCISEAL, which uses a three-dimensional whirling method developed by Athavale et al [21]. Moore benchmarked the CFD code by modeling the experimental data presented by Pelletti in 1990 for his master's thesis. He further compared the CFD results to Kirk's and Scharrer's Bulk-Flow theories. The comparison from Moore [12] is shown in Figure 2. Moore plotted Impedance (N/m), which is cross-coupling stiffness, versus processional frequency ratio (PFR). PFR is the ratio of rotor whirl to rotor spin.

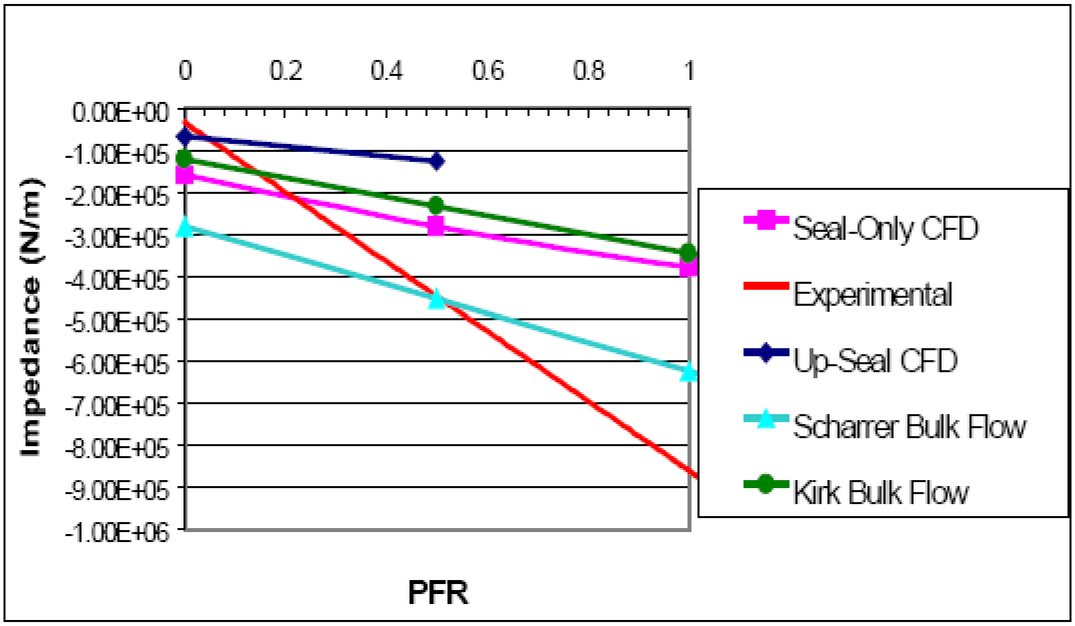


Figure 1-2 Comparison of seal models, 16 krpm, Pr = 0.403 [12].

The comparison showed good agreement of CFD to Kirk's, whereas Scharrer's had greatest deviation [12]. CFD performs labyrinth coefficients and leakage analysis accurately, but unfortunately has a drawback of computational time. Bulk-flow programs on the other hand can perform analysis in few seconds, but with reasonable accuracy. Bulk-flow continues to be used for day-to-day lateral rotordynamic stability analysis in the industry [12].

Guo and Kirk [13] in 2005 utilized a commercial CFD program, CFX TASCFlow, to calculate leakage and rotordynamic force components of a labyrinth seal. The leakage results on comparison with DYNLAB results showed good agreement, whereas prediction of the destabilizing force by DYNLAB was pessimistic as compared to TASCFlow.

CHAPTER 2

Pre- and Post- Processor Capabilities and Layout

A preprocessor and post-processor for a Labyrinth seal analysis code written by Dr. Kirk is developed to meet industry needs. The processor design utilizes Excel's Visual Basic for Application functions and macros. The preprocessor is designed in a simple Excel spreadsheet to facilitate easy data entry of labyrinth geometry and gas properties. It exports the data entered in to a fixed-format text file and feeds the file to the FORTRAN based program, DYNLAB. The post-processor imports the output file generated by DYNLAB into tables and generates plots to analyze the results.

This chapter covers the capabilities and describes the pre and post-processor layout. The programming involved in designing the processors is discussed in chapter 3. The preprocessor is comprised of three worksheets--Main, Geometric Parameters and Gas Property sheet.

2.1 Program Capabilities

LabyXL is a labyrinth type gas seals analysis program that uses a bulk flow small perturbation solution to solve for the stiffness and damping characteristics of the labyrinth gas seal. Gas leakage, pressure and temperature are also determined. The major features of LabyXL preprocessor and post-processor can be summarized as follows:

1. The program is capable of importing and generating a data file. Refer to Figure A-1 in Appendix A for a sample data file.

2. It provides a table for Geometric Parameters and Speed Case Parameters for easy understanding and data input.
3. All input boxes are color-coded (Figure 2-1) to identify if the variable is required or default could be used.
4. On opening the ‘Geometric Diagram’ sheet (after entering labyrinth geometric data), a macro generates the leak path geometric diagram for better understanding of the labyrinth geometry.
5. Gas property section provides a viscosity and temperature calculator for converting centipose units to Lbm / (Ft * s) and Fahrenheit to Rankine respectively.
6. Labyrinth options section provides a field for input sheet name and path for easy location of data sheet generated.
7. Post-Processor macro imports results from output text files into tables for data analysis.
8. In addition, it generates several plots for better analysis.

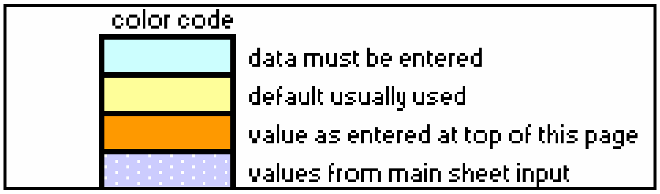
This program as a whole is a design tool for analysis of gas labyrinth seals typical of centrifugal compressor eye, shaft, and balance drum configurations. The major advantage of the labyrinth code is the ability to estimate the seal entrance swirl, given the impeller tip swirl, which is a standard output of any aerodynamic design code. The program has been tested and selected as the program of choice for toothed labyrinth designs by three major OEM compressor companies and two major oil companies in the US. The program is being used for last 20 years at these companies, and used as a consulting tool for the past 22 years. The program can evaluate tooth on rotor, on stator or interlocking teeth. The seal can be straight through or stepped. The program input can be adjusted to estimate the influence of honeycomb seal designs with typical cell size.

2.2 Preprocessor Design Layout

The LabyXL is an easy-to-use program, incorporated in Microsoft Excel spreadsheet. The spreadsheet consists of various macros in form of Buttons to automate series of tasks. The section discusses the layout of these macros and input fields. Macros are discussed in detail in the next chapter. The data input for the spreadsheet is divided in four parts – Control

Parameters (Figure 2-2), Geometrical Parameters (Figure 2-3), Gas Properties (Figure 2-5) and Labyrinth Options (Figure 2-7).

The input fields are color-coded to help the user identify if input is required or not. Figure 2-1 is a chart showing different color codes and its significance. Three comment lines are provided for remarks necessary for the proper labeling of the data set. The four input sections are discussed in the following section.



color code
data must be entered
default usually used
value as entered at top of this page
values from main sheet input

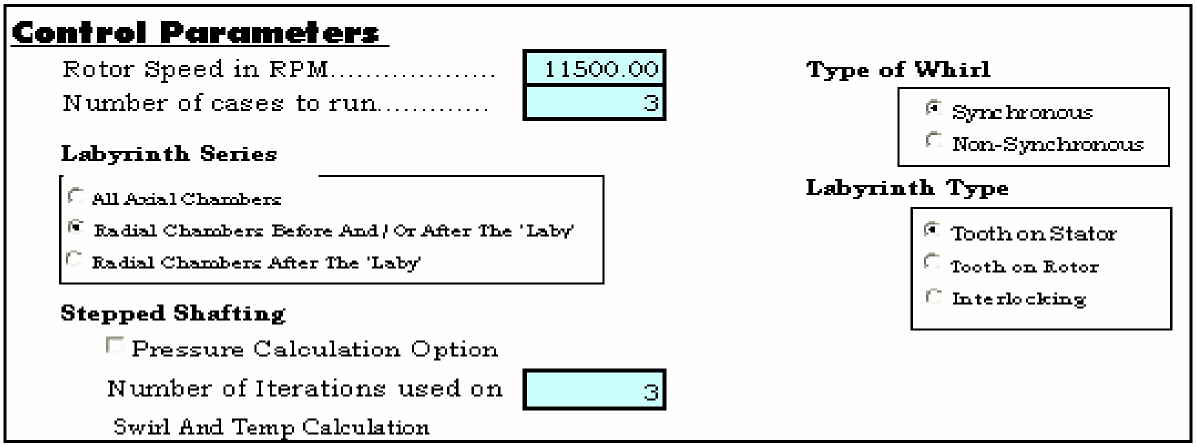
Figure 2-1 Input field color chart

1. Control Parameters

Control Parameters are the parameters required to run the Labyrinth seal analysis, it includes the following variables:

- The Speed of the Rotor in RPM
- Number of cases to run – Range 1 to 10 cases
- Type of Whirl
    - Synchronous
    - Non-Synchronous
- Labyrinth Series
    - All axial chambers (Refer to Figure B-3 in Appendix B)
    - Radial chambers before and/or after the Laby (Refer to Figure B-4 in Appendix B)
    - Radial chambers after the Laby (Refer to Figure B-5 in Appendix B)
- Labyrinth Type (Tooth Orientation – Refer to Figure B-6 in Appendix B)
    - Tooth on Stator
    - Tooth on Rotor

    - Interlocking
- Step Shafting Data
    - The Step shafting Pressure Option (Refer to Figure B-7 in Appendix B)
    - The number of iterations on swirl for Stepped Shafting and for Temperature Calculation



Control Parameters

Rotor Speed in RPM.................. 11500.00

Number of cases to run............ 3

Labyrinth Series

○ All Axial Chambers
● Radial Chambers Before And / Or After The 'Laby'
○ Radial Chambers After The 'Laby'

Stepped Shafting

☐ Pressure Calculation Option

Number of Iterations used on Swirl And Temp Calculation 3

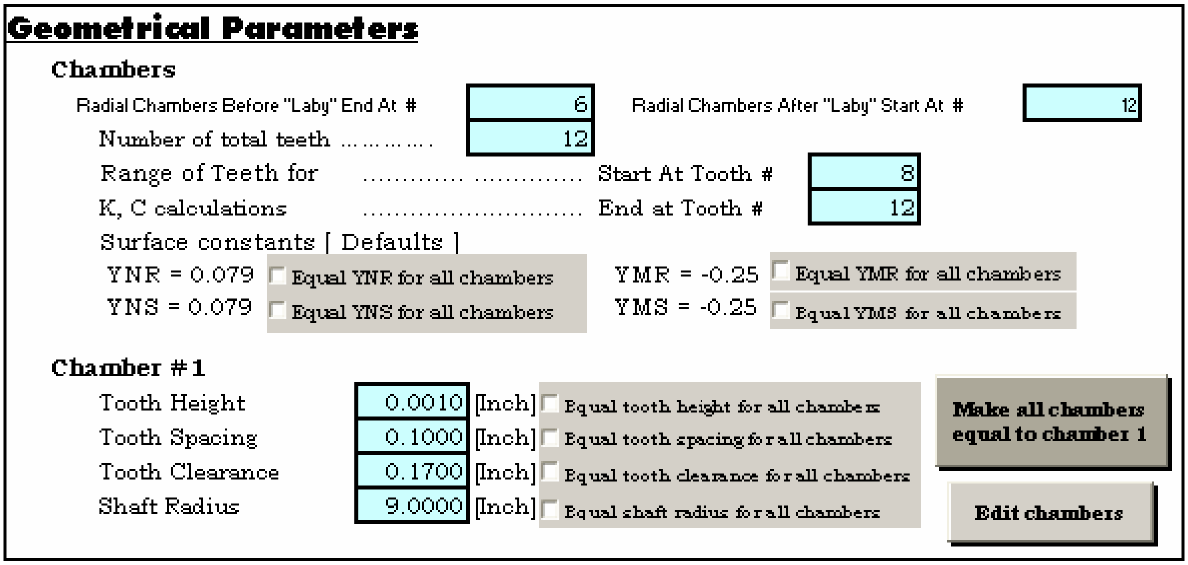
Type of Whirl

● Synchronous
○ Non-Synchronous

Labyrinth Type

● Tooth on Stator
○ Tooth on Rotor
○ Interlocking

Figure 2-2 Control Parameters



Geometrical Parameters

Chambers

Radial Chambers Before "Laby" End At # 6

Radial Chambers After "Laby" Start At # 12

Number of total teeth 12

Range of Teeth for K, C calculations .... Start At Tooth # 8

End at Tooth # 12

Surface constants [Defaults]

YNR = 0.079 ☐ Equal YNR for all chambers

YNS = 0.079 ☐ Equal YNS for all chambers

YMR = -0.25 ☐ Equal YMR for all chambers

YMS = -0.25 ☐ Equal YMS for all chambers

Chamber #1

Tooth Height 0.0010 [Inch] ☐ Equal tooth height for all chambers

Tooth Spacing 0.1000 [Inch] ☐ Equal tooth spacing for all chambers

Tooth Clearance 0.1700 [Inch] ☐ Equal tooth clearance for all chambers

Shaft Radius 9.0000 [Inch] ☐ Equal shaft radius for all chambers

Figure 2-3 Geometrical Parameters

2. Geometrical Parameters

This section shown in Figure 2-3 consists of geometrical variables. The section is further divided into two sections – Chambers and Chamber # 1. Chamber section consists of following variables:

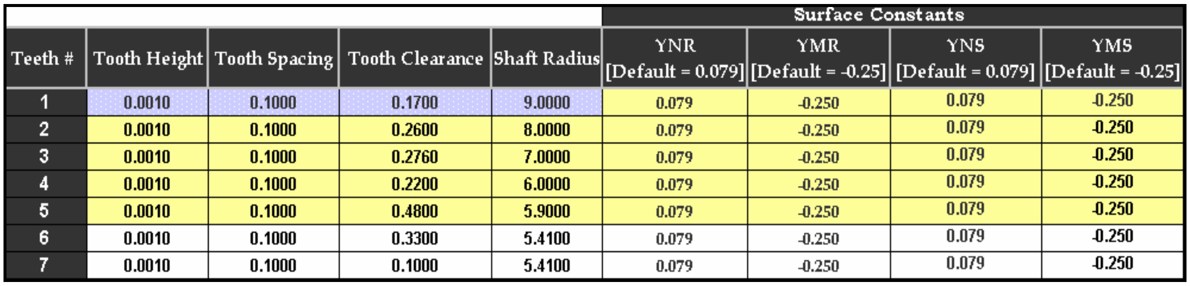
- The last tooth number at which the radial chambers end before the Laby
- The last tooth number at which the radial chambers end after the Laby
- Total number of teeth on the seal
- Range of teeth for the Stiffness and Damping calculation
- Surface constants
    - YNR
    - YNS
    - YMR
    - YMS

A checkbox is provided next to all surface constants to give an option to make all surface constants equal for all chambers. Thus, if a check mark is placed in the checkbox then the program will use a default value as indicated. A different value for surface constants could also be used by not placing a checkmark in the checkbox provided, and entering the desired value in the Geometric Parameter table shown in Figure 2-4.

The Chamber # 1 section of the Geometrical Parameter section consists of tooth geometry of chamber # 1; refer to Figure B-2 in Appendix B. It consists of the following variables:

- Tooth Height
- Tooth Spacing
- Tooth Clearance
- Shaft Radius

By placing a checkmark in the checkbox next to any geometric variable and clicking the “Make all chamber equal to chamber # 1” button makes that variable value equal for all chambers in the geometric parameter table shown in Figure 2-4.



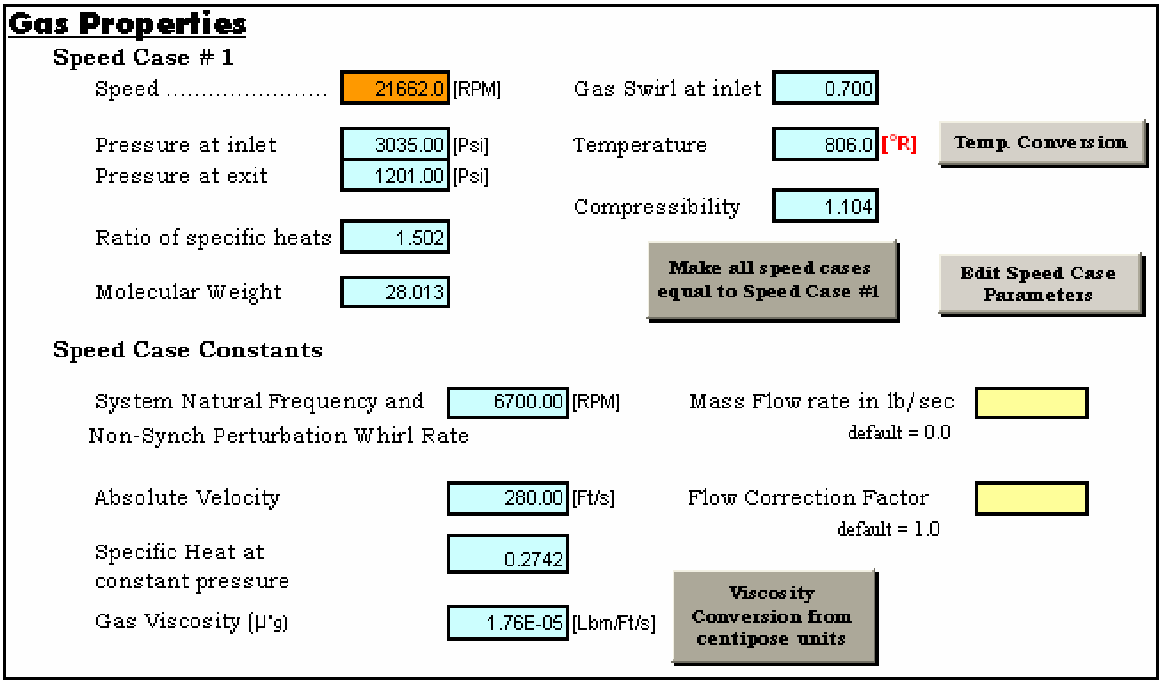
					Surface Constants			
Teeth #	Tooth Height	Tooth Spacing	Tooth Clearance	Shaft Radius	YNR [Default = 0.079]	YMR [Default = -0.25]	YNS [Default = 0.079]	YMS [Default = -0.25]
1	0.0010	0.1000	0.1700	9.0000	0.079	-0.250	0.079	-0.250
2	0.0010	0.1000	0.2600	8.0000	0.079	-0.250	0.079	-0.250
3	0.0010	0.1000	0.2760	7.0000	0.079	-0.250	0.079	-0.250
4	0.0010	0.1000	0.2200	6.0000	0.079	-0.250	0.079	-0.250
5	0.0010	0.1000	0.4800	5.9000	0.079	-0.250	0.079	-0.250
6	0.0010	0.1000	0.3300	5.4100	0.079	-0.250	0.079	-0.250
7	0.0010	0.1000	0.1000	5.4100	0.079	-0.250	0.079	-0.250

Figure 2-4 Geometric Parameter Table

By clicking on the "Edit Chamber" button shown in Figure 2-3 chamber parameters can be edited. Edit chamber button will open the Geometric Parameter table shown in Figure 2-4. The table consists of 50 chamber parameters with the above variables associated with each chamber.

3. Gas Properties

Figure 2-5 shows gas property parameters. This section is further divided in two sub-sections – Speed case # 1 and Speed Case Constants. Speed Case # 1 section consists of the following variables:



Gas Properties

Speed Case # 1

Speed .... 21662.0 [RPM]

Gas Swirl at inlet 0.700

Pressure at inlet 3035.00 [Psi]

Temperature 806.0 [°R]

Pressure at exit 1201.00 [Psi]

Compressibility 1.104

Ratio of specific heats 1.502

Molecular Weight 28.013

Speed Case Constants

System Natural Frequency and Non-Synch Perturbation Whirl Rate 6700.00 [RPM]

Mass Flow rate in lb/sec
default = 0.0

Absolute Velocity 280.00 [Ft/s]

Flow Correction Factor
default = 1.0

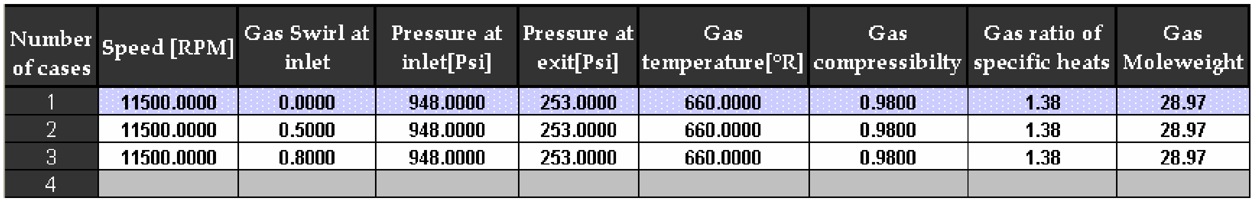
Specific Heat at constant pressure 0.2742

Gas Viscosity (μ*g) 1.76E-05 [Lbm/Ft/s]

Figure 2-5 Gas Properties

- Speed of shaft in RPM
- Gas Swirl at inlet
- Gas Pressure at inlet in psi
- Gas Pressure at exit in psi
- Gas Temperature in Rankin
- Ratio of Specific Heat
- Compressibility
- Molecular Weight

“Make all the speed case equal to Speed Case # 1” button makes all the speed case variables equal to variables of Speed Case # 1.



Number of cases	Speed [RPM]	Gas Swirl at inlet	Pressure at inlet[Psi]	Pressure at exit[Psi]	Gas temperature[°R]	Gas compressibilty	Gas ratio of specific heats	Gas Moleweight
1	11500.0000	0.0000	948.0000	253.0000	660.0000	0.9800	1.38	28.97
2	11500.0000	0.5000	948.0000	253.0000	660.0000	0.9800	1.38	28.97
3	11500.0000	0.8000	948.0000	253.0000	660.0000	0.9800	1.38	28.97
4								

Figure 2-6 Gas Properties Table

“Edit Speed Case Parameters” button shown in Figure 2-5 redirects to gas property sheet to edit speed case parameters. The gas property table (speed cases) is shown in Figure 2-6. The table consists 10 Speed Cases with the above variables associated with each speed case.

Speed Case Constants section consists of the following variables:

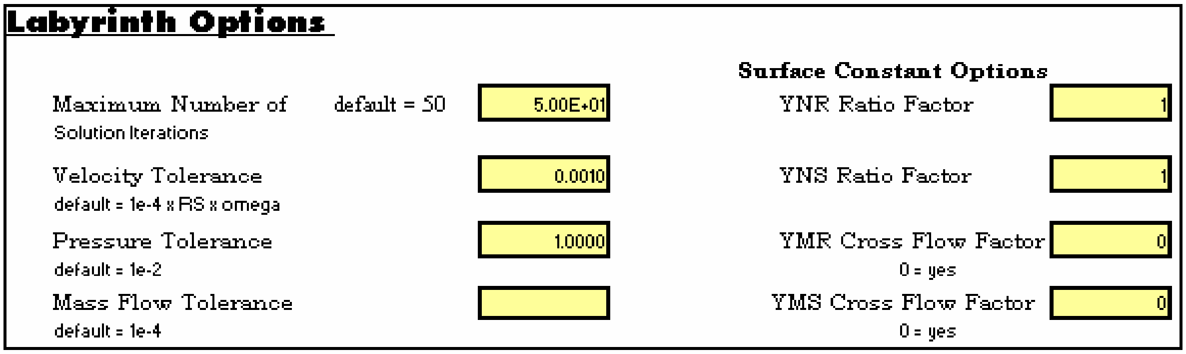
- System Natural Frequency and Non-Synch Perturbation Whirl Rate in RPM
- Mass Flow rate in lb / sec (Leave blank if using pressure solution)
- Absolute Velocity in Ft/s
- Flow correction Factor
- Specific Heat at constant pressure
- Gas Viscosity in Lbm/Ft/s

Temperature and gas viscosity calculators shown in Figure 2-5 are provided to convert from Fahrenheit to Rankine and centipose to Lbm / (ft * s) respectively.

4. Labyrinth Options

This section shown in Figure 2-7 shows the computing options, it has the following variables:

- Maximum number of Solution iterations (default = 50)
- Velocity Tolerance (default = $1e^{-4}$ x RS x omega)
- Pressure Tolerance (default = $1e^{-2}$)
- Mass Flow Tolerance (default = $1e^{-4}$)
- YNR Ratio Factor
- YNS Ratio Factor
- YMR Cross Flow Factor (0 = yes)
- YMS Cross Flow Factor (0 = yes)



Labyrinth Options

Maximum Number of Solution Iterations default = 50: 5.00E+01

Velocity Tolerance default = 1e-4 x RS x omega: 0.0010

Pressure Tolerance default = 1e-2: 1.0000

Mass Flow Tolerance default = 1e-4:

Surface Constant Options

YNR Ratio Factor: 1

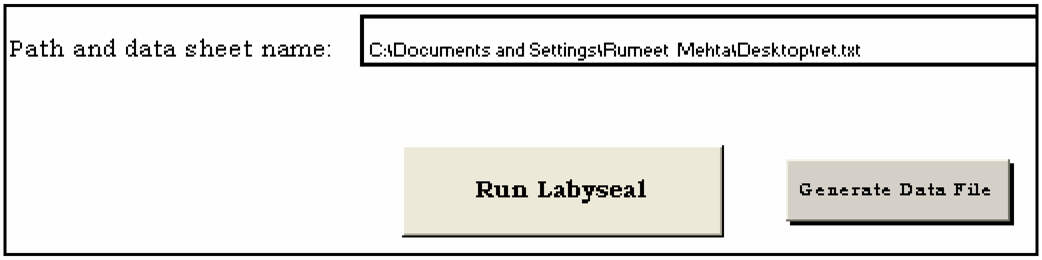
YNS Ratio Factor: 1

YMR Cross Flow Factor 0 = yes: 0

YMS Cross Flow Factor 0 = yes: 0

Figure 2-7 Labyrinth Options

“Run Labyseal” button shown in Figure 2-8 is provided to run the LabyXL program. It opens a save-data-file application box shown in Figure 2-9. The application allows the user to select the directory and assign a filename to the data sheet.



Path and data sheet name: C:\Documents and Settings\Rumeet Mehta\Desktop\ret.txt

Figure 2-8 Run button

Once the user saves the data file, a command prompt window pops-up, user should wait for it to close and then click the Ok button to view the results. To save a data file without running the analysis a “Generate Data File” button is provided. Location of the data file generated is saved in the “Path and data sheet name” box.

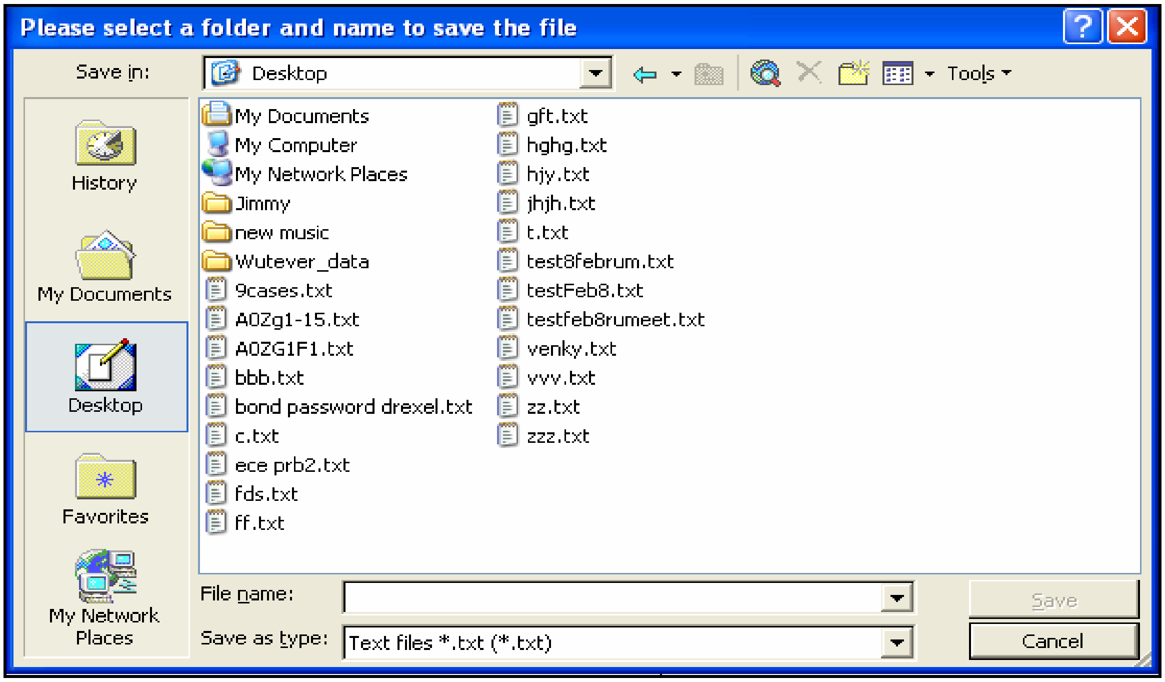


Figure 2-9 Save Data File Application box

The LabyXL program also has a macro to import a LabyXL data file. Data files generated from previous version of Labyrinth Seal can also be imported. “Import a Data File” button is situated above the comment lines on the top of the Main Sheet. “Reset Fields” button situated next to the “Import a Data File” button erases all the data fields.

2.3 Post-Processor Design Layout

The post-processor is designed to import data from output file into tables to organize the results. Several plots are generated to study gas properties in various chambers. If multiple cases are run, then parametric study can be performed as illustrated in Chapter 4. Furthermore, the program provides the user with a diagram of the leak path geometry. This helps the user to understand the radial and axial tooth location and fluid flow. Leak Path Geometric diagram in Figure 2-10 can be found on the 'Geometric Diagram' sheet. The macro automatically generates the diagram on entering the tooth geometry. Capabilities of the diagram are summarized below:

- It clearly identifies rotor and stator boundaries.
- The radial and axial teeth (K & C teeth) are explicitly displayed.
- Leak path can be accurately modeled.
- The diagram self-adjusts itself to any changes made to the geometric parameter table.

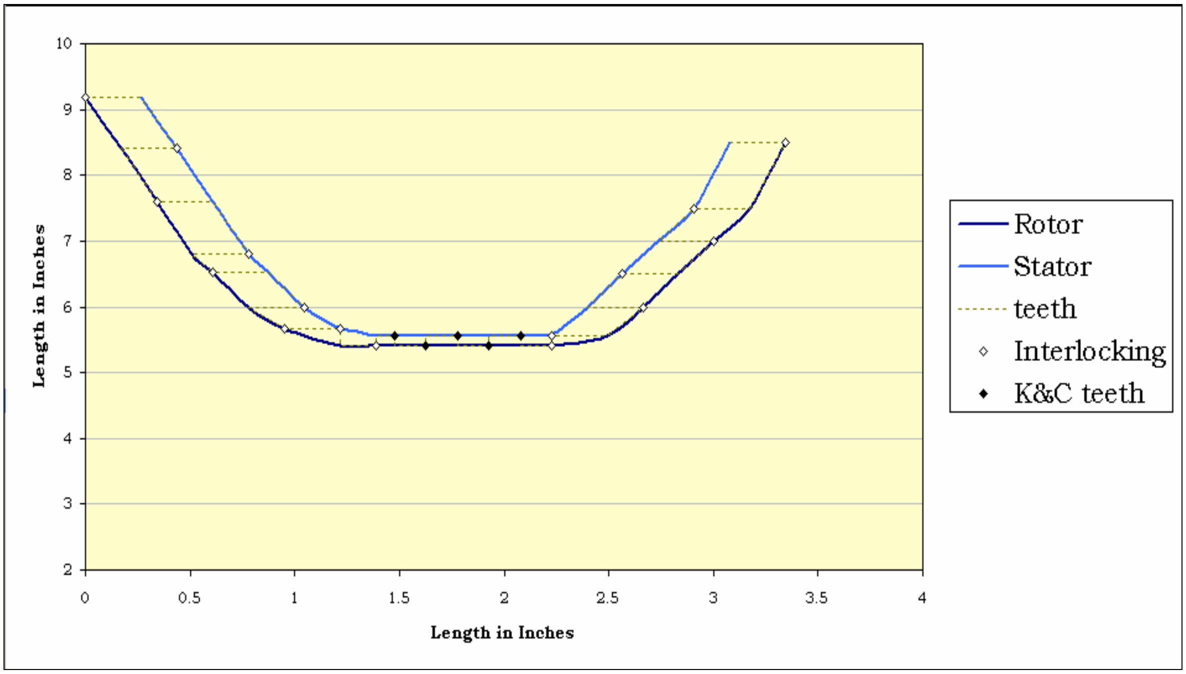
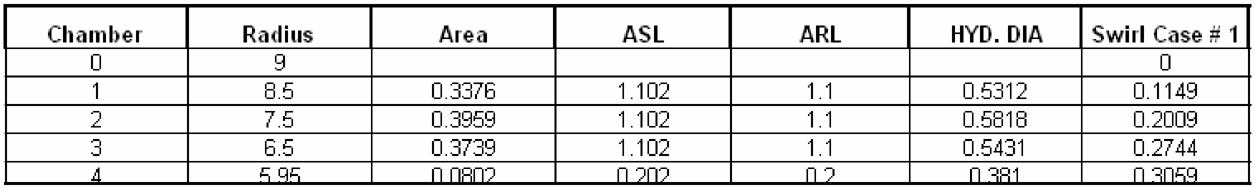


Figure 2-10   Leak-Path Geometric Diagram

The output of LabyXL comprises of two sheets – 'Results A' and 'Results B'.

'Results A' sheet displays two tables shown in Table 2-1 and Table 2-2.

Table 2-1 Results table – 'Results A' sheet



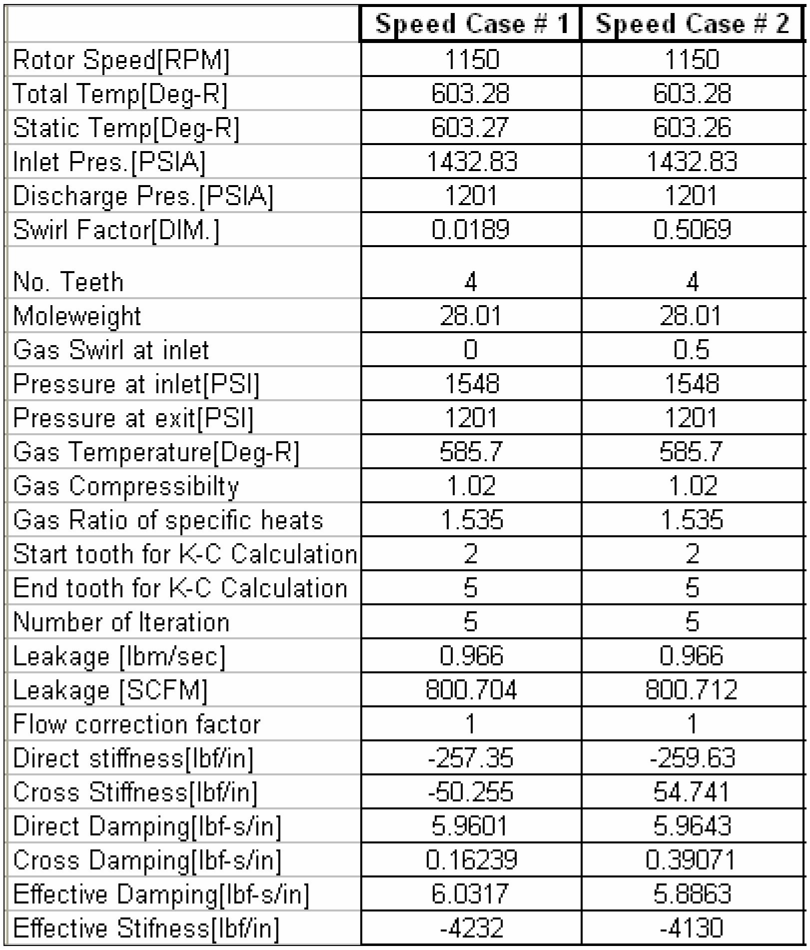
Chamber	Radius	Area	ASL	ARL	HYD. DIA	Swirl Case # 1
0	9					0
1	8.5	0.3376	1.102	1.1	0.5312	0.1149
2	7.5	0.3959	1.102	1.1	0.5818	0.2009
3	6.5	0.3739	1.102	1.1	0.5431	0.2744
4	5.95	0.0802	0.202	0.2	0.381	0.3059

Table 2-1 shows the following variables:

- Chamber number
- Radius
- Area of the chamber
- ASL (Area wetted stator length)
- ARL (Area wetter rotor length)
- HYD. Diameter (Hydraulic diameter)
- Swirl for various cases

Table 2-2 shows a detail list of variables for various speed cases generated. Maximum number of ten speed cases can be analyzed.

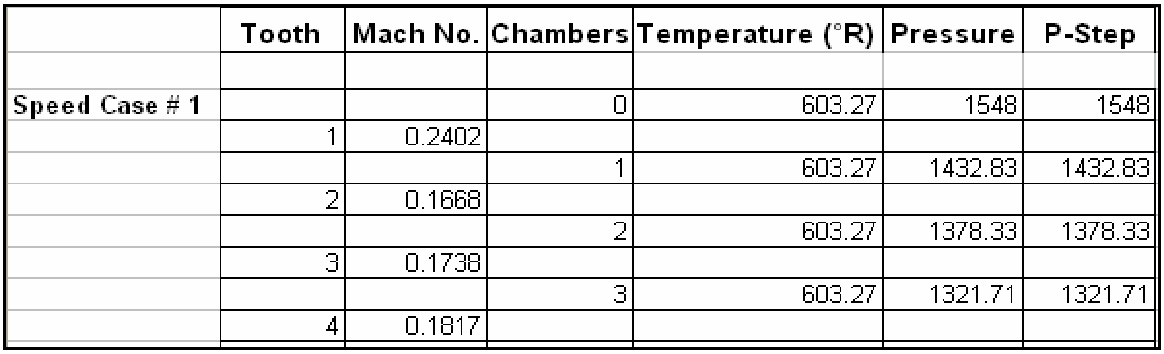
Table 2-2 List of various speed case results



	Speed Case # 1	Speed Case # 2
Rotor Speed[RPM]	1150	1150
Total Temp[Deg-R]	603.28	603.28
Static Temp[Deg-R]	603.27	603.26
Inlet Pres.[PSIA]	1432.83	1432.83
Discharge Pres.[PSIA]	1201	1201
Swirl Factor[DIM.]	0.0189	0.5069
No. Teeth	4	4
Moleweight	28.01	28.01
Gas Swirl at inlet	0	0.5
Pressure at inlet[PSI]	1548	1548
Pressure at exit[PSI]	1201	1201
Gas Temperature[Deg-R]	585.7	585.7
Gas Compressibilty	1.02	1.02
Gas Ratio of specific heats	1.535	1.535
Start tooth for K-C Calculation	2	2
End tooth for K-C Calculation	5	5
Number of Iteration	5	5
Leakage [lbm/sec]	0.966	0.966
Leakage [SCFM]	800.704	800.712
Flow correction factor	1	1
Direct stiffness[lbf/in]	-257.35	-259.63
Cross Stiffness[lbf/in]	-50.255	54.741
Direct Damping[lbf-s/in]	5.9601	5.9643
Cross Damping[lbf-s/in]	0.16239	0.39071
Effective Damping[lbf-s/in]	6.0317	5.8863
Effective Stifness[lbf/in]	-4232	-4130

'Results B' sheet displays Mach number, Temperature, Pressure and Pressure step for each chamber for various speed cases. Table 2-3 shows the table of results on 'Results B' sheet.

Table 2-3 Results table – 'Results B' sheet



	Tooth	Mach No.	Chambers	Temperature (°R)	Pressure	P-Step
Speed Case # 1			0	603.27	1548	1548
	1	0.2402				
			1	603.27	1432.83	1432.83
	2	0.1668				
			2	603.27	1378.33	1378.33
	3	0.1738				
			3	603.27	1321.71	1321.71
	4	0.1817				

‘Results A’ sheet has the following plots:

- Swirl Vs Chamber (Figure 2-11)
- Area, ASL, ARL and HYD. DIA Vs Chamber (Figure 2-12)
- Effective Damping & Stiffness Vs Speed Cases (Figure 2-13)

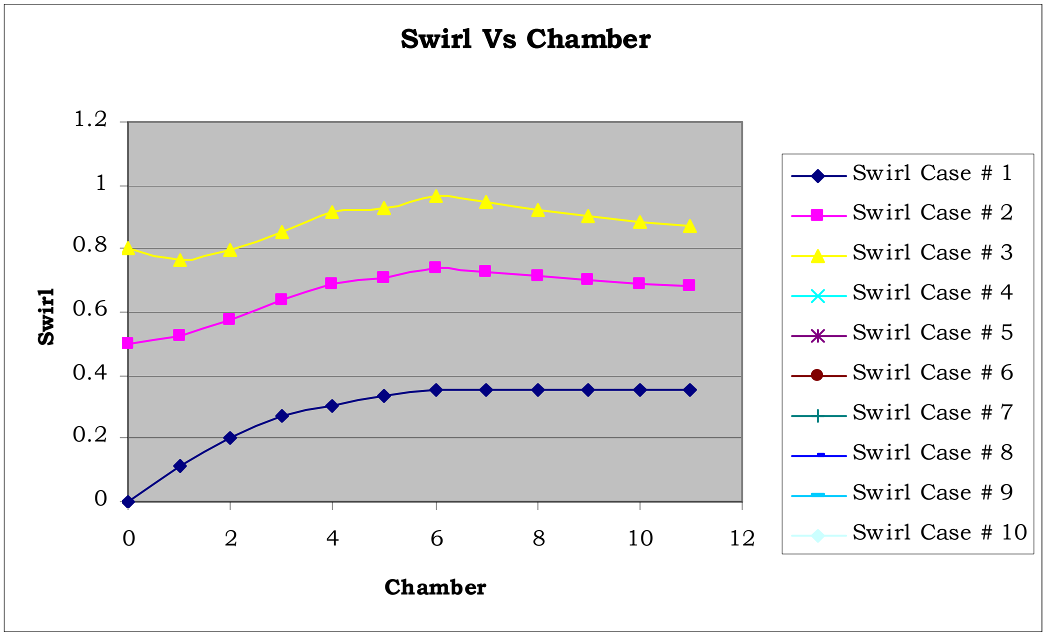


Figure 2-11 Plot of Swirl Vs Chamber

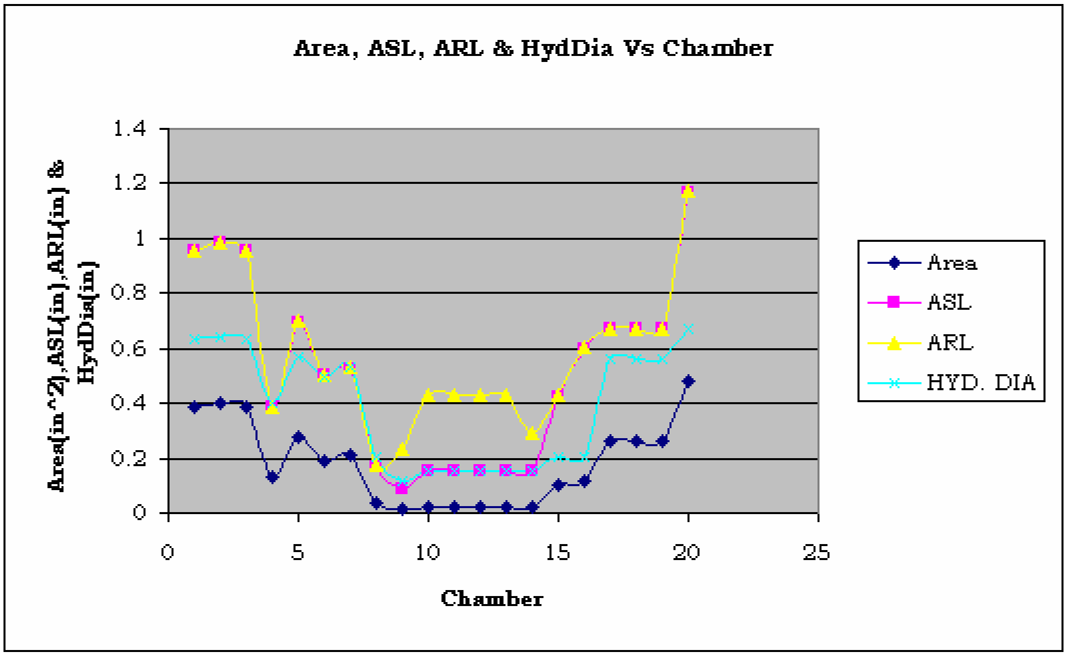


Figure 2-12 Plot of Area, ASL, ARL and HYD. DIA Vs Chamber

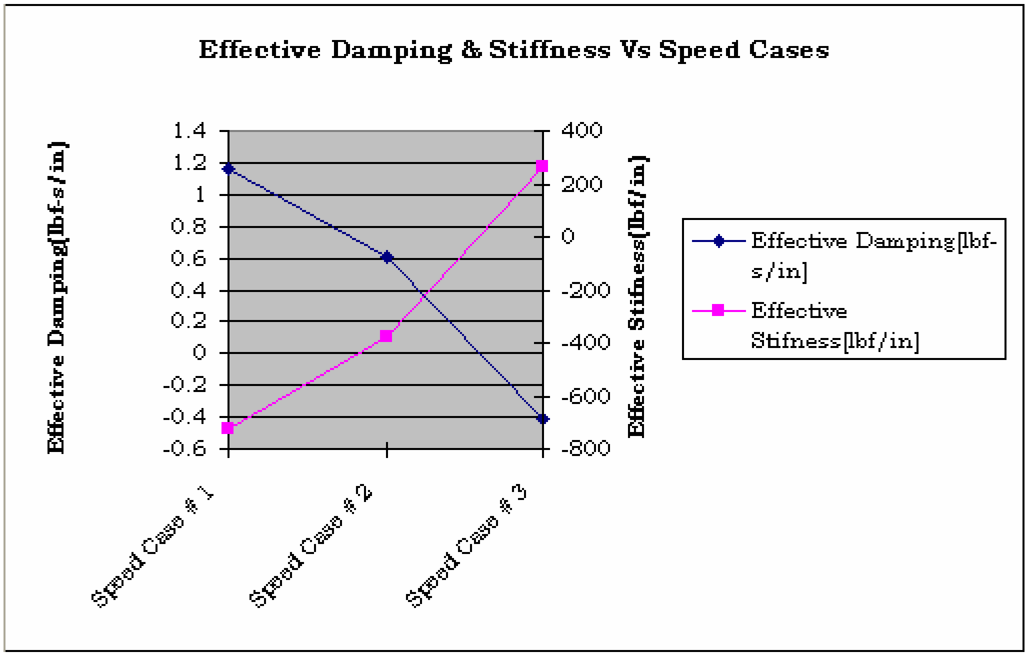


Figure 2-13 Plot of Effective Damping & Stiffness Vs Speed Cases

Labyrinth seal designer and rotordynamists are mostly interested in reducing the effective cross-coupling stiffness (Qe). Forward whirling can be minimized and instability problem can be solved, by reducing Qe. Figure 2-13 shows a plot of Effective stiffness (Qe) and Effective damping for various speed cases. Thus, this plot is crucial for stability analysis.

'Results B' sheet has the following plots:

- Mach Number Vs Tooth (Figure 2-14)
- Temperature Vs Chamber (Figure 2-15)
- Pressure Vs Chamber (Figure 2-16)

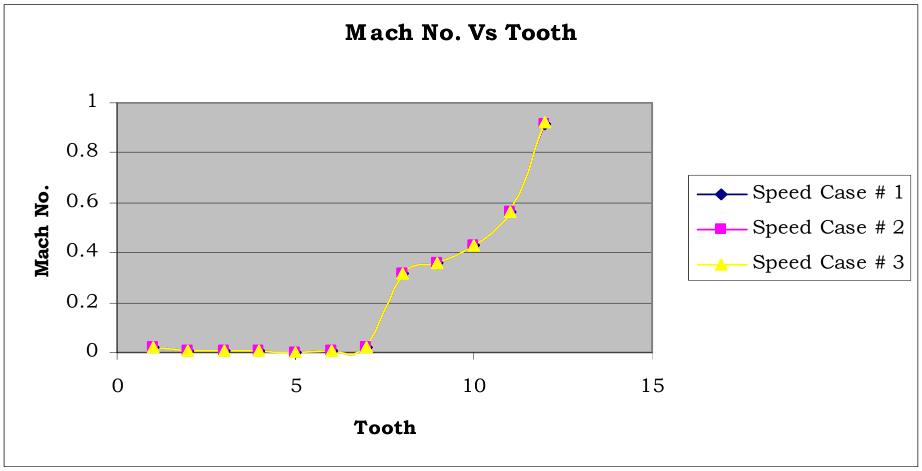


Figure 2-14 Plot of Mach No. Vs Tooth

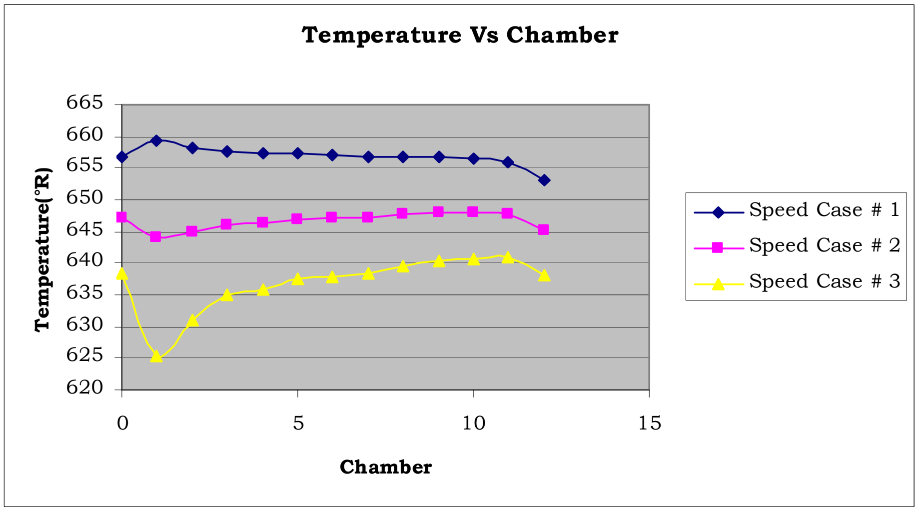


Figure 2-15 Plot of Temperature Vs Chamber

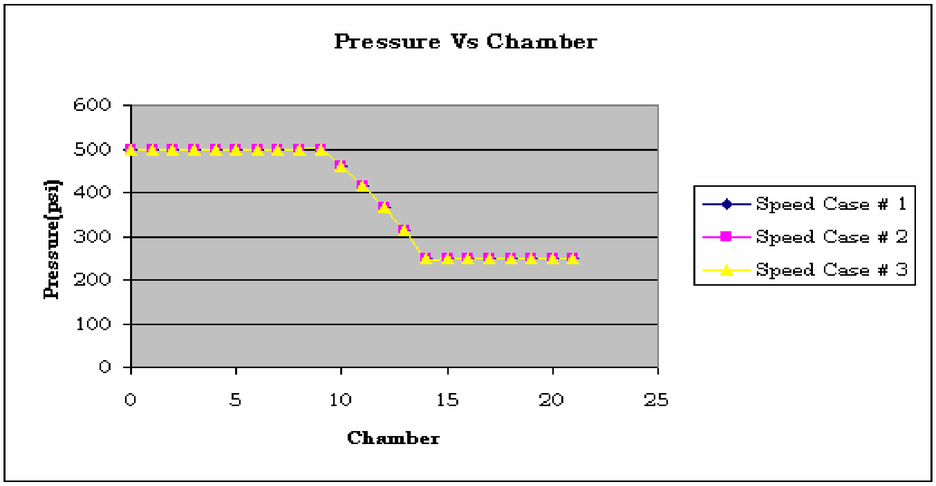


Figure 2-16 Plot of Pressure Vs Chamber

CHAPTER 3

LabyXL Macros

A macro is a set of commands including functions that are stored in a Microsoft Visual Basic module and can be run whenever user needs to perform a task. LabyXL program spreadsheet comprises of preprocessor and post-processor macros in form of check box, text box, option buttons and command buttons. This chapter illustrates preprocessor and post-processor macros and serves as a technical user's manual.

3.1 Preprocessor Macros

The preprocessor macros are formulated to provide a user-friendly interface for easy data entry. Input data is processed into an output fixed-format data file, which serves as an input data file for DYNLAB. A schematic representation of the process is shown in Figure 3-1. The post-processor starts after the *Run Labyseal* button, and includes the geometric leak path diagram as seen in the flowchart. Likewise, the preprocessor is comprised of everything above the Run Labyseal button. Input fields, process macros and results are represented by parallelograms, rectangle and display symbol respectively.

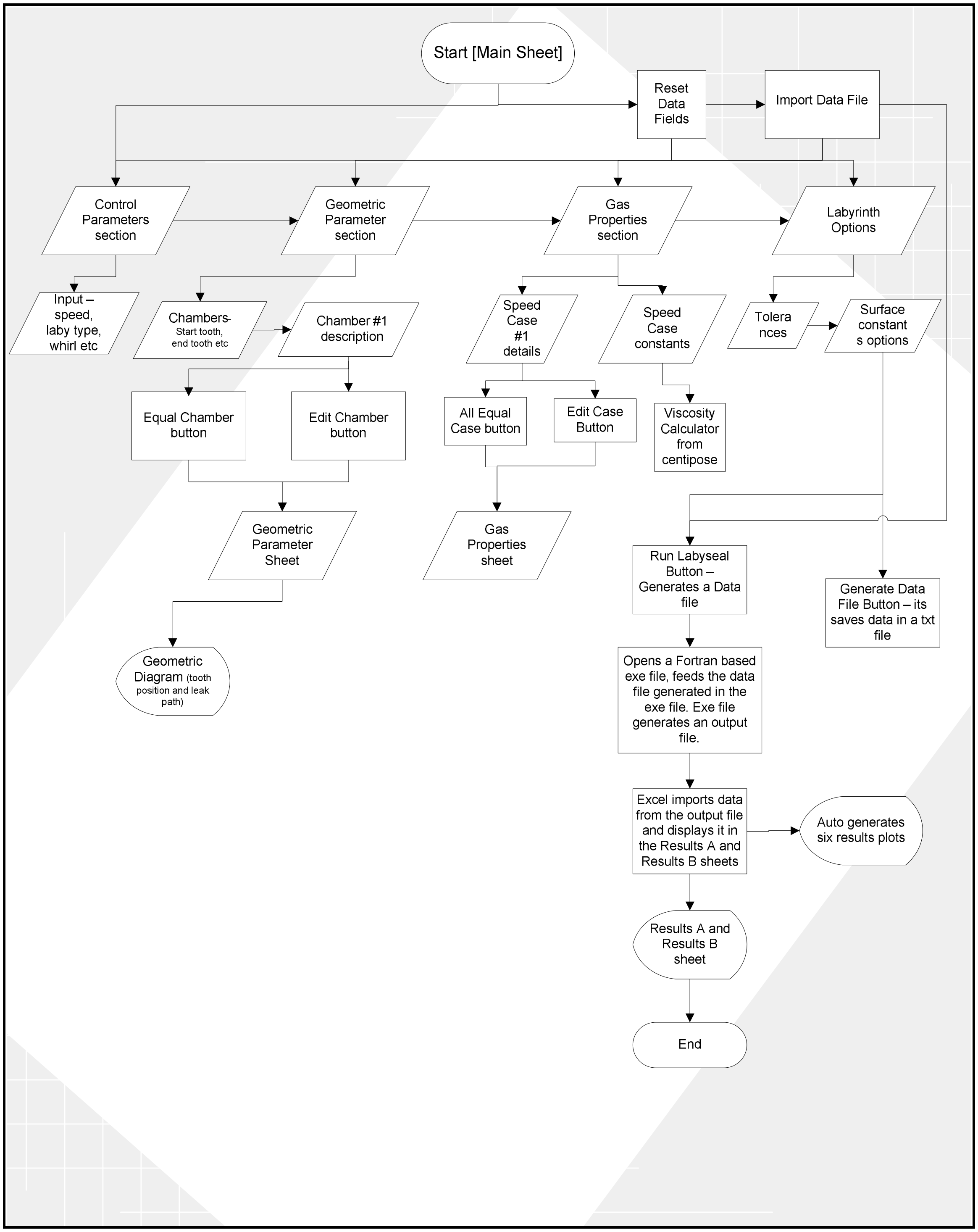


Figure 3-1 Process Flowchart

Macros consisting of preprocessor macros are as follows:

- **Import Data file**

The Import data file macro opens a *GetOpenFileName* application, so that the user can search the file on his computer, then select, and import it. The file has to be a LabyXL data file generated by either by *Run Labyseal* button or *Generate Data File* button, shown in Figure 2-8 in chapter 2. A sample of the data file can be found in the Appendix A. The macro imports all the values for the LabyXL data fields from the data file. The macro is located under Microsoft Excel Objects – Sheet1(Main). Partial code for the macro is shown below.

```
Private Sub CommandButton2_Click()
Dim fileToOpen As Variant
fileToOpen = Application _
   .GetOpenFilename("Text Files (*.txt), *.txt, Dat Files (*.dat), *.dat, All Files(*.*), *.*")
If fileToOpen = False Then
   Exit Sub
End If
Open fileToOpen For Input As #1
Line Input #1, d
Line Input #1, e
Sheet1.Range("E79") = fileToOpen
Sheet1.TextBox1.Value = Mid(A, 1, 80)
Sheet1.TextBox3.Value = Mid(c, 1, 80)
Sheet1.Range("F15") = Mid(e, 51, 10)
If Mid(e, 70, 1) = 1 Then
Sheet1.OptionButton2.Value = True
Else
Sheet1.OptionButton1.Value = True
End If
If bbb Mod 7 = 0 And bbb <> 0 And bbb <> Mid(f, 59, 2) Then
Line Input #1, h
aaa = 0
End If
```

- **Reset Data Fields**

The Reset Data Fields macro prompts the user, by opening a message box displaying “ALL FIELDS RESET! Click OK to continue or Cancel to quit”. If the user clicks on Cancel then the macro ends but if the user clicks on OK, then the macro erases all the data fields. The full macro could be found under Sheet1(Main). Sample of the code is shown below.

```
Private Sub CommandButton4_Click()
```

```
response = MsgBox("All FIELDS RESET! click OK to continue or cancel to QUIT",
vbOKCancel)
If response = vbOK Then
GoTo A
Else
GoTo d
End If
A:
Sheet1.TextBox1.Value = ClearContents
Sheet1.TextBox2.Value = ClearContents
Sheet1.TextBox3.Value = ClearContents
Range("E50:E52").ClearContents
Range("E45:E52").ClearContents
Range("I45:I49").ClearContents
Sheet3.Range("B5:I5").Interior.ColorIndex = 24
Sheet3.Range("B5:I5").Interior.Pattern = xlGray8
Sheet3.Range("B5:I5").Interior.PatternColorIndex = 2
d:
End Sub
```

- **Option Button**

Option button macros are utilized in Control Parameters in the Main Sheet for Type of Whirl, Labyrinth Series and Labyrinth Type. The options for each type are grouped together by assigning a different name to each one. Grouping is important for proper functioning of option buttons. The option button macro has been incorporated in the Run Labyrinth macro. It is located in Module 7 of the VBA project. A sample of the syntax is shown below.

```
Sub Datasheetgenerate()
If Sheet1.OptionButton4.Value = True Then
YY = 1
End If
If Sheet1.OptionButton5.Value = True Then
YY = 2
End If
If Sheet1.OptionButton6.Value = True Then
x = 1
End If
```

- **Check box**

Check boxes are used for pressure calculation option, surface constants, and tooth geometry. If the checkbox is clicked then its value becomes true or else it is false. The syntax for the checkbox can be found in the Module 7. A sample is shown below.

```
Sub chkbox7_click()
If Sheet1.CheckBox7.Value = True Then YNS = "0"
If Sheet1.CheckBox7.Value = False Then YNS = "1"
End Sub
Sub chkbox8_click()
If Sheet1.CheckBox8.Value = True Then YMR = "0"
If Sheet1.CheckBox8.Value = False Then YMR = "1"
End Sub
```

- **Make all Chambers equal to Chamber #1 button macro**

The macro starts with prompting the user that if he is sure that he wants all chambers parameters to be equal to chamber # 1 parameters. If the user clicks cancel, then the macro ends but if the user clicks Ok (yes), then the macro verifies that are all the Chamber # 1 parameters entered or not. If any data field is empty then a message box flashes and asks the user to input that parameter and the macro ends.

```
Private Sub CommandButton1_Click()
response = MsgBox("All current chambers will be equal to chamber 1", vbOKCancel)
If response = vbOK Then
GoTo A
Else
GoTo d
End If
A:
If Sheet1.Range("E37") = "" Then
MsgBox ("Please enter a value for Tooth Height")
GoTo d
End If
If Sheet1.Range("E38") = "" Then
MsgBox ("Please enter a value for Tooth Spacing")
GoTo d
End If
```

Considering, if all chamber parameters are entered then the macro checks for check marks for tooth parameters and surface constants. If the value is false, meaning no check mark then it will copy the given value in all the fields, for the user to edit any value. However, if the value is true then it will copy the given value only for the first tooth and the remaining will be blank. Shown below is a part of the above macro.

```
Dim i As Integer
i = 0
If Sheet1.CheckBox2.Value = False Then
```

```
Do
 sheet2.Cells(7 + i, 2) = Sheet1.Range("E37")
 sheet2.Cells(7 + i, 2).Interior.ColorIndex = xlNone
   i = i + 1
Loop Until i = (Sheet1.Range("F29").Value)
Else
sheet2.Cells(7, 2) = Sheet1.Range("E37")
End If
i = 0

If Sheet1.CheckBox3.Value = False Then
Do
sheet2.Cells(7 + i, 3) = Sheet1.Range("E38")
sheet2.Cells(7 + i, 3).Interior.ColorIndex = xlNone
  i = i + 1
Loop Until i = (Sheet1.Range("F29").Value)
Else
sheet2.Cells(7, 3) = Sheet1.Range("E38")
End If

i = 0
If Sheet1.CheckBox7.Value = False Then
Do
   sheet2.Cells(7 + i, 8) = 0.079
   sheet2.Cells(7 + i, 8).Interior.ColorIndex = xlNone

   i = i + 1
Loop Until i = (Sheet1.Range("F29").Value)
Else
sheet2.Cells(7, 8) = 0.079
End If
```

Furthermore, the macro color-codes the geometric parameter table. The dummy cells are colored grey with color index equal to 15; radial chambers before the laby are colored light yellow with color index 36. The axial chambers for K & C calculation are colored tan with color index of 40. Radial chambers after the laby are colored light green with color index of 35. A sample of color coding syntax is shown below.

```
Sheets("Geometric Parameters").Range("B7:I56").ClearContents
Sheets("Geometric Parameters").Range("B7:I56").Interior.ColorIndex = 15

' shading color index 40 for axial chambers - k c calculation
Dim r As Integer
Dim q As Integer
r = Sheet1.Range("I30")
q = Sheet1.Range("I31")
p = q - r
```

```
t = 0
s = 0
Do Until p = t - 1
sheet2.Cells(6 + r + t, 2 + s).Interior.ColorIndex = 40
s = s + 1
If s = 8 Then
s = 0
t = t + 1
End If
Loop

' shading for radial before laby
r = Sheet1.Range("F28")
t = 0
s = 0
Do Until t = r - 1
If r = 0 Then
GoTo z
End If
sheet2.Cells(7 + t, 2 + s).Interior.ColorIndex = 36
s = s + 1
If s = 8 Then
s = 0
t = t + 1
End If
Loop
z:
b:
y:
sheet2.Range("B7:E7").Interior.ColorIndex = 24
sheet2.Range("B7:E7").Interior.Pattern = xlGray8
sheet2.Range("B7:E7").Interior.PatternColorIndex = 2
Sheet3.Range("B5:I5").Interior.ColorIndex = 24
Sheet3.Range("B5:I5").Interior.Pattern = xlGray8
Sheet3.Range("B5:I5").Interior.PatternColorIndex = 2
Sheets("Geometric Parameters").Select
d:
End Sub
```

- **Edit Chambers button macro**

This macro is similar to Make all chamber equal to chamber # 1 macro. It checks for missing geometric parameters and prompts the user if any data is missing, checks for check marks and if check mark is present then colors the column grey (dummy) in the Geometric Parameter table. Unlike the ‘Make all chambers equal’ macro, it does not copy or delete any data from the table. In a nut shell the edit chamber macro, checks for any changes or missing data and opens the Geometric Parameter sheet. Sample of the code is shown below.

```
Private Sub CommandButton5_Click()
If Sheet1.Range("E37") = "" Then
MsgBox ("Please enter a value for Tooth Height")
GoTo d
End If

If Sheet1.Range("E38") = "" Then
MsgBox ("Please enter a value for Tooth Spacing")
GoTo d
End If

Dim i As Integer
i = 0
If Sheet1.CheckBox2.Value = False Then

Do
Sheet2.Cells(7, 2) = Sheet1.Range("E37")
Sheet2.Cells(7 + i, 2).Interior.ColorIndex = xlNone
i = i + 1
Loop Until i = (Sheet1.Range("F29").Value)
Else
Sheet2.Cells(7, 2) = Sheet1.Range("E37")
End If
' shading for radial before laby

r = Sheet1.Range("F28")
t = 0
s = 0
Do Until t = r - 1
If r = 0 Then
GoTo z
End If
Sheet2.Cells(7 + t, 2 + s).Interior.ColorIndex = 36
s = s + 1
If s = 8 Then
s = 0
t = t + 1
End If
Loop
z:
Sheet2.Activate
d:
End Sub
```

- **Make all Speed Cases equal to Speed Case # 1 button macro**

The macro checks for Speed Case # 1 parameters. If any data field is empty then a message box flashes and asks the user to input that parameter and the macro ends. Considering all the parameters for Speed Case # 1 are entered, the macro prompts the user that if he is sure that he wants all Speed cases to be equal. If the user clicks cancel, then the macro ends but if the user clicks Ok, then the macro copies Speed case # 1 parameters to all the remaining speed cases. For instance, if a user chooses five speed cases then the Make all speed cases equal macro will make the first five speed cases equal and the remaining will be colored grey.

```
Private Sub CommandButton3_Click()
If Sheet1.Range("E47") = "" Then
MsgBox ("Please enter a value for Pressure at Inlet")
GoTo d
End If
If Sheet1.Range("E47") = "" Then
MsgBox ("Please enter a value for Pressure at inlet")
GoTo d
End If
response = MsgBox("All Speed Cases will equal to Speed Case # 1", vbOKCancel)
If response = vbOK Then
GoTo A
Else
GoTo d
End If
A:
i = 0
Do
   Sheet3.Cells(5 + i, 8) = Sheet1.Range("E50")
   Sheet3.Cells(5 + i, 8).Interior.ColorIndex = xlNone
   i = i + 1
Loop Until i = (Sheet1.Range("F16").Value)

i = 0
Do
   Sheet3.Cells(5 + i, 9) = Sheet1.Range("E52")
   Sheet3.Cells(5 + i, 9).Interior.ColorIndex = xlNone
    i = i + 1
Loop Until i = (Sheet1.Range("F16").Value)
Sheet2.Range("B7:E7").Interior.ColorIndex = 24
Sheet2.Range("B7:E7").Interior.Pattern = xlGray8
Sheet2.Range("B7:E7").Interior.PatternColorIndex = 2

Sheet3.Range("B5:I5").Interior.ColorIndex = 24
Sheet3.Range("B5:I5").Interior.Pattern = xlGray8
Sheet3.Range("B5:I5").Interior.PatternColorIndex = 2
Sheets("Gas Properties").Select
d:
End Sub
```

- **Edit Speed Case button macro**

The Edit Speed Case macro, similar to Make all speed case equal macro, verifies that are all the Speed Case # 1 parameters entered or not. If any data field is empty then a message box flashes and asks the user to input that parameter, and the macro ends. If there is no missing data then, it copies parameters of Speed Case # 1 from the main sheet to the Gas Property table, keeping the remaining speed cases undisturbed and it opens the Gas Properties sheet. A sample of the code is shown below, and the code can be found in VB applications Sheet1 (main).

```
Private Sub CommandButton6_Click()
Dim i As Integer
If Sheet1.Range("E47") = "" Then
MsgBox ("Please enter a value for Pressure at Inlet")
GoTo d
End If
If Sheet1.Range("E47") = "" Then
MsgBox ("Please enter a value for Pressure at inlet")
GoTo d
End If
Sheets("Gas Properties").Range("B5:I14").Interior.ColorIndex = 15
i = 0
Do
   Sheet3.Cells(5, 2) = Sheet1.Range("F15")
   Sheet3.Cells(5 + i, 2).Interior.ColorIndex = xlNone
     i = i + 1
Loop Until i = (Sheet1.Range("F16").Value)

Sheet2.Range("B7:E7").Interior.ColorIndex = 24
Sheet2.Range("B7:E7").Interior.Pattern = xlGray8
Sheet2.Range("B7:E7").Interior.PatternColorIndex = 2

Sheet3.Range("B5:I5").Interior.ColorIndex = 24
Sheet3.Range("B5:I5").Interior.Pattern = xlGray8
Sheet3.Range("B5:I5").Interior.PatternColorIndex = 2
Sheets("Gas Properties").Select
d:
End Sub
```

- **Viscosity Calculator macro**

This macro converts gas viscosity from centipose units to Lbm / (ft*sec). It opens an Input Box for user to enter gas viscosity. The equation for the conversion is:

Gas viscosity (Lbm/ft/sec) = cp * 12 * 386 * 1.45E-7 **(3-1)**

As soon as the macro receives the input in centipose, it converts it to Lbm/ft*sec and pastes it in the gas viscosity input field. The syntax is shown below.

```
Private Sub CommandButton8_Click()
Dim myvalue
myvalue = InputBox("Enter a value for centipose(cp)" & Chr(10) & Chr(10) & "Gas Visocity =
cp*12.0*386.0*1.45E-7", "Gas Visocity Calculator")
If myvalue = "" Then
GoTo h
Else
Sheet1.Range("F63").Value = (myvalue * 12 * 386 * 0.000000145)
End If
h:
End Sub
```

- **Generate Data File macro**

As the name implies, the macro extracts data from the Excel spreadsheets into a fixed format text file. The following are the steps in which the macro saves the data.

1. The macro begins by calling a function *checkfield*s, to check for any missing data on the main sheet. If any data is missing, a message-box displaying the missing parameter pops-up, and the macro ends. The function uses a counter called *trapy* to check for missing fields. If any data is missing then *trapy* will be less than 25, and if trapy is less than 25 then the macro is forced to end. The function is located in Module 7 and the Generate data file macro is located in Sheet1 (Main) in VBA project. Sample syntax is shown below.

```
Function checkfields()
trapy = 0
Dim mycheck
IsNumeric (Sheet1.Range("F15").Value)
If IsNumeric(Sheet1.Range("F15").Value) And Sheet1.Range("F15").Value <> ""
Then
trapy = trapy + 1
Else
MsgBox ("Rotor Speed (F15) field Missing!!")
End If
If IsNumeric(Sheet1.Range("F59")) And Sheet1.Range("F59") <> "" Then
trapy = trapy + 1
Else
MsgBox ("Absolute Velocity (F59) field Missing!!")
```

```
End If
End Function

Private Sub CommandButton7_Click()
Call checkfields
If trapy < 25 Then
GoTo endit
End If
```

2. The macro calls all the Checkbox subroutines to check their values. Zero is assigned to the variable if the value is true and one if the value is false. Syntax is shown below.

```
Call chkbox2_click
Call chkbox3_click
Call chkbox4_click
Call chkbox5_click
Call chkbox6_click
Call chkbox7_click
Call chkbox8_click
Call chkbox9_click

Sub chkbox7_click()
If Sheet1.CheckBox7.Value = True Then YNS = "0"
If Sheet1.CheckBox7.Value = False Then YNS = "1"

End Sub
Sub chkbox8_click()
If Sheet1.CheckBox8.Value = True Then YMR = "0"
If Sheet1.CheckBox8.Value = False Then YMR = "1"
End Sub.
```

3. The macro calls for a function, *GetSaveAsTxtFilename.* The function opens an application called *GetSaveAsFilename.* The application displays the standard open-dialog-box and gets a file name and path from the user to save it. The file path and name is then saved on the “Main” sheet in cell E79.

```
Call GetSaveAsTxtFilename
If fun = 1 Then
 GoTo Dumo          ‘Sub ends
 End If

Function GetSaveAsTxtFilename(Optional InitialFileName As Variant) As String
Dim vFilename As Variant
fun = 0
If IsMissing(InitialFileName) Then
   InitialFileName = ""
```

```
End If
vFilename = _
  Application.GetSaveAsFilename( _
  InitialFileName:=InitialFileName, _
  Title:="Please select a folder and name to save the file", _
  fileFilter:="Text files *.txt (*.txt),")
If vFilename = False Then
     GetSaveAsTxtFilename = ""
‘if cancel is pressed
fun = 1
Else
   GetSaveAsTxtFilename = vFilename
   Sheet1.Range("E79") = vFilename
End If
End Function

Set filename = Sheet1.Range("E79")
```

4. The data file created by the user is opened to save the data. Before printing any data in, the macro truncates the path name from the string variable, *filename,* in order to get just the name of the data file. This is done to save the results file in the same name but with *.out* extension. The string variable, *temp5,* stores the truncated name of the data file.

```
Open filename For Output As #1
Dim Temp1 As String
Dim Temp2 As String
Dim temp4 As String
Dim Temp3 As Integer
Dim temp5 As String
temp$ = CurDir
Temp1$ = Len(filename)
Temp2$ = Len(temp$)
Temp3 = Temp1$ - Temp2$ - 1
temp4 = Right$(filename, Temp3)
temp5 = Mid(temp4, 1, Temp3 - 4)
```

5. The macro starts printing the data from the Mainsheet to the data file, which includes variables of checkboxes, option buttons, and textboxes. Each print command prints data on the new line.

```
If Sheet1.OptionButton1.Value = True Then
y = 0
End If
Print #1, Sheet1.TextBox1.Value
Print #1, Sheet1.TextBox2.Value
```

```
Print #1, Sheet1.TextBox3.Value
Print #1,
Print #1, "CROTOR SPEED-RPM;NSPD;TYPE WHIRL,0=SYN,1=NON;SPD =" &
Format(Range("F15"), "000.00E+00;-00.00E+00") & "   " & Format(Range("F16"),
"00") & "    " & Format(y, "0")
Print #1, "CRAD OPT;SERIES;TYP 1 STA./2 ROT/3 I-LOCK;STEP;I;IRS=" &
Format(Range("F28"), "00") & "ST=" & Format(YY, "0") & Format(x, "0"); " IS=" &
Format(ISS, "0") & " IB=" & Format(Range("F24"), "0")
```

6. Geometrical Parameter table variable is printed in a way such that maximum of seven values can be printed on one line. If it exceeds seven then it prints on the next line. This is achieved my using the Mod function, it returns the remainder after number is divided by divisor. Here the divisor is seven. Thus, if the function returns a zero then the macro prints to the next line. Printing of only seven values on a line is done to follows the DYNLAB data input file format. The syntax is shown below.

```
Print #1, "CTOOTH HEIGHT(IF KEY=1,INSERT LINE(S) 7G10.2)KEY =" &
Format(keyb, "0000000000") & "B=" & Format(Sheet1.Range("E37"), "+00.00E+00")
If (keyb = "1") Then
 n = 0
 For Each toothheight In Sheet2.Range("B7", Sheet2.Range("B7").End(xlDown))
  strnme = toothheight.Value
    If n Mod 7 = 0 And n <> 0 Then
     Print #1,
     End If
  Print #1, Format(toothheight, "000.00E+00;-00.00E+00");
  n = n + 1
Next toothheight
Print #1,
End If
```

7. The macro uses a *Do* loop to print values from the gas property table to the data sheet. It prints until variable *caseno* exceeds variable *NSPD*. Variable *NSPD* stores the number of cases selected by the user. If printing is successful then a message box displays the name and path of the filename. Syntax is shown below.

```
Print #1, "C  SPEED  SWIRL     PS        PE        TABS      Z        GAMMA     MW
VABS     MUXG     CP       Ncr"

Dim caseno As Integer
caseno = 1
Do Until caseno > NSPD
Print #1, Format(Sheet3.Range("B" & 4 + caseno), "000.00E+00;-00.00E+00") &
Format(Sheet3.Range("C" & 4 + caseno), "000.00E+00;-00.00E+00") &
```

```
Format(Sheet3.Range("D"    &    4    +    caseno),    "000.00E+00;-00.00E+00")    &
Format(Sheet3.Range("E"    &    4    +    caseno),    "000.00E+00;-00.00E+00")    &
Format(Sheet3.Range("F"    &    4    +    caseno),    "000.00E+00;-00.00E+00")    &
Format(Sheet3.Range("G"    &    4    +    caseno),    "000.00E+00;-00.00E+00")    &
Format(Sheet3.Range("H"    &    4    +    caseno),    "000.00E+00;-00.00E+00")    &
Format(Sheet3.Range("I"    &    4    +    caseno),    "000.00E+00;-00.00E+00")    &
Format(Sheet3.Range("J"    &    4    +    caseno),    "000.00E+00;-00.00E+00")    &
Format(Sheet3.Range("K"    &    4    +    caseno),    "000.00E+00;-00.00E+00")    &
Format(Sheet3.Range("L"    &    4    +    caseno),    "000.00E+00;-00.00E+00")    &
Format(Sheet3.Range("M" & 4 + caseno), "000.00E+00;-00.00E+00")
caseno = caseno + 1
Loop

Close #1
MsgBox ("Successfull! Data File saved in " & filename)
```

3.2 Post-Processor Macros

LabyXL's post-processor is developed to model the labyrinth seal accurately and to study influence of change in various parameters. The post-processor generates a gas leak-path graph with tooth location, for the user to visualize the labyrinth geometry. Furthermore, it imports and tabulates the results, and generates six different graphs to better analyze the results. The post-processor comprises of two major macros – Geometric Diagram macro and Run Labyseal macro.

- **Geometric Diagram macro**

The macro automatically generates the leak path and tooth location of the labyrinth seal. Stator and rotor boundaries formulate the leak path. Table 3.1 gives the detail calculations for X and Y-axis coordinates for both stator and rotor boundary points. Labyrinth teeth for K & C calculation are highlighted in black, whereas dummy teeth are white. Refer to Figure 2-10 for the geometric diagram. Part of the macro is shown below.

```
ActiveChart.SeriesCollection(1).Select
With Selection
        .MarkerBackgroundColorIndex = 1
        .MarkerForegroundColorIndex = 1
        .MarkerStyle = xlNone
```

```
        .Smooth = True
        .Shadow = False
    End With

Sheet6.Range("o3").Select
End If

ActiveSheet.ChartObjects("Chart 11").Activate

If Sheet1.OptionButton6.Value = True Then
ActiveChart.SeriesCollection(5).XValues = "='Geometric Diagram'!R35C22:R85C22"
    ActiveChart.SeriesCollection(5).Values = "='Geometric Diagram'!R35C23:R85C23"
    ActiveChart.SeriesCollection(5).Name = "=""K&C teeth"""
    End If
```

Table 3-1 Rotor and Stator Boundary Line Calculation

	Tooth #	Rotor boundary		Stator boundary	
		X- coordinate **(B)**	Y- coordinate **(C)**	X – coordinate **(D)**	Y – coordinate **(E)**
Radial teeth before labyrinth	**1**	0	Shaft rad.	B1 + Ht. + clearance	Shaft rad.
	2	B1 + SpacingT1	Shaft rad.	B2 + Ht. + clearance	Shaft rad.
	3	B2 + SpacingT2	Shaft rad.	B3 + Ht. + clearance	Shaft rad.
	4	B3 + SpacingT3	Shaft rad.	B4 + Ht. + clearance	Shaft rad.
	5	B4 + SpacingT4	Shaft rad.	B5 + Ht. + clearance	Shaft rad.
	6	B5 + SpacingT5	Shaft rad.	B6 + Ht. + clearance	Shaft rad.
	7	B6 + SpacingT6	Shaft rad.	B7 + Ht. + clearance	Shaft rad.
Axial teeth	**8**	B7 + SpacingT7	Shaft rad.	B8	Shaft rad. + Ht. + Clearance
	9	B8 + SpacingT8	Shaft rad.	B9	Shaft rad. + Ht. + Clearance
	10	B9 + SpacingT9	Shaft rad.	B10	Shaft rad. + Ht. + Clearance
	11	B10 + SpacingT10	Shaft rad.	B11	Shaft rad. + Ht. + Clearance
	12	B11 + SpacingT11	Shaft rad.	B12	Shaft rad. + Ht. + Clearance
	13	B12 + SpacingT12	Shaft rad.	B13	Shaft rad. + Ht. + Clearance
	14	B13 + SpacingT13	Shaft rad.	B14	Shaft rad. + Ht. + Clearance
Radial teeth after the Labyrinth	**15**	B14 + SpacingT14	Shaft rad.	B15 – Ht. – clearance	Shaft rad.
	16	B15 + SpacingT15	Shaft rad.	B16 – Ht. – clearance	Shaft rad.
	17	B16 + SpacingT16	Shaft rad.	B16 – Ht. – clearance	Shaft rad.
	18	B17 + SpacingT17	Shaft rad.	B17 – Ht. – clearance	Shaft rad.
	19	B18 + SpacingT18	Shaft rad.	B18 – Ht. – clearance	Shaft rad.
	20	B19 + SpacingT19	Shaft rad.	B19 – Ht. – clearance	Shaft rad.
	21	B20 + SpacingT20	Shaft rad.	B20 – Ht. – clearance	Shaft rad.

B# represents the cell in column B and the tooth row number

C# represents the cell in column C and the tooth row number

SpacingT# represents the spacing of the respective tooth number.

Clearance represents the clearance of the respective tooth

Ht. represents the height of the respective tooth

Shaft rad. represents the shaft radius of the respective tooth

- **Run Labyseal macro**

Run Labyseal button macro includes the entire Generate Data sheet macro besides it includes the following.

1. The Run macro finishes all the tasks for Generate Data Sheet macro then it generates a text file named answers.txt in a folder called Labyseal. The macro prints the data-sheet path on the first line of answers.txt; on the second line, it prints the output file name, with the same name as the Data file name but with .out extension. On the third and fourth line, it prints current.out and labxlin.txt. All the three output files have the same path as the data file. Once the answers.txt file has been created, the *Shell* command first opens the command prompt then the FORTRAN based executable program file called laby2008.exe. The Run macro feeds answers.txt file to the executable program.

```
Open "C:\Labyseal\answers.txt" For Output As #1
Print #1, filename
Print #1, temp$ & "\" & temp5 & ".out"
Print #1, temp$ & "\current.out"
Print #1, temp$ & "\Labxlin.txt"
Print #1,
Close

cs = Environ$("COMSPEC")
Shell cs & " /c C:\Labyseal\laby2006.exe < C:\Labyseal\answers.txt",
vbMaximizedFocus
```

2. The macro deletes all the contents of the results section. The syntax is shown below.

```
Sheet4.Range("A14:Q120").ClearContents
Sheet5.Range("A11:G450").ClearContents
Sheet4.Range("A15:Q120").Font.Bold = False
Sheet5.Range("A11:G450").Font.Bold = False
Sheet4.Range("A15:Q120").Borders.LineStyle = xlNone
Sheet4.Range("A15:Q120").Font.ColorIndex = 1
Sheet5.Range("A11:G450").Font.ColorIndex = 1
Sheet4.ChartObjects.Delete
 sheet4.Activate
Sheet5.ChartObjects.Delete
```

3. The macro opens the data sheet saved by the user and acquires the directory information. The output file “labxlin.txt” is found in that directory, and is renamed to “labx.txt”. Before renaming the file the macro checks for previously saved files and deletes them. A *Do* loop is used to rename the file. The syntax is shown below.

```
A = Sheet1.Range("E79")
Open A For Input As #1
c = CurDir
d = CurDir & "\labxlin.txt"
labx = CurDir & "\labx.txt"
Close #1

If Len(Dir(labx)) > 0 Then Kill labx

‘’Test for previous files and delete them.


msg = MsgBox("Successful!! To see results click OK", vbOKOnly)
If msg = vbOK Then

Do Until Len(Dir(labx)) > 0

 ‘‘Begin a loop to test for final output file, labx.txt.

  Name (d) As (labx)

  ‘‘Attempt to rename
  ‘‘will fail until temp.txt is closed


On Error Resume Next
        Loop
Else
GoTo q
End If
```

4. The macro opens labx.txt to extract data. It imports the data from the labx.txt file to results section A and B. The macro uses the syntax ‘*Line Input #1, h*’ to go to the next line in the text file. The data is imported in three tables.

```
Open labx For Input As #1
Line Input #1, h

g = Mid(h, 2, 6)
Line Input #1, h
Line Input #1, h
```

Table1

```
Sheet4.Cells(14 + ccc, 6) = Mid(h, 42, 8)
Sheet4.Cells(14 + ccc, 6).Borders.LineStyle = xlContinuous
Sheet4.Cells(14 + ccc, 7) = Mid(h, 52, 8)
Sheet4.Cells(14 + ccc, 7).Borders.LineStyle = xlContinuous

ccc = ccc + 1
Line Input #1, h
Loop
```

Table 2

```
Sheet4.Cells(17 + ccc, 1) = "Rotor Speed[RPM]"
Sheet4’.Cells(18 + ccc, 1) = "Total Temp[Deg-R]"
Sheet4.Cells(19 + ccc, 1) = "Static Temp[Deg-R]"

Line Input #1, h
Sheet4.Cells(23 + ccc, 2 + ww) = Mid(h, 27, 10)
Sheet4.Cells(23 + ccc, 2 + ww).Borders.LineStyle = xlContinuous

Line Input #1, h
Sheet4.Cells(24 + ccc, 2 + ww) = Mid(h, 27, 10)
Sheet4.Cells(24 + ccc, 2 + ww).Borders.LineStyle = xlContinuous


‘' do loop for the speed cases from sheet3

Do Until t = 6
Sheet4.Cells(25 + ccc, 2 + ww) = Sheet3.Cells(5 + ww, 3 + t)
Sheet4.Cells(25 + ccc, 2 + ww).Borders.LineStyle = xlContinuous

ccc = ccc + 1
t = t + 1
Loop

'‘data import starting from start teeth for KC

Line Input #1, h
Sheet4.Cells(25 + ccc, 2 + ww) = Mid(h, 27, 10)
Sheet4.Cells(25 + ccc, 2 + ww).Borders.LineStyle = xlContinuous
```

Table 3

```
Sheet5.Cells(11 + ss, 1) = "Speed Case # " & dd
Sheet5.Cells(11 + ss, 1).Font.Bold = True

Dim na As Integer

Do Until ss = (dd * 2 * Sheet1.Range("F29").Value) + 1 + (ww)

If IsNumeric(Mid(h, 2, 8)) Then
Sheet5.Cells(11 + ss, 2) = Mid(h, 2, 8)
Else
Sheet5.Cells(11 + ss, 2) = "=NA()"
Sheet5.Cells(11 + ss, 2).Font.ColorIndex = 2
End If

Sheet5.Cells(11 + ss, 2).Borders.LineStyle = xlContinuous
```

5. The macro generates six plots:
    - Swirl Vs Chamber
    - Area, ASL, ARL & Hyd. Diameter Vs Chamber
    - Effective Damping and Stiffness Vs Speed Cases
    - Mach number Vs Tooth
    - Temperature Vs Chamber
    - Pressure Vs Chamber

The Run Labyseal macro calls a function called *pressplot* to generate Pressure Vs chamber plot. Syntax is shown below.

```
Function pressplot()

Sheet5.Activate
Sheet5.Select
Dim nosteth As Integer
Dim num As Integer
Dim num2 As Integer
Dim casenum As Integer
casenum = 1
Dim startethrow As Integer
startethrow = 11

nosteth = Sheet1.Range("F29")
num = (2 * nosteth) + 11
```

```
num2 = 11

‘’ Adds the chart to the active sheet

Charts.Add
ActiveChart.ChartType = xlXYScatterSmooth
ActiveChart.SeriesCollection.NewSeries
ActiveChart.Location Where:=xlLocationAsObject, Name:="Results B"

‘’ Selects the type of chart


Do Until casenum = Sheet1.Range("F16") + 1
ActiveChart.SeriesCollection(casenum).Name = "='Results B'!R" & num2 & "C1"
ActiveChart.SeriesCollection(casenum).Values = "='Results B'!R" & startethrow &
"C6:R" & num & "C6"
ActiveChart.SeriesCollection(casenum).XValues = "='Results B'!R" & startethrow
& "C4:R" & num & "C4"
casenum = casenum + 1
num2 = num2 + (2 * nosteth) + 1
startethrow = startethrow + (2 * nosteth) + 1
num = num + (2 * nosteth) + 1
ActiveChart.Location Where:=xlLocationAsObject, Name:="Results B"

’’ Adds a new series to the active chart

ActiveChart.SeriesCollection.NewSeries
Loop
ActiveChart.SeriesCollection(casenum).Delete

‘’ Labels the X, Y axis and the title

With ActiveChart
.HasTitle = True
.ChartTitle.Characters.Text = "Pressure Vs Chamber"
.Axes(xlCategory, xlPrimary).HasTitle = True
.Axes(xlCategory, xlPrimary).AxisTitle.Characters.Text = "Chamber"
.Axes(xlValue, xlPrimary).HasTitle = True
.Axes(xlValue, xlPrimary).AxisTitle.Characters.Text = "Pressure"
  End With

  With ActiveChart
.HasAxis(xlCategory, xlPrimary) = True
.HasAxis(xlValue, xlPrimary) = True
 End With
 ActiveChart.Axes(xlCategory, xlPrimary).CategoryType = xlAutomatic

                Set rngi = Sheet5.Range("I50:P66")
With Sheet5.ChartObjects(3)
```

```
‘’ Places the chart at the right position with the right size

.Top = rngi.Top
.Left = rngi.Left
.Width = rngi.Width
.Height = rngi.Height
End With

End Function
```

The Run Labyseal macro ends after calling the TempPlot and PressPlot functions.

CHAPTER 4

Parametric Study

Parametric study plays a vital role in understanding influence of various factors governing the dynamics of a system. The objective of this parametric study is to examine influence of different operating conditions and gas properties on effective cross-coupling stiffness. Effect of synchronous and non-synchronous rotor whirl on parameters of major influence is also examined. Investigation is performed on API Rotor Stability Survey [2006], impeller # 1 eye and balance piston labyrinth seal models using LabyXL program developed herein. This study will help rotordynamic analysts to solve instability problems more efficiently.

This chapter covers modeling of all API survey labyrinth seals and comparison with actual respondents. Furthermore, a parametric study is performed on API's impeller # 1 eye labyrinth and Balance Piston labyrinth seal.

4.1 API Seal Modeling and Comparison

In order to improve American Petroleum Institute (API) specifications, API conducted a survey of several turbomachinery analysts to determine dynamic coefficients of tilt pad bearing, first and last impeller eye labyrinth and labyrinth balance piston. This research focuses on modeling of first and last impeller eye labyrinth and balance piston labyrinth by utilizing LabyXL program.

The three labyrinth seals mentioned above are modeled using the parameters provided by API, shown in Table 4.1. All labyrinth seals are modeled as teeth on rotor for an operating speed of 21662 rpm. Swirl ratio of 0.7 and the critical speed location at operating of 6700 cpm is assumed. The absolute velocity for each labyrinth seal was calculated by using,

$$\mathbf{V_{abs} = r\omega * sr} \tag{4-1}$$

where, V_{abs} = absolute velocity in ft/sec
r = shaft radius in inches
ω = shaft speed in radians/sec
sr = swirl ratio of gas at inlet

Table 4-1 API labyrinth seal parameters

Operating conditions	**Impeller eye # 1**	**Impeller eye # 5**	**Balance Piston**
Gas	Nitrogen	Nitrogen	Nitrogen
Speed (rpm)	21662	21662	21662
Critical speed (cpm)	6700	6700	6700
Inlet Pressure (psi)	1548	3035	3035
Discharge Pressure (psi)	1201	2637	1201
Inlet temperature (°R)	585.7	805.7	805.7
Geometric Parameters			
# of Teeth	4	4	11
Diameter (in)	5.25	5.25	5.00
Tooth height (in)	0.089	0.089	0.100
Tooth spacing (in)	0.098	0.098	0.155
Tooth clearance (in)	0.005	0.005	0.005
Gas Properties			
Compressibility	1.02	1.104	1.104
Mole weight	28..0134	28..0134	28..0134
Specific Heat Ratio	1.535	1.502	1.502
Viscosity (cP)	0.021	0.026	0.026

Three cases are run using the above parameters. Table 4-2 shows results for synchronous and non-synchronous type of whirl. Effective cross-coupling stiffness is calculated using equation 4-2 developed by Kirk [5].

$$\mathbf{Qe = Kxy - Cxx{*}\omega_{Ncr}} \qquad \mathbf{(4\text{-}2)}$$

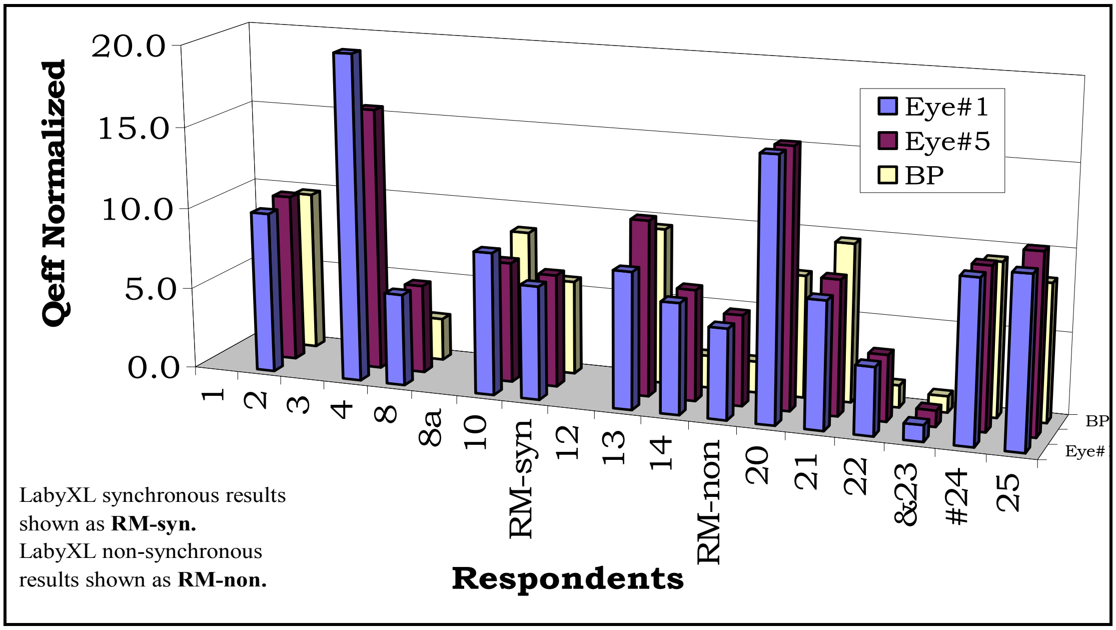
where,

Qe = effective cross-coupling stiffness in lbf/in
Kxy = cross-coupling stiffness in lbf/in
Cxx = direct damping in lbf-s/in
ω_{Ncr} = rotor natural frequency in rad/sec.

Results are then compared to the results of the API survey respondents in Figure 4-1. Two respondents with major deviation have been removed from the comparison to get a better insight.

Table 4-2 Results for the dynamic coefficients of the API survey

Component		**Stiffness (lbf/in)**				**Damping (lbf-sec/in)**				**Qe (lbf/in)**
		Kxx	Kxy	Kyx	Kyy	Cxx	Cxy	Cyx	Cyy	
Imp # 1 eye laby	Syn	-641.06	4193.50	-4193.50	-641.06	2.08	0.10	-0.10	2.08	**2734.6**
	Non-Syn	-786.11	2623.20	-2623.20	-786.11	0.64	0.24	-0.24	0.64	**2174.9**
Imp # 5 eye laby	Syn	-1288.10	5379.10	-5379.10	-1288.10	2.66	0.31	-0.31	2.66	**3510**
	Non-Syn	-1149.30	3413.00	-3413.00	-1149.00	0.84	0.35	-0.35	0.84	**2827.9**
Bal. Piston	Syn	-75232	23923	-23923	-75232	10.23	31.00	-31.00	10.23	**16741**
	Non-Syn	-19564	6581.9	-6581.9	-19564	1.41	7.00	-7.00	1.41	**5592**



LabyXL synchronous results shown as **RM-syn.**
LabyXL non-synchronous results shown as **RM-non.**

Figure 4-1 API survey results [22] for Normalized Destabilizing Force compared with LabyXL Synchronous and Non-synchronous results.

API stiffness results are normalized using the minimum stiffness supplied, and same respondents damping results are used to normalize damping coefficients. Effective cross-coupling (Qeff) is then calculated using the normalized values. Comparison plots with actual values (not normalized) can be found in Appendix C.

Kocur et. al [22] studied the variability of the survey response and concluded: *"To date, there remain significant differences across the industry in the prediction of the dynamic coefficients for fluid film tilt pad bearings and labyrinth seals."* Well, one of the major differences could be due to using synchronous or non-synchronous assumption. LabyXL results for synchronous and non-synchronous are plotted in Figure 4-1. As far as LabyXL credibility is concerned, Kirk et. al [8] and Moore [12] have verified DYNLAB (now called LabyXL) results with CFD, which has shown good agreement. Moreover, it is clearly seen in Figure 4-1 that LabyXL results lie in the ballpark of the median of survey results. Thus, assuming LabyXL results are near accurate a parametric study is performed using LabyXL on API seals.

4.2 Influence of Various Parameters of Labyrinth Eye Seal on Effective Cross-coupling Stiffness

Effects of operating conditions and gas properties on effective cross-coupling stiffness (aerodynamic excitation) are investigated by using Impeller # 1 eye labyrinth seal API model. All parameters from Table 4.1 remain constant except for the parameter under investigation. In the parametric study figures, the reference case, API LabyXL result, is circled in black.

The results shown in Figure 4-2 and 4-3 make clear that increase in rotor speed and gas inlet swirl ratio aggravate the excitation. The swirl ratio, quite interestingly, at least for this particular case, if reduced to 0.4 would make the destabilizing force negative. Meaning, the destabilizing force would act as a stabilizing force or could even produce backward rotor whirl instead of forward. Pressure ratio on the other hand if increased reduces the magnitude of Qe, as seen in Figure 4-4. (Note: increasing the pressure ratio for labyrinth seal would mean reducing the pressure drop across the seal). All conclusions made above apply to both – synchronous and non-synchronous type of whirl.

Figure 4-5 and 4-6 show results of variation of first natural frequency (Ncr) by setting rotor speed constant at 21662 rpm and by setting rotor speed equal to Ncr respectively. By varying Ncr, rotor whirl frequency (at first natural frequency) may also vary; since, LabyXL assumes both equal. The cross-coupling stiffness (Kxy) and direct damping (Cxx) remain constant for the synchronous case as expected, but Qe significantly decreases (refer to Figure 4-5) as Ncr increases because, in order to calculate Qe (Equation 4-2), Ncr is multiplied with Cxx and subtracted from Kxy. For the non-synchronous case, Kxy and Cxx increase with increase in Ncr (not shown in the figure). However, Qe gradually decreases due to substantial increase in direct damping. Due to this gradual reduction, Qe for the non-synchronous case eventually becomes greater than Qe for the synchronous case when Ncr is about half the rotor speed. When rotor speed is set equal to Ncr (seen in Figure 4-6), in other words when synchronous and non-synchronous conditions are same, the system may experience *resonance* or critical condition and Qe results in a negative value and further decreases as rotor speed and Ncr increase.

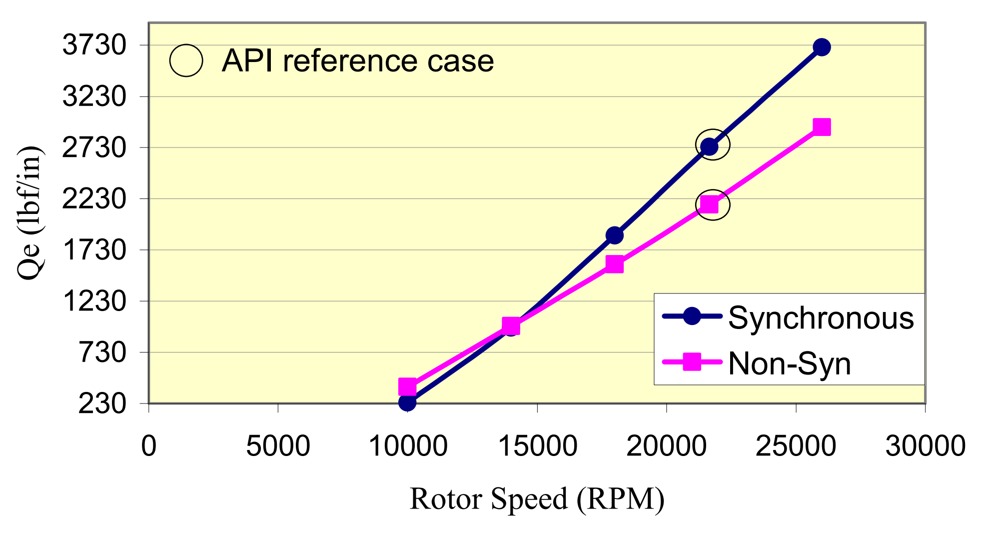


Figure 4-2 Influence of Rotor Speed on Effective Cross-Coupling Stiffness

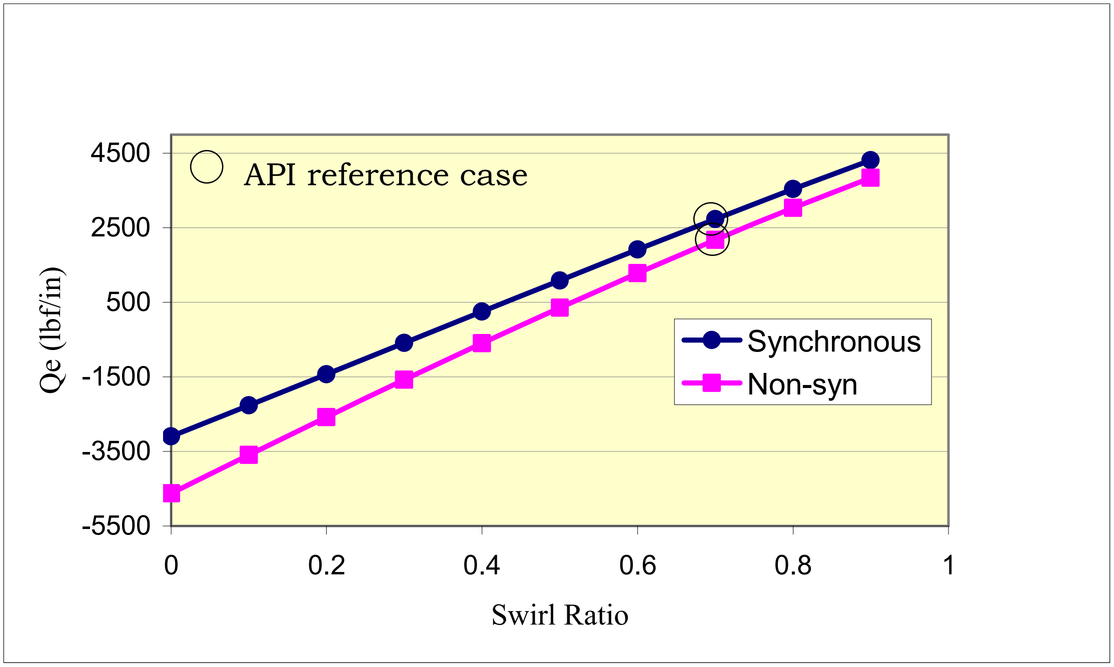


Figure 4-3 Influence of Inlet Gas Swirl Ratio on Effective Cross-Coupling Stiffness

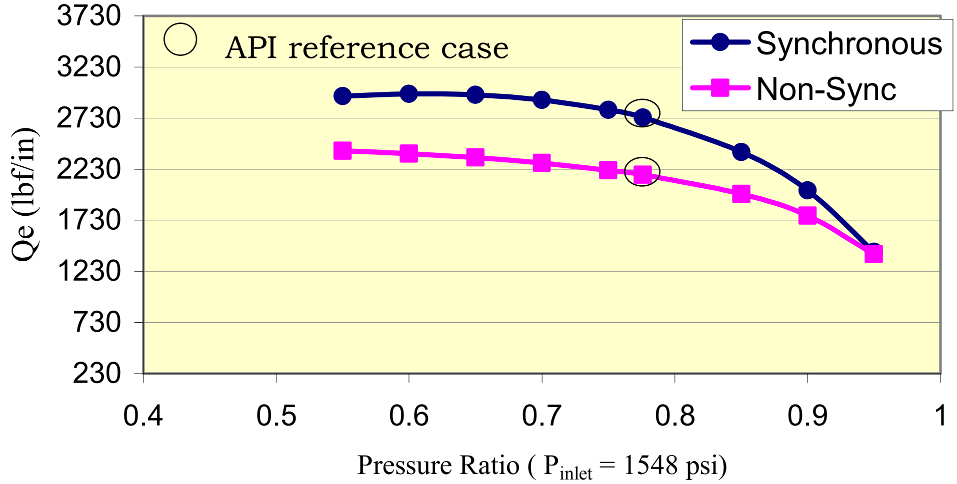


Figure 4-4 Influence of Pressure Ratio on Effective Cross-Coupling Stiffness

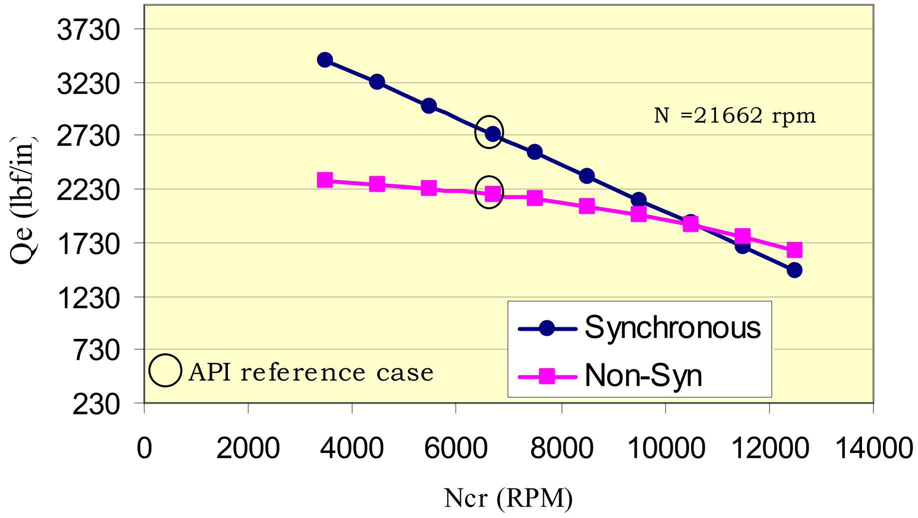


Figure 4-5 Influence of Rotor Natural Frequency by setting Rotor Speed Constant, on Effective Cross-Coupling Stiffness

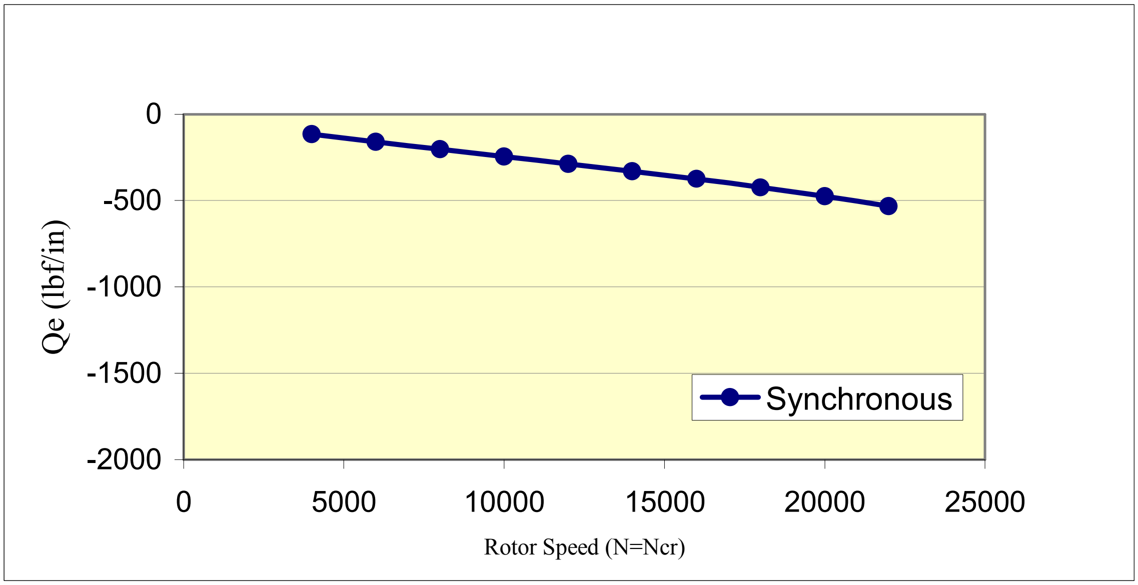


Figure 4-6 Influence of Rotor Natural Frequency by setting Ncr = N, on Effective Cross-Coupling Stiffness

Influence of gas properties such as temperature and compressibility shown in Figure 4-7 and 4-8 affect Qe in an adverse manner compared to operating conditions (rotor speed and swirl). An increase in temperature and gas compressibility improves the stability of the system by reducing the aerodynamic excitation. Whereas, effect of specific heat ratio, absolute velocity of gas and specific heat shown in Figure 4-9, 4-10 and 4-11 respectively, have negligible influence on Qe. Figure 4-12 show influence of mole weight on Qe. Mole weight is the only inimical gas property that on increase aggravates the excitation. Thus, using lighter gas in labyrinth eye seals is favorable.

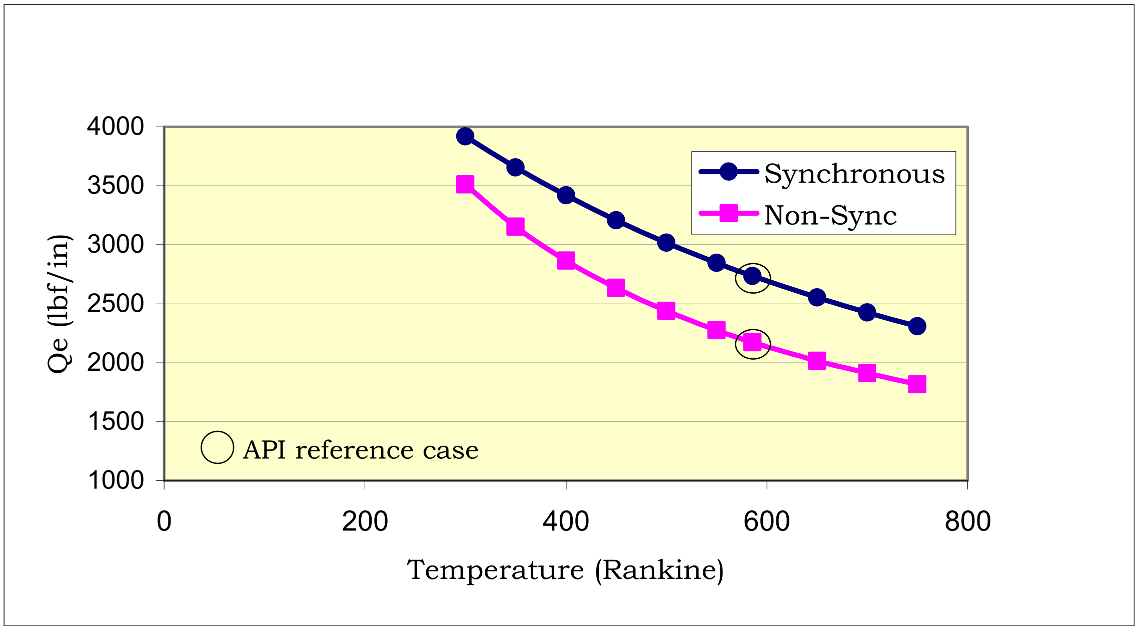


Figure 4-7 Influence of Temperature on Effective Cross-Coupling Stiffness

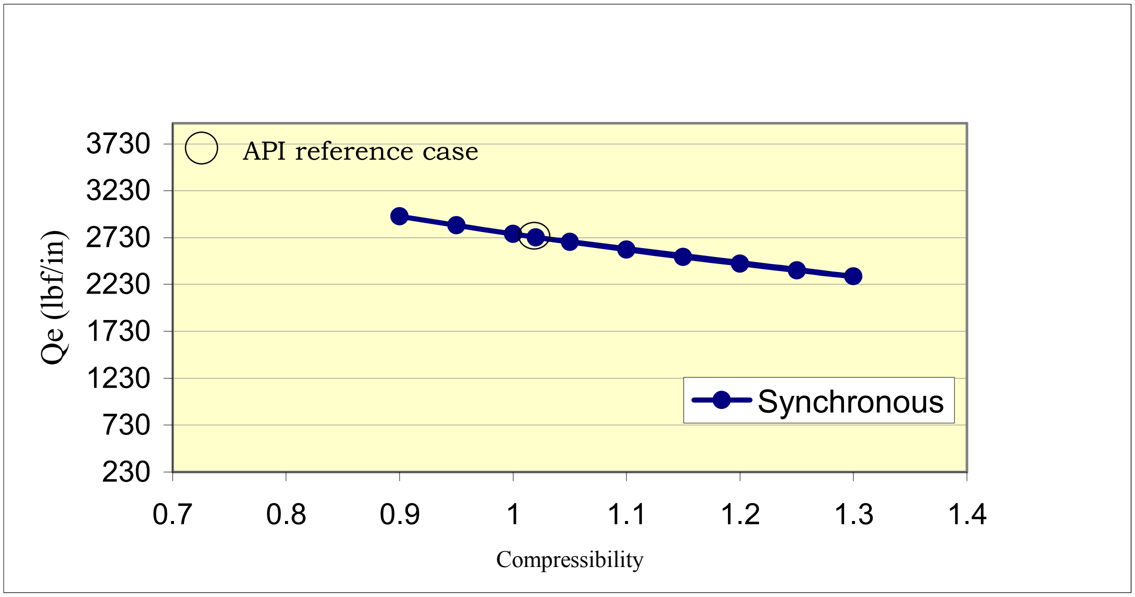


Figure 4-8 Influence of Gas Compressibility on Effective Cross-Coupling Stiffness

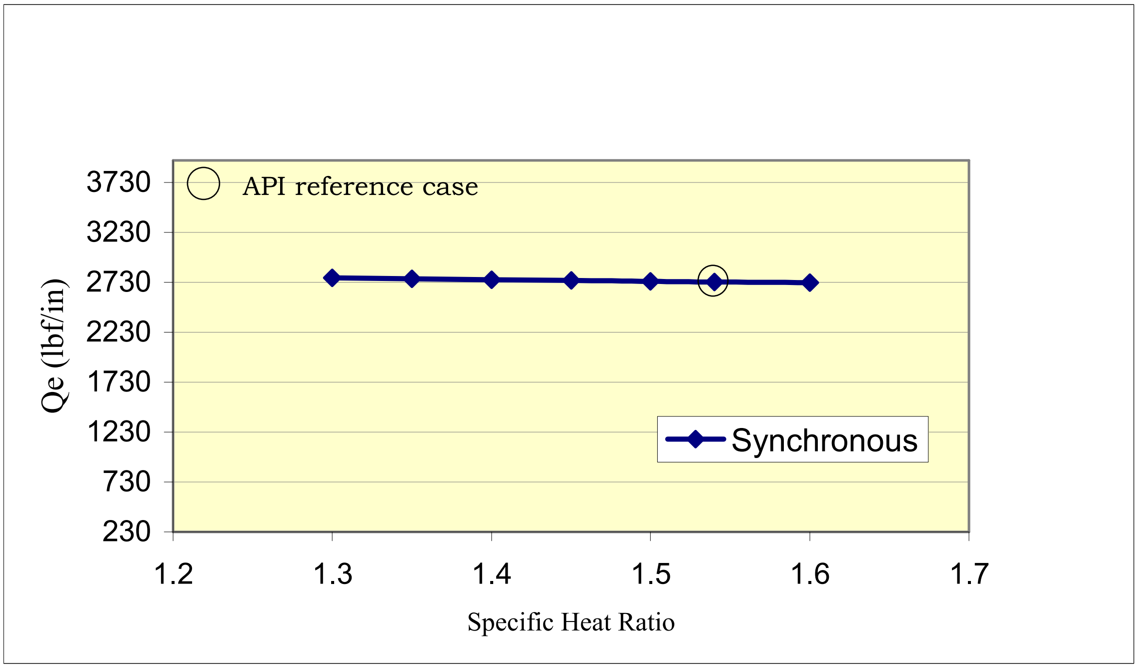


Figure 4-9 Influence of Specific Heat Ratio on Effective Cross-Coupling Stiffness

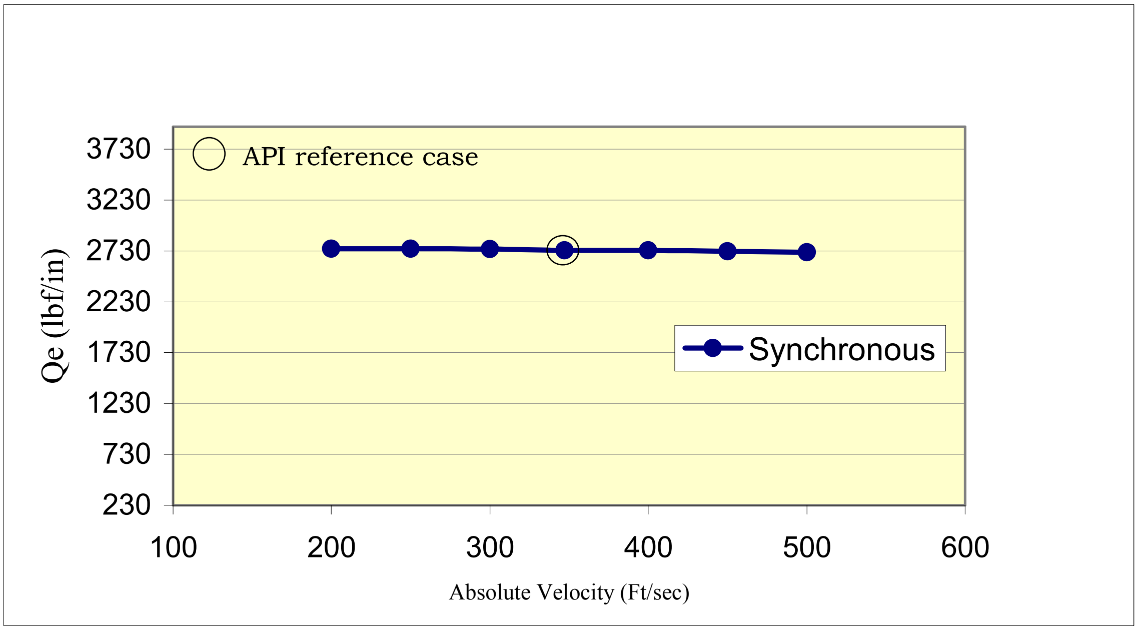


Figure 4-10 Influence of Absolute Velocity of Gas on Effective Cross-Coupling Stiffness

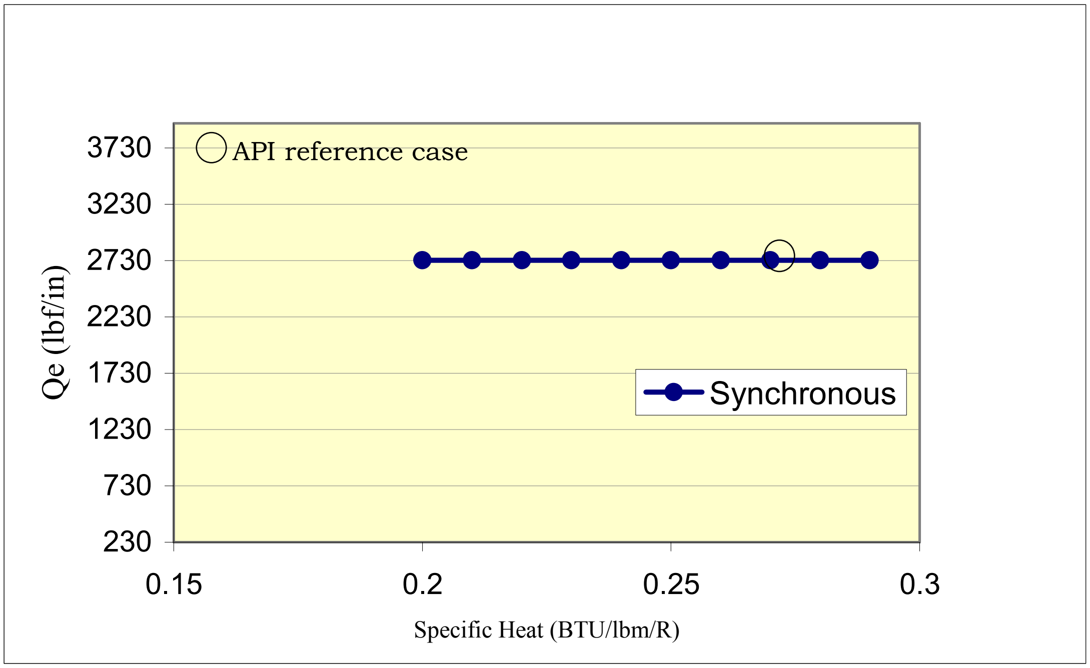


Figure 4-11 Influence of Specific Heat on Effective Cross-Coupling Stiffness

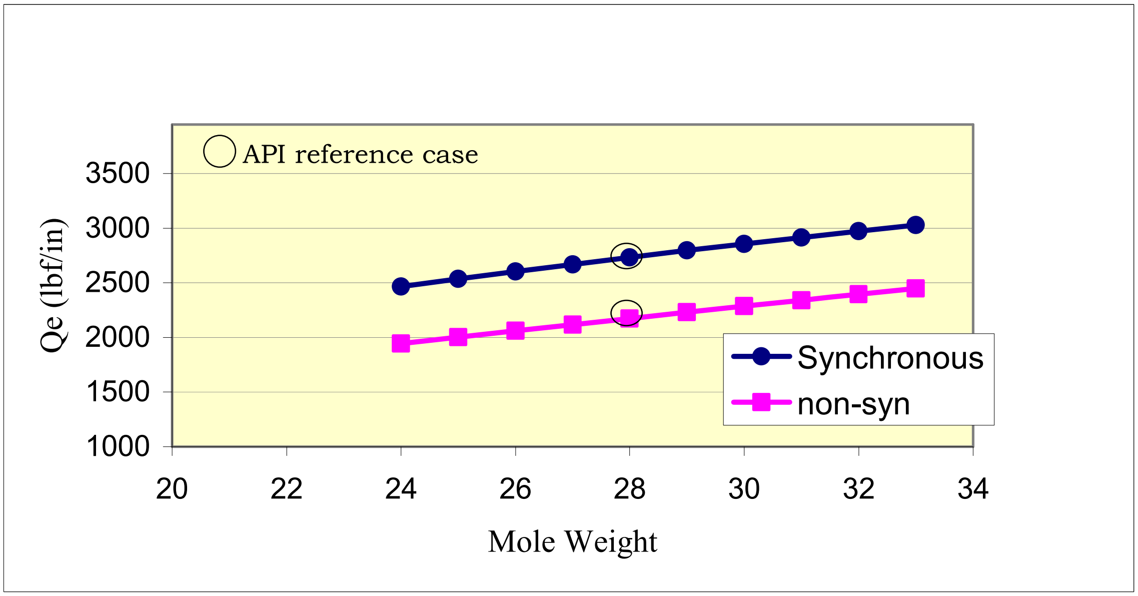


Figure 4-12 Influence of Mole Weight on Effective Cross-Coupling Stiffness

4.3 Influence of Various Parameters of Balance Piston Labyrinth Seal on Effective Cross-Coupling Stiffness

Effects of operating conditions and gas properties on effective cross-coupling stiffness (Qe_{BP}) are investigated here by using API's Balance Piston labyrinth seal model. All parameters in Table 4.1 are held constant except for the parameter under investigation, similar to labyrinth eye seal study.

Operating conditions have a major influence on effective cross-coupling stiffness for the balance piston labyrinth, as shown in Figure 4-13 and 4-14. For synchronous assumption, magnitude of excitation exponentially increases with rotor speed and directly increases with swirl ratio. Qe for the impeller # 1 labyrinth eye seal, at a constant speed of 21662 rpm, equals 2735 lbf/in; whereas, for the balance piston seal at the same speed , Qe_{BP} is 6x greater (reference case). This eccentric behavior of the balance piston labyrinth could be due to high inlet pressure and an increase in number of axial teeth compared to eye seal. However, for non-synchronous assumption, with increase in rotor speed or swirl ratio, Qe_{BP} increases only gradually.

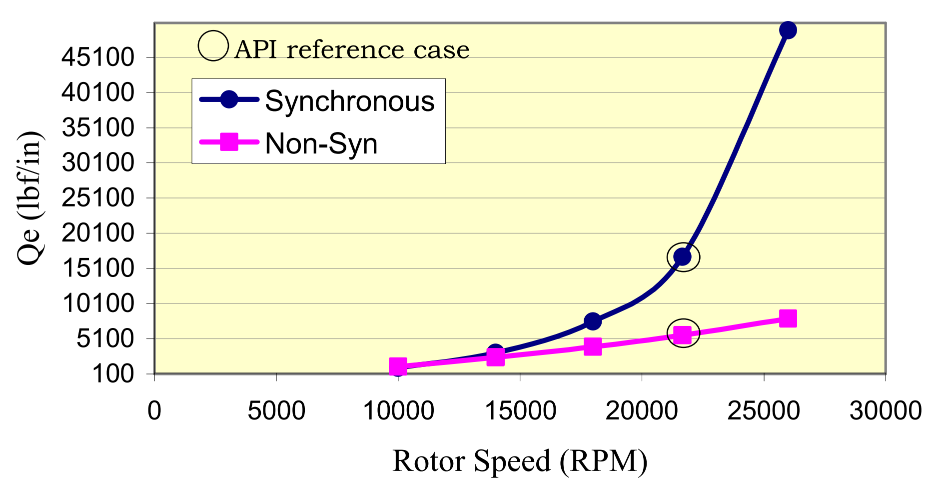


Figure 4-13 Influence of Rotor Speed on Effective Cross-Coupling Stiffness (Balance Piston Labyrinth Seal)

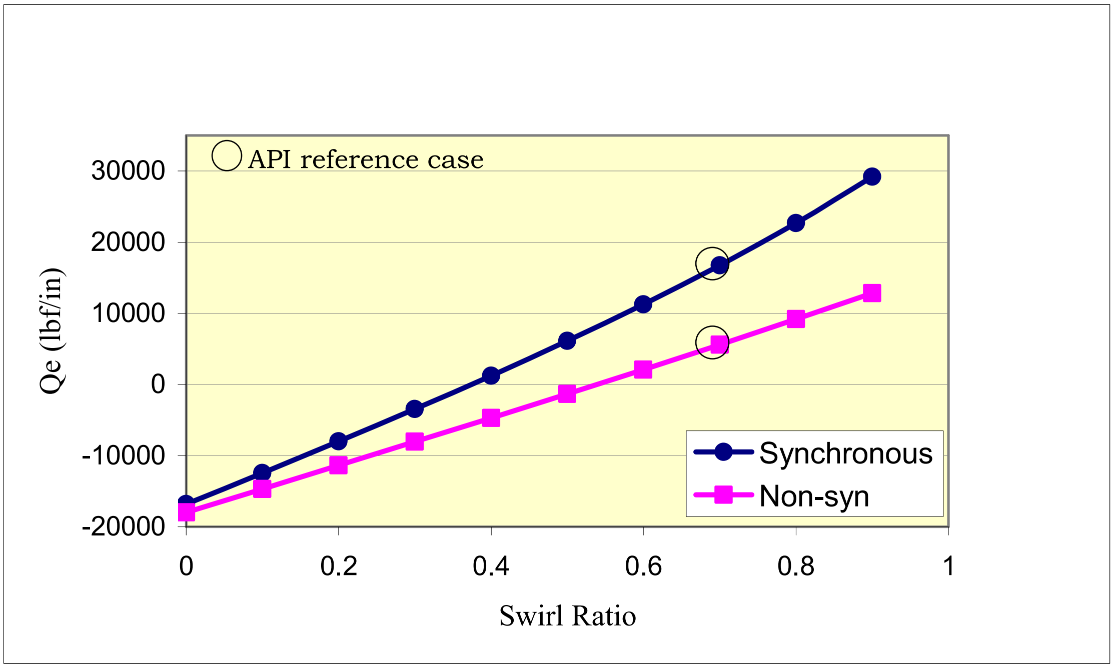


Figure 4-14 Influence of Inlet Gas Swirl Ratio on Effective Cross-Coupling Stiffness (Balance Piston Labyrinth Seal)

Effect of pressure ratio (Pr) variation, in Figure 4-15, for non-synchronous type of case, on Qe_{BP} has minimal influence. However, for synchronous type of case instead of Qe decreasing with increase in Pr, as in the case of Impeller # 1 labyrinth eye seal, Qe_{BP} radically increases. Figure 4-16 show results of variation of Ncr by setting rotor speed (N) constant at 21662 rpm. A similar trend to eye seal (Figure 4-5) is observed here, except Qe_{BP} for non-synchronous case remains constant and both curves cross each other at a higher Ncr. Likewise, Figure 4-17 show results of variation of Ncr and N by setting both equal. On comparing the results with eye seal (Figure 4-6), adverse influence on Qe_{BP} is observed.

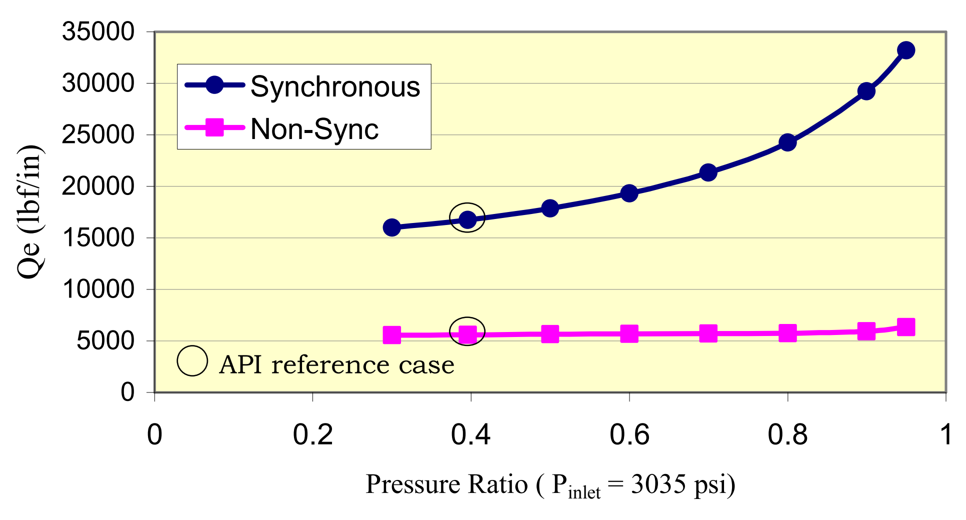


Figure 4-15 Influence of Pressure Ratio on Effective Cross-Coupling Stiffness (Balance Piston Labyrinth Seal)

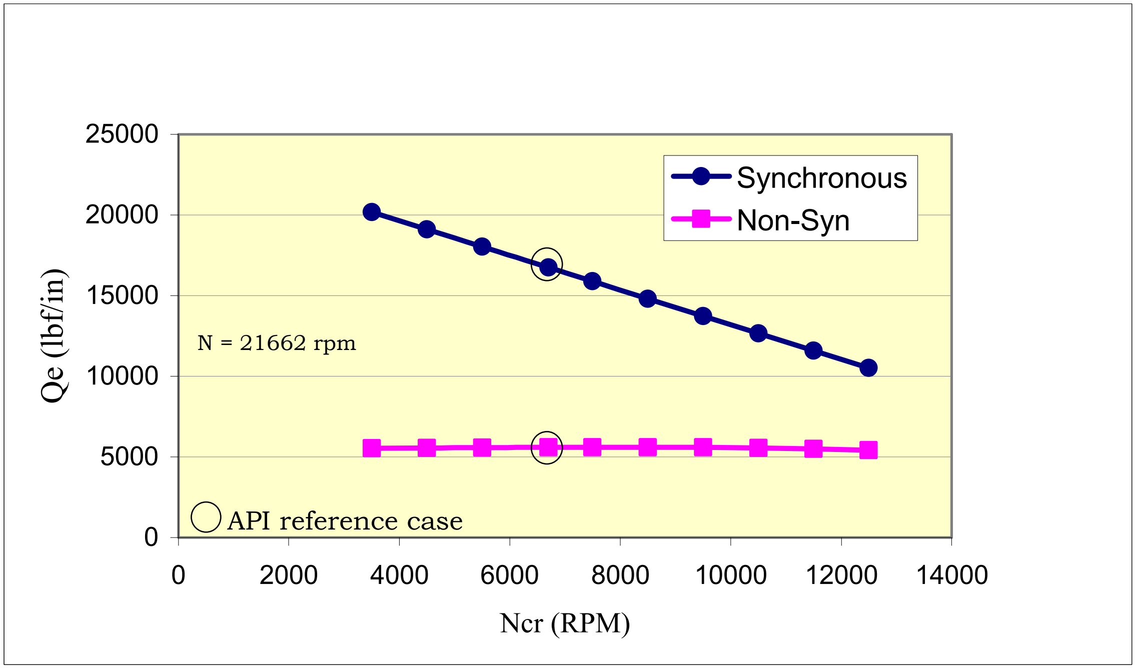


Figure 4-16 Influence of Ncr on Effective Cross-Coupling Stiffness by setting N constant (Balance Piston Labyrinth Seal)

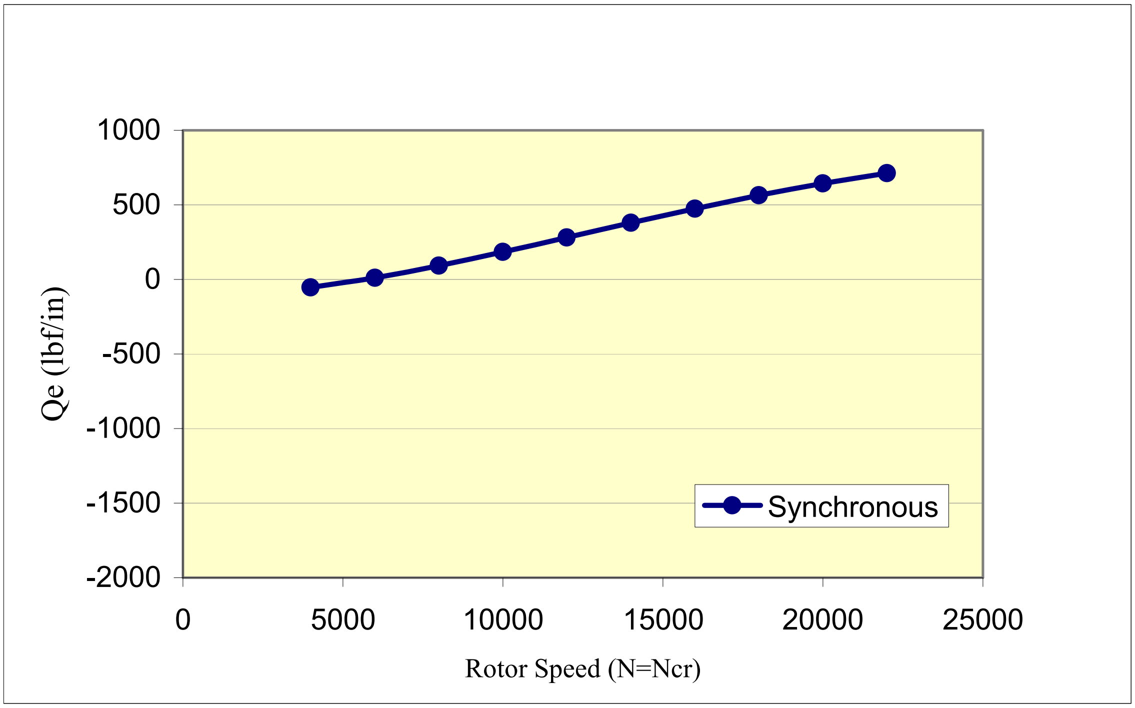


Figure 4-17 Influence of Ncr and N on Effective Cross-Coupling Stiffness by setting N = Ncr (Balance Piston Labyrinth Seal)

Figure 4-18 show influence of temperature on effective cross-coupling stiffness for the balance piston labyrinth seal (refer to Table 4-1 for seal parameters). For synchronous assumption, Qe_{BP} with temperature has an inverse exponential relationship. However, for the non-synchronous assumption, Qe_{BP} decreases gradually as temperatures increases. Figure 4-19 show influence of mole weight on Qe_{BP} for the balance piston labyrinth seal. For synchronous and non-synchronous assumption, Qe_{BP} increases with mole weight. However, for synchronous assumption, Qe_{BP} increases predominantly.

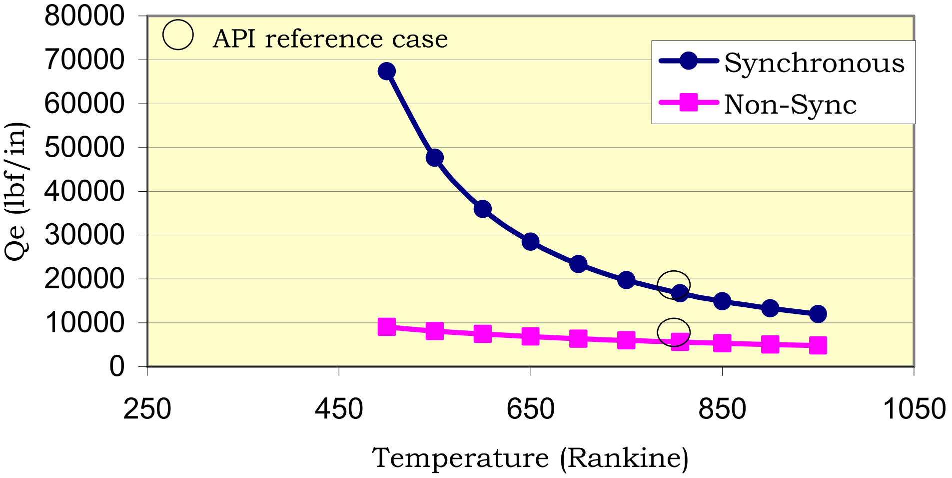


Figure 4-18 Influence of Temperature on Effective Cross-Coupling Stiffness

(Balance Piston Labyrinth Seal)

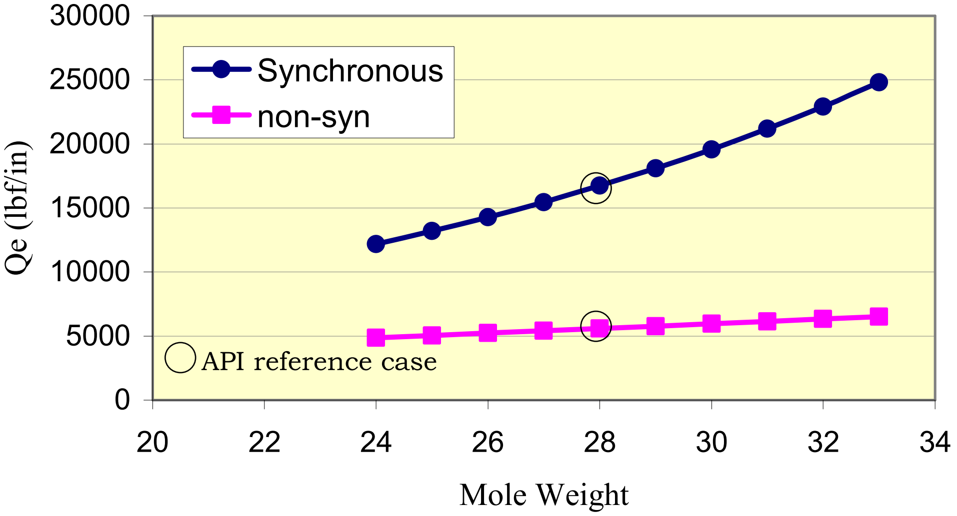


Figure 4-19 Influence of Mole Weight on Effective Cross-Coupling Stiffness

(Balance Piston Labyrinth Seal)

CHAPTER 5

Results and Conclusion

5.1 LabyXL Pre and Post-Processor Summary and Validation

A preprocessor and post-processor for Labyrinth seal analysis program using Microsoft Excel's visual basic application is developed herein. The LabyXL has two versions – SI and English. To demonstrate application of LabyXL, API stability survey labyrinth seals are modeled and a parametric study is performed. Capabilities of LabyXL are summarized below:

1. The program is capable of importing and generating a data file. It provides a table for Geometric Parameters and Speed Case Parameters for easy understanding and data input.
2. The program generates a leak path geometric diagram to better model the labyrinth seal.
3. Gas property section provides a viscosity and temperature calculator for converting centipose units to Lbm / (Ft * s) and Fahrenheit to Rankine respectively.
4. Labyrinth options section provides a field for input sheet name and path for easy location of data sheet generated.
5. Post-Processor macro imports results from output text files into tables for data analysis.
6. In addition, it generates several plots for better analysis.

To validate LabyXL pre and post-processor ability to generate accurate data file and import results from output file, LabyXL results are compared with DYNLAB results. DYLAB is an older version of LabyXL, which uses an obsolete FORTRAN based preprocessor with limited functions. Impeller # 1 eye labyrinth seal modeled in chapter 4 is used to perform the validation. Table 5-1 show results of LabyXL for dynamic coefficients, compared with results of DYNLAB output file. The comparison is in excellent agreement.

Table 5-1 Comparison of LabyXL and DYNLAB results for API Impeller # 1 eye seal (synchronous case)

Processor	Stiffness (lbf/in)				Damping (lbf-sec/in)				Qe (lbf/in)
	Kxx	Kxy	Kyx	Kyy	Cxx	Cxy	Cyx	Cyy	
LabyXL	-641.06	4193.5	-4193.5	-641.06	2.0793	0.107	-0.107	2.0793	**2734.6**
DYNLAB	-641.06	4193.5	-4193.5	-641.06	2.0793	0.107	-0.107	2.0793	**2734.59**

5.2 Parametric Study Conclusions and Recommendations

The following conclusions and recommendations can be made from the parametric study performed on API impeller # 1 eye seal and balance piston labyrinth seal:

- Rotor speed and swirl ratio have a major influence on Qe in both cases. Moreover, for balance piston labyrinth the effects are magnified.
- A small decrease in swirl ratio can significantly reduce the excitation for both cases. Thus, placing radial chambers or swirl brakes [16] before the axial chambers is recommended.

- It is apparent from comparing both cases that longer the labyrinth seals greater the excitation.

- At high inlet pressure (as in case of balance piston), high-pressure drop is desirable. Whereas, for low pressure at inlet (as in case of Imp#1 eye seal), low-pressure drop is favorable.

- Gas properties such as temperature and mole weight could significantly affect the effective cross-coupling stiffness for both cases. Thus, for reducing excitation higher temperature and lower mole weight is favorable.

5.3 Future Work and Conclusion

An Excel based pre and post-processor has been successfully developed to analyze and model gas labyrinth seals. An option to use either SI units or English units has also been made available. However, the following recommendations can be considered for further development:

- LabyXL provides the user with an option to run multiple cases (maximum 10) by varying operating conditions and gas properties. The program can be modified to include an option to run multiple cases by varying geometric parameters.

- A gas property lookup macro could be incorporated which would fill in all the gas properties once the gas name, temperature and pressure are specified.

- Presently, LabyXL has a default surface friction factor used for all types of material. An option to choose the labyrinth material can be provided in order to calculate accurate surface constants for improved LabyXL predictions.

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APPENDIX A

Example Input Data File
for 8 speed cases

Sample Input File

The sample input file is a text file generated by the Labyrinth Seal Analysis program. A sample of this data file is shown in Figure A-1.

```
Virginia Tech Rotor Lab CFD Evaluation  1.0/1.0
tip  swirl influence  0.2472  .085,  -0.3
 A0ZG1F1  tooth height = 0.14    1-12-07  rgk

CROTOR SPEED-RPM;NSPD;TYPE WHIRL,0=SYN,1=NON;SPD =110.97E+02   08
0
CRAD OPT;SERIES;TYP 1 STA./2 ROT/3 I-LOCK;STEP;I;IRS=08ST=11 IS=1 IB=3
CRADIAL OPT.;NUMBER OF TEETH; PLUS RANGE FOR
KXY;IRE=16NT=21NS=10NE=14
CTOOTH HEIGHT(IF KEY=1,INSERT LINE(S) 7G10.2)KEY
=0000000001B=+10.00E-04
100.00E-05100.00E-05100.00E-05100.00E-05100.00E-05100.00E-05100.00E-05
100.00E-05100.00E-05140.00E-03140.00E-03140.00E-03140.00E-03140.00E-03
100.00E-05100.00E-05100.00E-05100.00E-05100.00E-05100.00E-05100.00E-05
CTOOTH SPACING ( KEY=1,INSERT LINE(S) 7G10.2)KEY
=0000000001L=+17.00E-02
170.00E-03170.00E-03170.00E-03100.00E-03170.00E-03170.00E-03267.00E-03
170.00E-03900.00E-04150.00E-03150.00E-03150.00E-03150.00E-03150.00E-03
266.00E-03170.00E-03170.00E-03170.00E-03170.00E-03170.00E-03170.00E-03
CTOOTH CLEARANCE(KEY=1,INSERT LINE(S) 7G10.2)KEY
=0000000001C=266.00E-03
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266.00E-03160.00E-03115.00E-04115.00E-04115.00E-04115.00E-04115.00E-04
160.00E-03266.00E-03266.00E-03266.00E-03266.00E-03266.00E-03266.00E-03
CSHAFT RADIUS   (KEY=1,INSERT LINE(S) 7G10.2)KEY =0000000001RS919.00E-
02
919.00E-02840.60E-02759.40E-02681.00E-02652.60E-02600.00E-02567.00E-02
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CSURFACE CONSTANT(DEFAULT=0.079);*F5.1;KEY   YNR =790.00E-
04001.0INR=1
790.00E-04850.00E-04850.00E-04850.00E-04850.00E-04850.00E-04850.00E-04
790.00E-04790.00E-04790.00E-04790.00E-04790.00E-04790.00E-04790.00E-04
790.00E-04790.00E-04790.00E-04790.00E-04790.00E-04790.00E-04790.00E-04
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IMR=1
-25.00E-02-30.00E-02-30.00E-02-30.00E-02-30.00E-02-30.00E-02-30.00E-02
-25.00E-02-25.00E-02-25.00E-02-25.00E-02-25.00E-02-25.00E-02-25.00E-02
-25.00E-02-25.00E-02-25.00E-02-25.00E-02-25.00E-02-25.00E-02-25.00E-02
```

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04001.0INS=1
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-25.00E-02-25.00E-02-25.00E-02-25.00E-02-25.00E-02-25.00E-02-25.00E-02
CGAS SWIRL AT INLET(PERCENT SPD); NCR-RPM; SWIRL =247.20E-
03NC600.00E+01
CGAS PRESSURE AT INLET; GAS VELOCITY (FT/SEC) PS =500.00E+00
V500.00E-01
CGAS PRESSURE AT EXIT ;                   PE =250.00E+00
CGAS MOLEWEIGHT                          MW =289.70E-01
CGAS TEMPERATURE                         TABS =660.00E+00
CGAS COMPRESSIBILITY                      Z =980.00E-03
CGAS RATIO OF SPECIFIC HEATS; AND CP       GAMMA =138.00E-02CP245.00E-
03
CGAS VISCOSITY MU * G (LBM/FT/SEC)         MUXG =122.40E-07
CMASS FLOW (LB/SEC)(IF P(I)>0); FCFAC,F5.1: MDOT =
CCHAMBER PRESSURES 7G10.2 PER LINE(IF KEY=1) KEY =        0
CCHAMBER TEMP. 7G10.2 (IF KEY=1;-2=VARA;0=TABS)  =       -2
CMAX SOLUTION ITERATIONS,VC,MDOT(DEFAULT=50)ITER =50
CTOLERANCE DFAULT = 1E-4*RS*OMEGA         TOLERV =100.00E-05
CPRESSURE TOLERANCE (DEFAULT = 0.01)      TOLERP =100.00E-02
CMASS FLOW TOLERANCE (DEFAULT = 0.0001)   TOLERP =
CPRINTMATRIX SETUP ( = 1 TO PRINT ALL)    KEYDMP =        0
C(IF NSPD>1INPUT NSPD LINES AS FOLLOWS<6G10.2,2F5.1>0 DEFAULTS
INIT. V.
C   SPEED    SWIRL      PS      PE     TABS      Z  GAMMA  MW
110.97E+02247.20E-03500.00E+00250.00E+00660.00E+00980.00E-0301.3828.97
110.97E+02500.00E-03500.00E+00250.00E+00660.00E+00980.00E-0301.3828.97
110.97E+02600.00E-03500.00E+00250.00E+00660.00E+00980.00E-0301.3828.97
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110.97E+02140.00E-02500.00E+00250.00E+00660.00E+00980.00E-0301.3828.97
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Figure A-1 Sample Data File

APPENDIX B

Labyrinth Types and Nomenclature for LabyXL

Labyrinth Types and Nomenclature

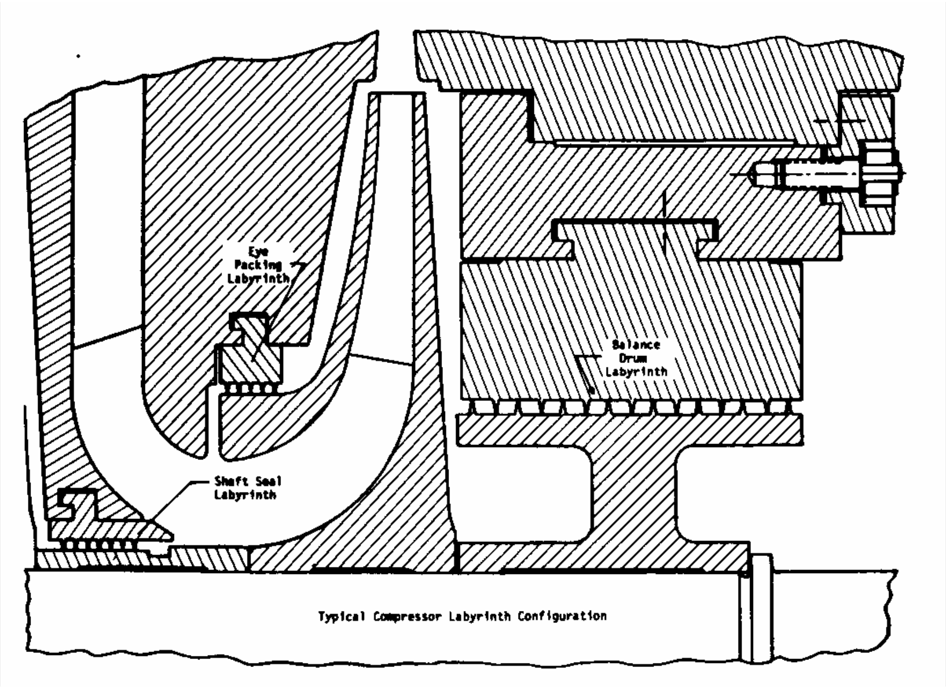


Figure B-1a Typical Compressor Labyrinth Seal Configuration

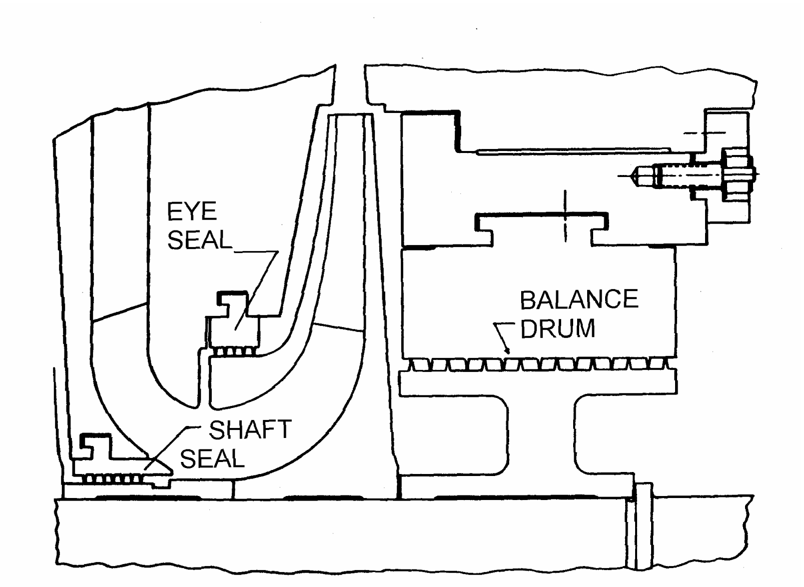


Figure B-1b Typical Compressor Labyrinth Seal Configuration

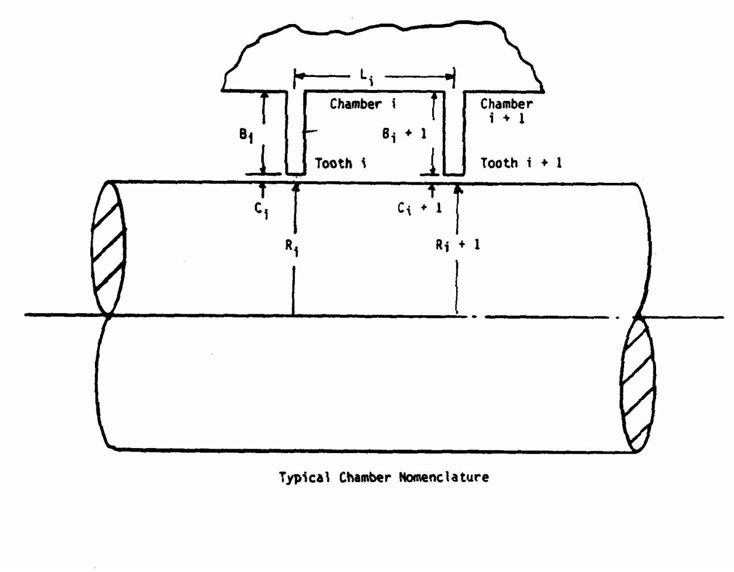


Figure B-2 Typical Chamber Nomenclature

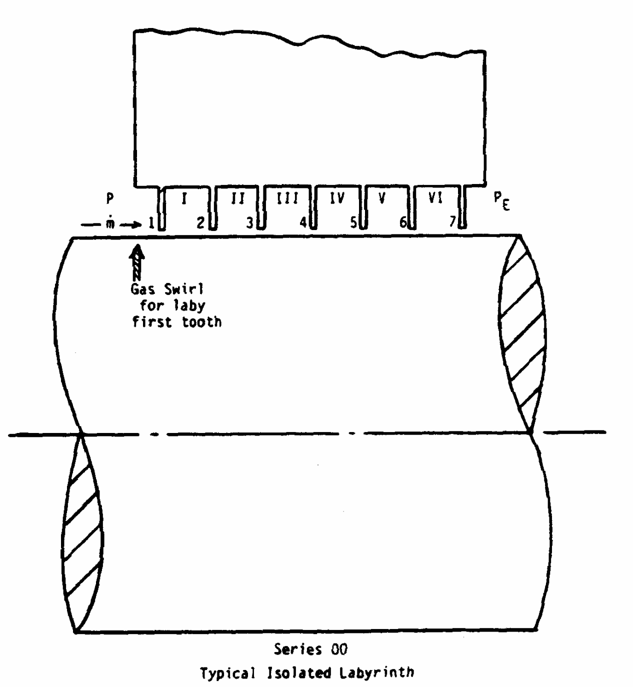
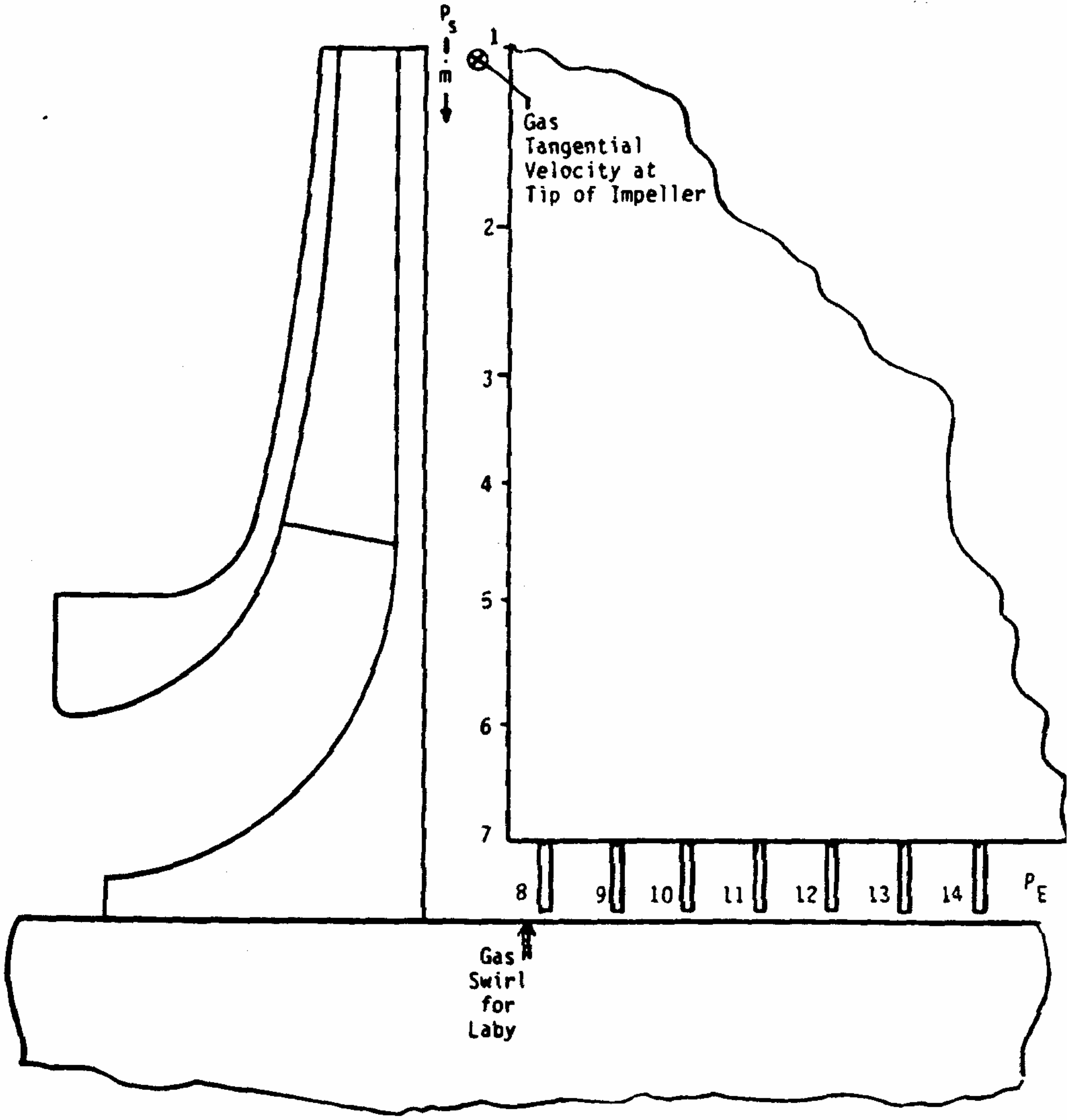
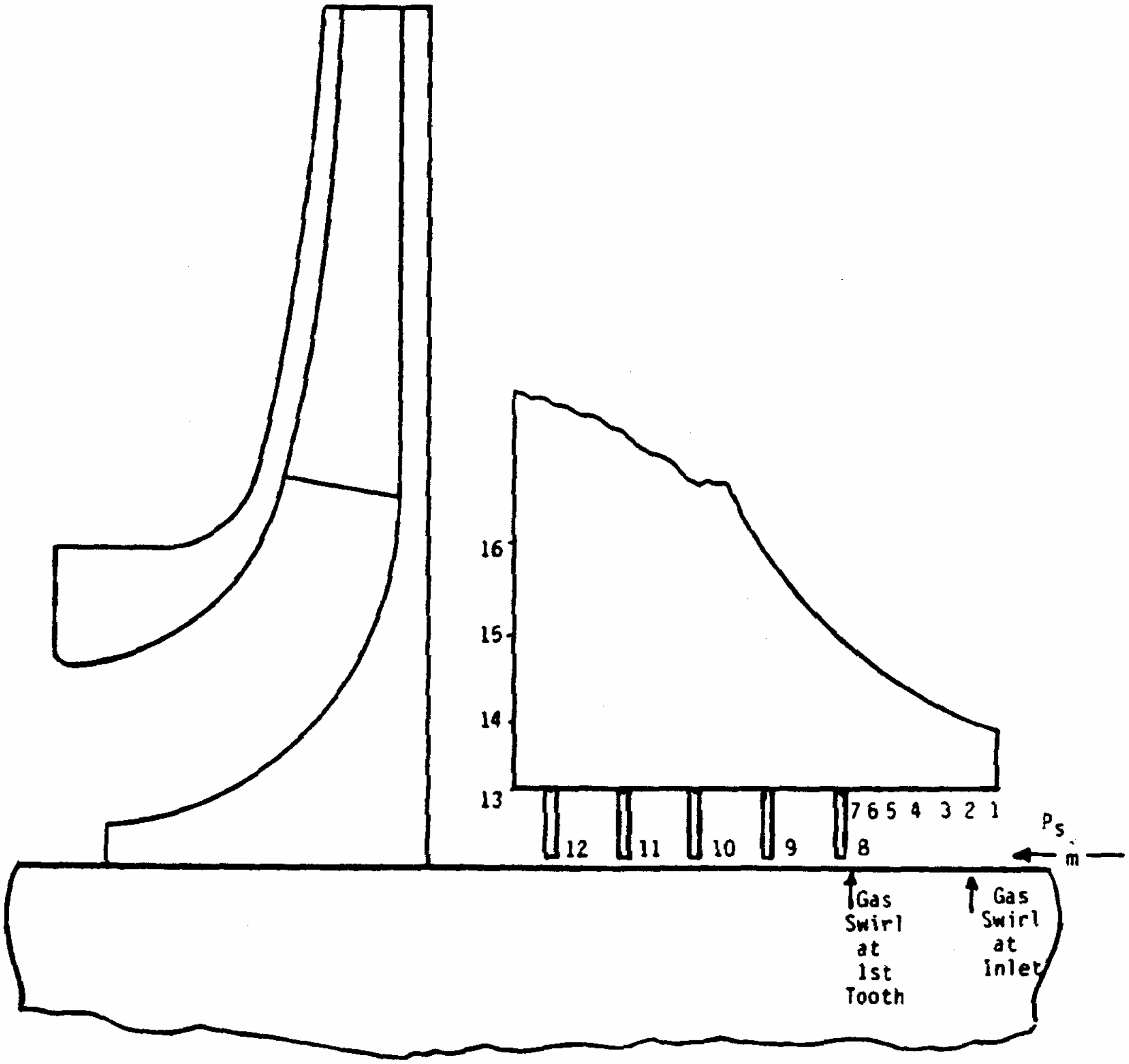


Figure B-3 Labyrinth Series – All Axial Chambers



Series 10
Typical System for Balance Drum Configuration

Figure B-4 Labyrinth Series – Radial before and after the Laby



Series 20
Typical System for Shaft Seal Labyrinth

Figure B-5 Labyrinth Series – Radial chamber after the Laby

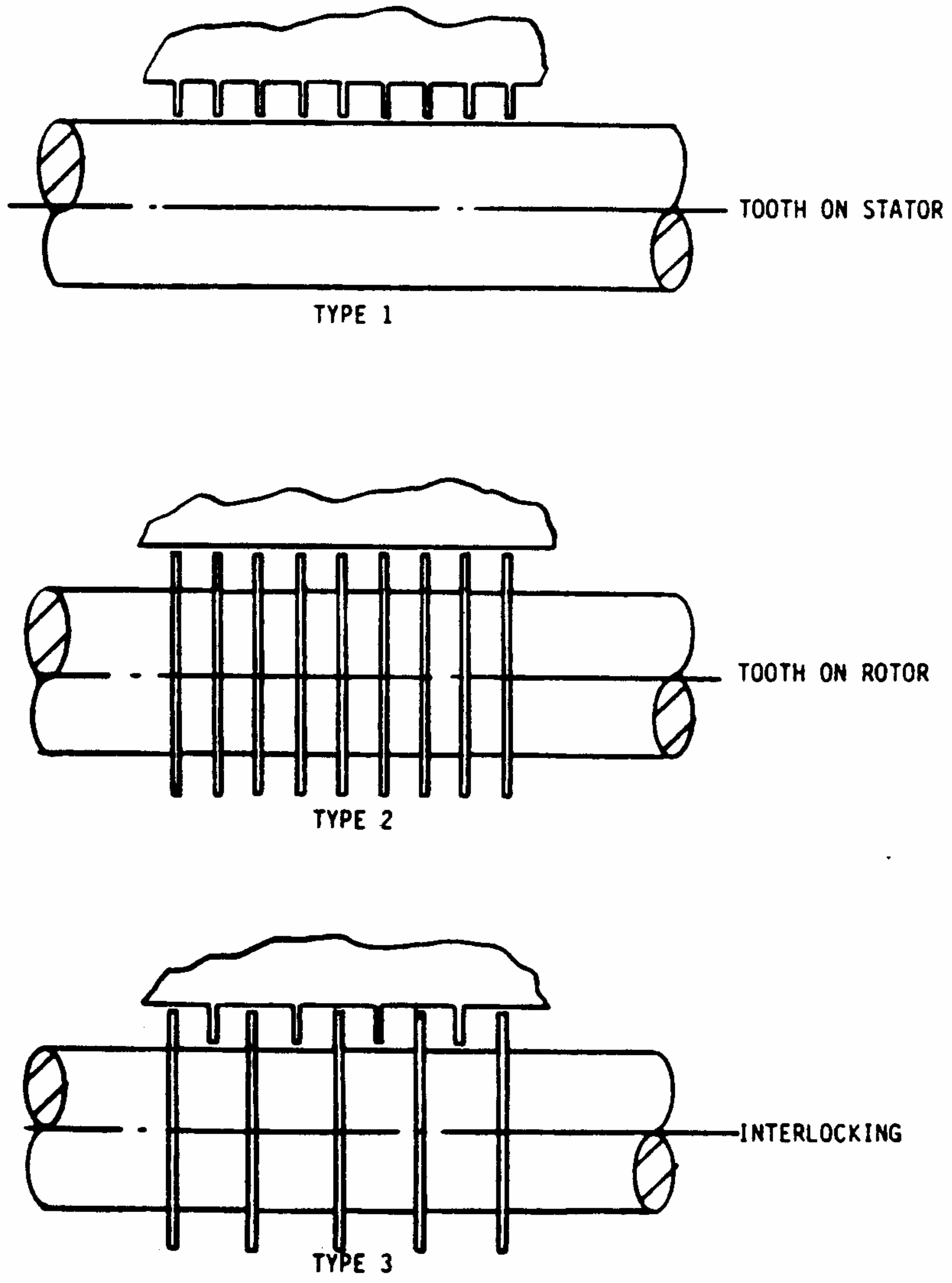
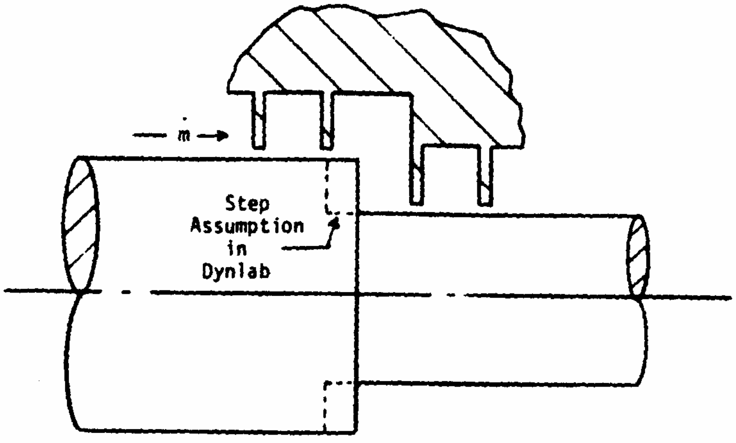
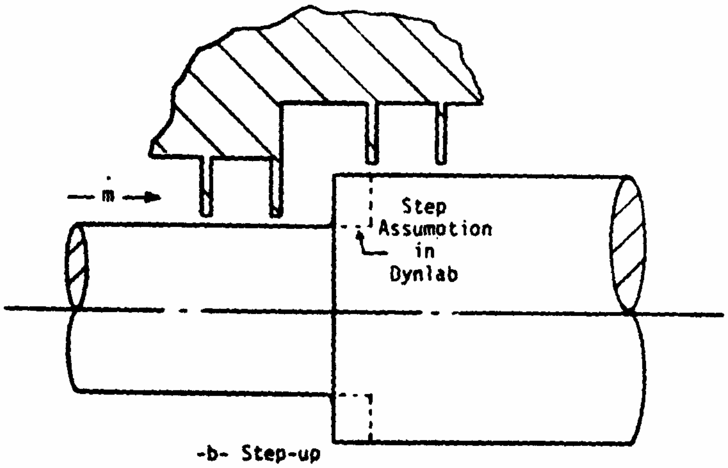


Figure B-6 Labyrinth Seal Types



-a- Step-down



-b- Step-up

Chamber Configuration for Stepped Shaft Labyrinth

Figure B-7 Typical Stepped Shafting Assumption

APPENDIX C

Comparison of LabyXL results with API survey results

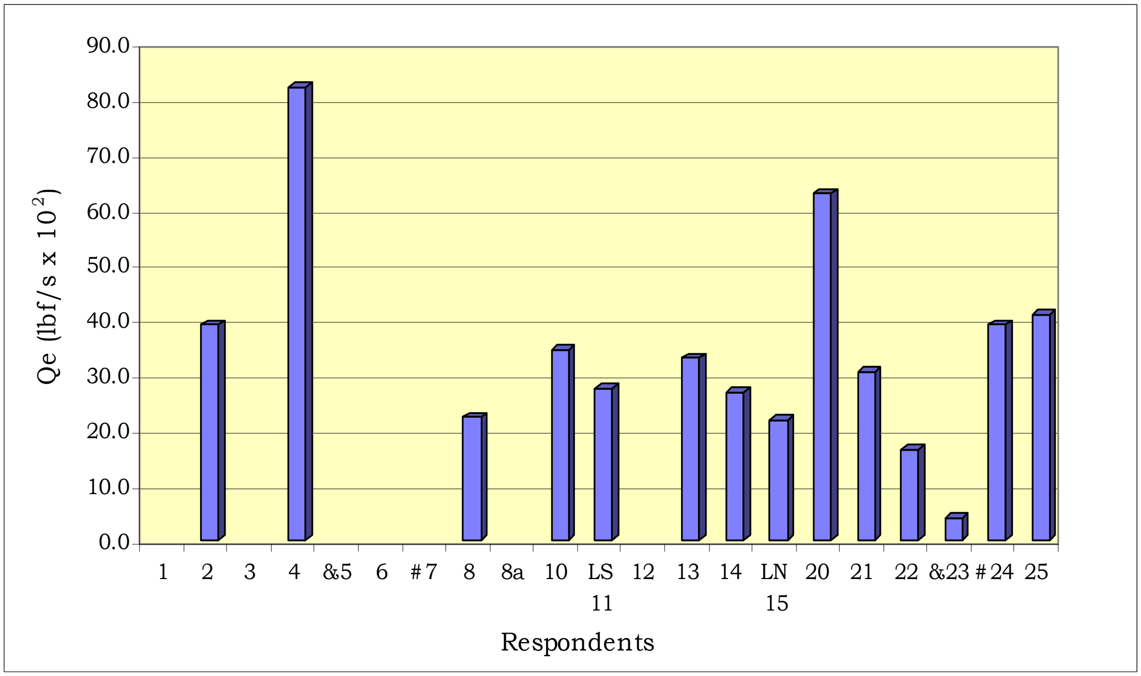


Figure C-1 Survey Results for Impeller # 1 compared with Synchronous (LS 11) and Non-synchronous (LN 15) LabyXL results.

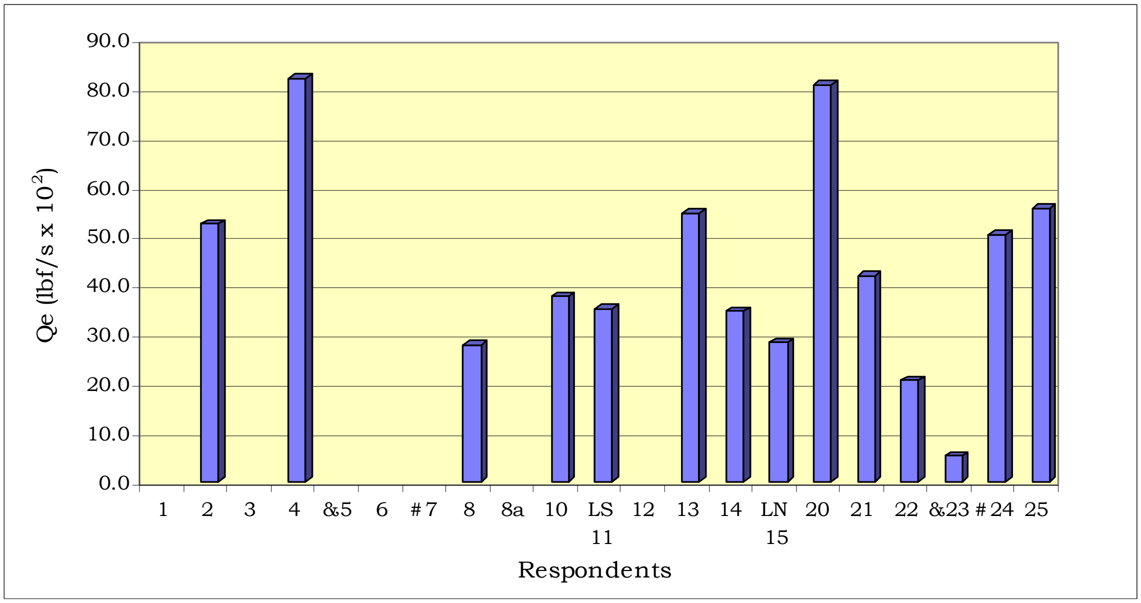


Figure C-2 Survey Results for Impeller # 5 compared with Synchronous (LS 11) and Non-synchronous (LN 15) LabyXL results.

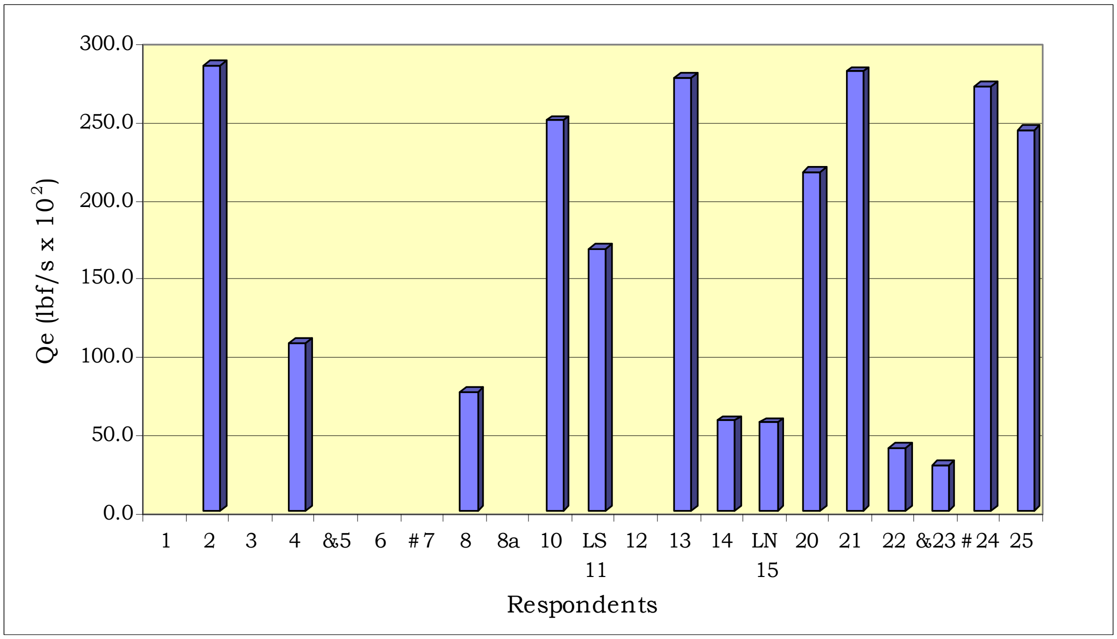


Figure C-3 Survey Results for Balance Piston labyrinth seal compared with Synchronous (LS 11) and Non-synchronous (LN 15) LabyXL results.

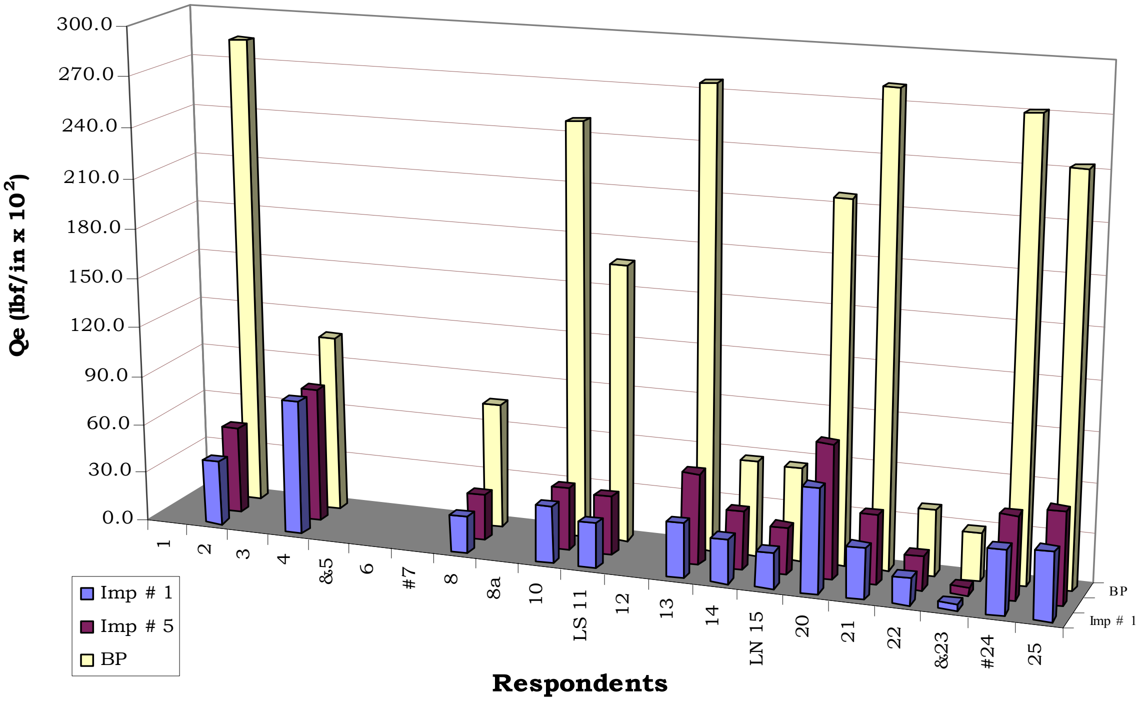


Figure C-4 LabyXL results Synchronous (LS) and Non-synchronous (LN) compared with API Survey Results for all three Labyrinths.