Chapter 12
Vibrational Study of Labyrinth Seals for Turbomachines

S. M. Sanjay kumar and C. Suresh

Abstract Turbomachinery is one of the most complex machinery that we have today. They have a variety of applications ranging from aircraft engines to huge industrial machines like power generators and marine propulsion. In this study, dynamic stability aspects are evaluated based on Campbell's criteria. Campbell introduced the concept of traveling waves in his investigations on turbine disk failures. The same concepts are extended to the dynamic stability of Labyrinth seals, which have cylindrical shell-type vibrations. Evaluation of Campbell's criteria involves three main areas—evaluation of frequency versus the nodal diameter (f/N), evaluation of intersection of each frequency line with the per revolution line and evaluation of interaction points for each frequency line with respect to other stationary or rotating component. All these criteria were studied, and it was felt necessary that the process of evaluating by plotting the above graphs needs to be automated to save post-processing time and also to standardize the procedure. The user has to extract the frequencies from a standard FEA package like ANSYS and input them in the marked cells in the Excel-based tool. Standard color-coding like yellow for input fields, blue color for operating speeds, and red color for design margin is used in the tool. Also, a set of clear instructions is provided in one of the worksheets.

Keywords Cylindrical shell · Campbell's criteria · Labyrinth seals · Frequency · Dynamic stability

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12.1 Introduction

Turbomachinery is one of the most complex machinery that we have today. They have a variety of applications ranging from aircraft engines to huge industrial machines like power generators and marine propulsion. These turbomachines have a large number of rotating components, which are supported by bearings. One of the most important features in the design and manufacture of a jet engine is the elimination of the possibility of vibration occurring at the various natural frequencies of its disk wheels, buckets and various seals.

A Labyrinth seal is a flow restrictor, and in gas turbines, it is used between a rotating and a stationary part or between two independently rotating parts to minimize the leakage flow of air or hot gas. Their design requirements vary extensively depending upon where they are used in the engine. The objective of the designer is to provide a geometry, which presents maximum resistance to flow and maintains the minimum clearance throughout the life of the gas turbine.

The Labyrinth seal can be conceptually shown in Fig. 12.1. It consists of a stationary and a rotating component or in some cases both the components are rotating. The operating clearances are typically around approximately 0.25 mm. Some of the important design parameters are mechanical, thermal and acoustic stability.

A number of papers were studied to understand what has been done so far in the area of axisymmetric vibrations of disks and cylindrical shells. A brief summary of a few important ones is discussed.

Campbell [1] has investigated the reasons for turbine disk wheel failures. He introduces the concept of traveling waves and stationary waves. The definition of Campbell criteria for the design of turbine wheels for axial vibration, which in general can be applied for vibrations in axisymmetric structures evolved from this pioneering work. The concept of standing waves, which is one of the major reasons for turbine disk failures, is discussed in this paper.
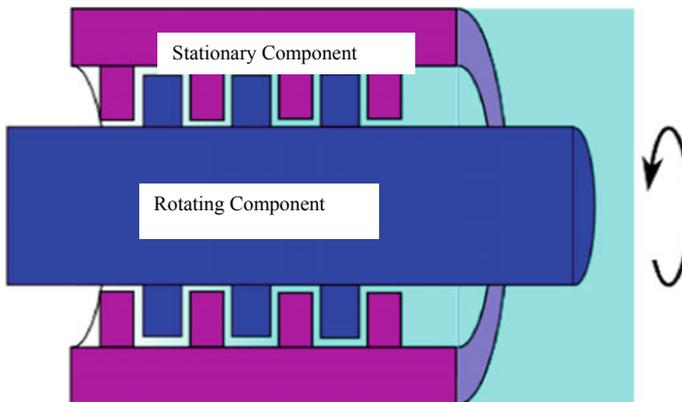
Fig. 12.1 The concept of a Labyrinth seal
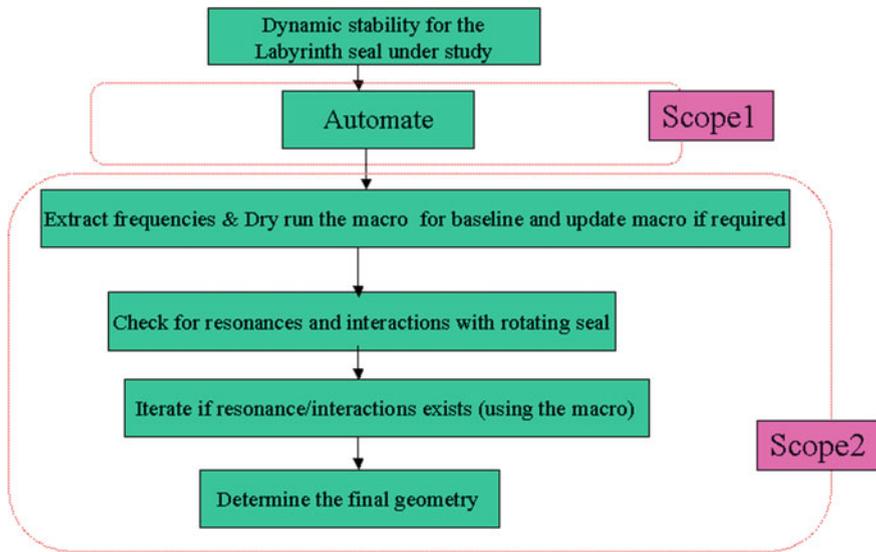
Fig. 12.2 Scope of the project

Heckman and Campbell [2] built the concepts described earlier for tangential vibrations. The condition for exciting a vibration in a rotating member is explained here. It is interesting to note in this work that at critical speeds, the tangential vibrations repeat the same path for each revolution. Any part of it describes a circumferential wave, which is stationary in space, although this is a longitudinal wave while the axial vibration consists of transverse waves. Macke [3] investigated on short compressor casing segments. He explained the motion of a rotating cylindrical shell and the differences in vibrations of disks and cylindrical shells.

Mehdigholi [4] investigated the harmonic excitation of a rotating disk. In both of these vibration interactions, the critical speeds and conditions should be identified and examined in order to take them into consideration in practice. Singh et al. [5] evaluated interferences, and the safe diagram compares not only the frequencies of exciting harmonics with the natural frequencies of blades but also the shape of these harmonics with the normal mode shapes of a completely bladed disk including packet blading.

After studying the design requirements of Labyrinth seals and the importance of dynamic stability using Campbell's criteria, the scope of the project is defined as shown in Fig. 12.2. The scope of the project can be divided into two broad categories:

Scope 1   To automate the process of evaluating Campbell's criteria with a suitable user-friendly tool.

Scope 2   The tool developed in scope 1 needs to be tested with several dry runs, and the program needs to be corrected if required. Then the tool needs to be validated with a suitable case study.

12.2 Tool Development

Labyrinth seal design parameters consist of thermal stability, dynamic stability, acoustic coupling, leakage, stress and wear characteristics. Dynamic stability involves evaluation of Campbell's criteria. As shown in Fig. 12.3, evaluation of Campbell's criteria involves three main areas—evaluation of frequency versus nodal diameter (f/N), evaluation of intersection of each frequency line with the per revolution line and evaluation of interaction points for each frequency line with respect to other stationary or rotating component. The manual process of evaluating Campbell's criteria currently used was a cumbersome and time consuming. It involved calculations that could very well be handled by the programed computer-based tool. Figure 12.3 shows the broad level scope of automation in the evaluation of Campbell's criteria.

12.2.1 Objectives of the Tool

The objectives of the tool to evaluate Campbell's criteria for Labyrinth seals are:

1. Plot frequency versus nodal diameter (f/N) curve and check for the trend with respect to the engine baseline speed and 120% margin line.
2. Plot a combined Campbell plot to check for the trend of the resonances within the operating range with respect to the stationary observer.
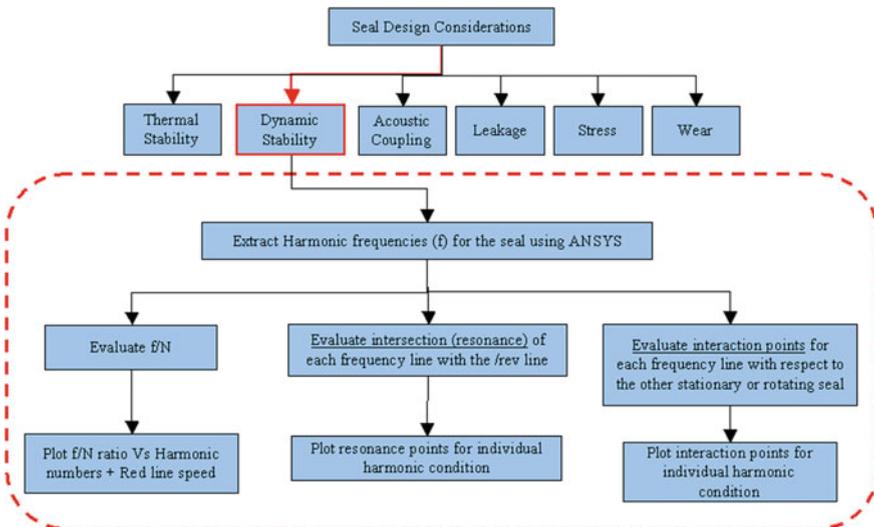
Fig. 12.3 Automation scope for evaluation of Campbell's criteria

3. Evaluate the rpm at which the resonance occurs for individual harmonics and report if within the operating range (Include provision for analyzing stators and rotors with respect to the stationary observer). Report major/minor resonances if any.
4. Plot interactions for stator–rotor conditions and evaluate rpm at which interaction occurs. Report interactions if any within the operating range.
5. The tool must have provision for both disk-type and cylindrical shell-type components.
6. Allow provision for further inclusion of rotor–rotor interaction evaluations.
7. The tool must be user friendly.

12.2.2 Selection of a Host Application

Any application that supports the use of a programing language for applications is called a host application. Microsoft Excel is selected as the host application. Apart from the obvious advantage of being easily available on any PC with windows platform, the other advantages that Excel offers are:

1. Macro generation process is quick.
2. Calculations can be handled using multiple worksheets with one of the worksheets dedicated for user interface and inputs.
3. All the required plots can be generated at the click of a button and also can be stored in a separate directory.
4. Calculations like finding the intersection of per revolution line and the frequency line based on the slope at intersecting points can be easily handled.

12.3 Modal Analysis of Forward Stationary Seal

A section of the forward stationary seal is as shown in Fig. 12.5. The component is axisymmetric except for the 60 oval-shaped holes as shown in Fig. 12.4. A 2D axisymmetric section is shown in Fig. 12.5. The use of an axisymmetric model greatly reduces the modeling and analysis time compared to that of an equivalent three-dimensional model. The region, which has holes, is modeled with orthotropic properties. The analysis is carried out in ANSYS. The objectives of the analysis are to obtain forward stationary seal frequencies and check for the resonance with existing rotating seal frequencies at the rub strip location.

Modify the geometry (forward stationary seal only) if required to eliminate resonance/interaction.

The following assumptions are followed for the analysis as mentioned below:

1. A 2D axisymmetric geometry of the forward stationary seal is used.
2. Appropriate constraining as shown in Fig. 12.5 simulates the bolting of forward stationary seal to Bearing Housing.

Fig. 12.4 Section of UG
model

60 oval Holes
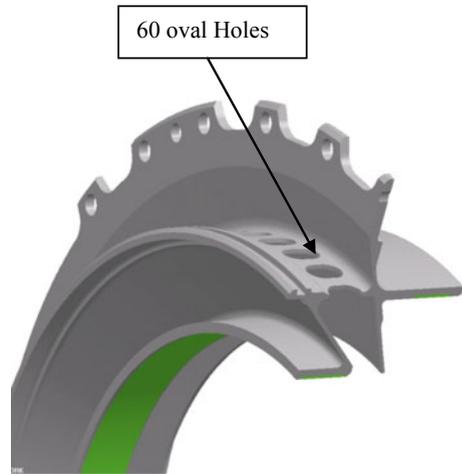
Fig. 12.5 2D cross section

FWD

AFT

Rub Strip
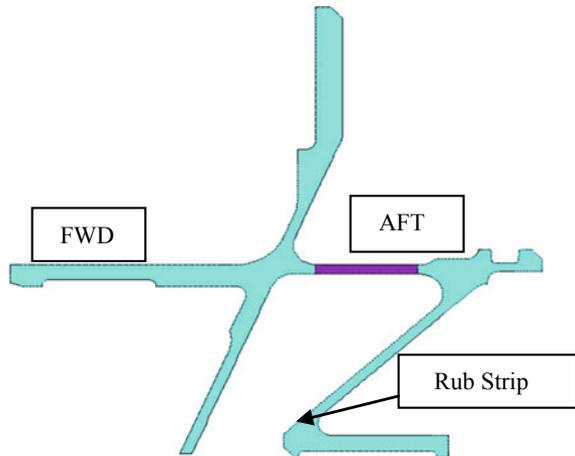
3. Reference temperature of 500 F is used in the analysis.
4. Orthotropic material properties are used for the vent holes in the 2D axisymmetric model.
5. High pressure turbine (HPT) shaft speed is 12,800 rpm and 120% HPT speed 15,360 rpm. (120% maximum exciting frequency is 256 Hz).
6. 2D axisymmetric plane 25 element is used.

The material properties are as listed in Table 12.1.

Table 12.1 Material properties

		Temperature = 260 °C	
Property	Units	Isotropic (material 1)	Vent hole—material 2 (21% material available)
EX	MPa	1.9389E+05	4.07E+04
EY	MPa	1.9389E+05	4.07E+04
EZ	MPa	1.9389E+05	6.89E+00
NUXY		0.3175	0.3175
NUYZ		0.3175	1.00E−03
NUXZ		0.3175	0.3175
DENS	kg/m^3	8248.612	1743.834

12.3.1   CASE 1: Oval-Shaped Holes Changed to Round Holes

In case 1, the oval-shaped holes are changed to an equal number of round holes in order to shift the frequencies out of the operating envelope which failed to qualify the Campbell criteria and cannot be used in the final design of Labyrinth seal (Fig. 12.6).

Figures 12.7 and 12.8 show the frequency versus nodal diameter (f/N) ratio Campbell diagram for forward stationary seal and forward rotating seal, respectively, which indicates that there is no resonance occurring since the f/N ratio curve lies beyond the operating speed and the red line speed.

Figures 12.9 and 12.10 show the combined Campbell diagram for forward stationary seal and forward rotating seal, respectively, which indicates that there is no resonance occurring since the line joining the intersection of per revolution line and the harmonic frequency lines indicated by the red line lies beyond the operating speed and the red line speed.

Fig. 12.6 Modifications to baseline model (Case 1)

60 round holes with dia 0.5" and centered on the web
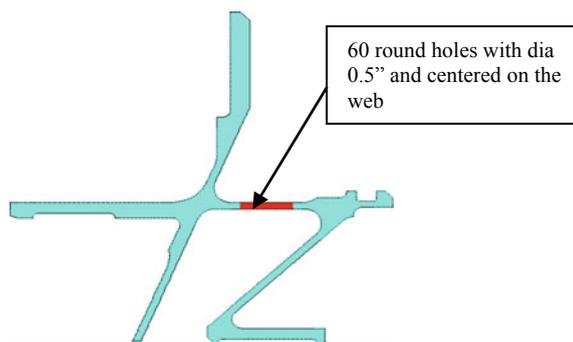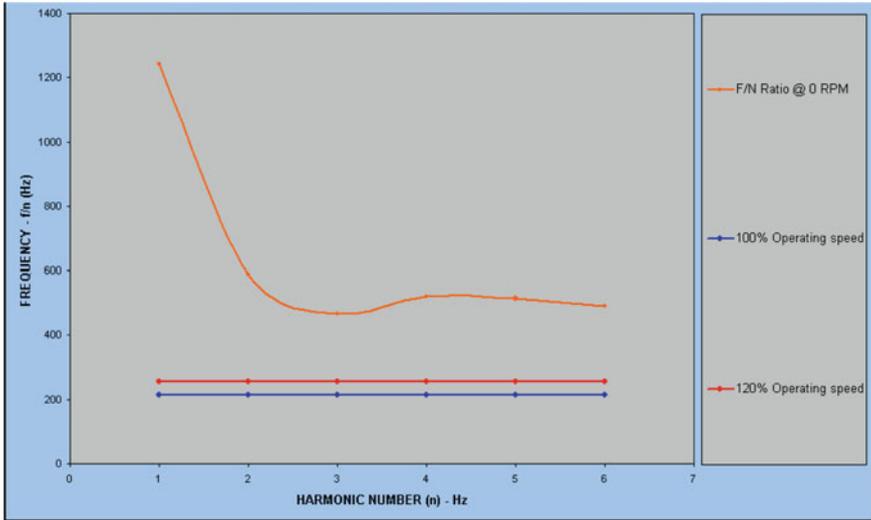
Fig. 12.7 Campbell diagram for forward stationary seal
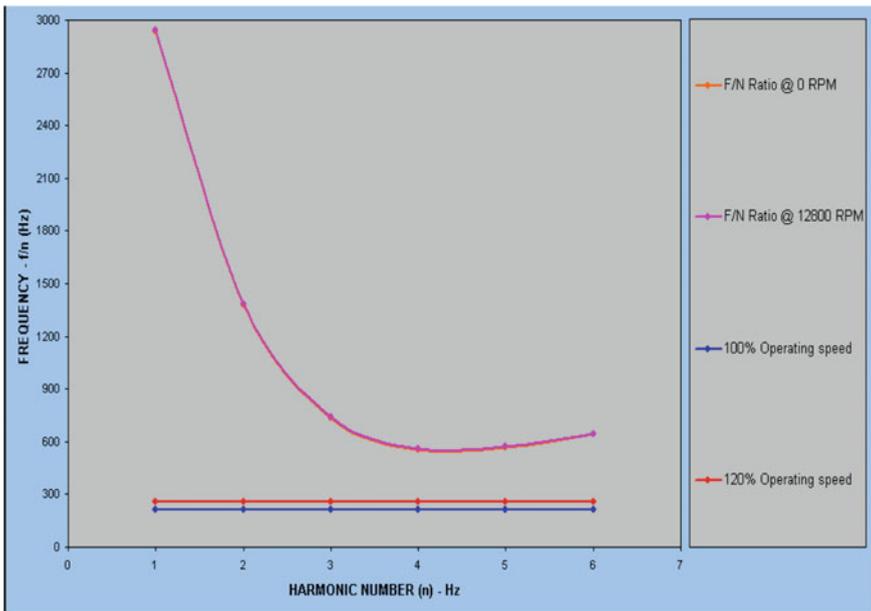
Fig. 12.8 Campbell diagram for forward rotating seal
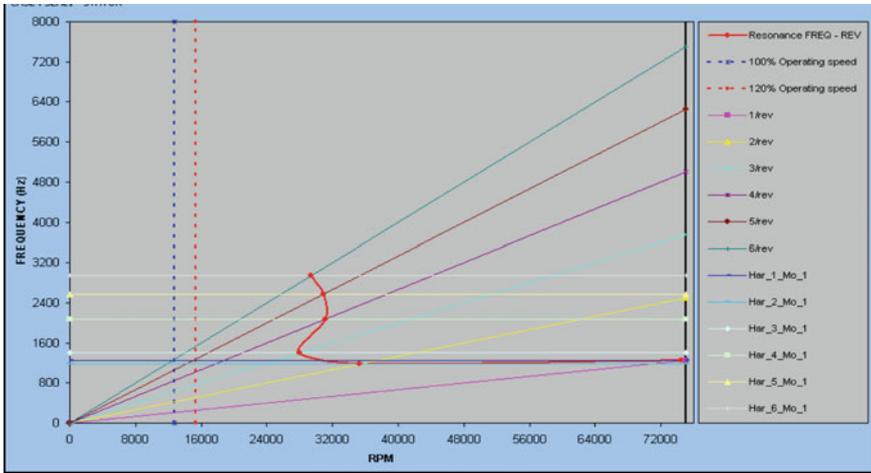
Fig. 12.9 Combined Campbell diagram for forward stationary seal
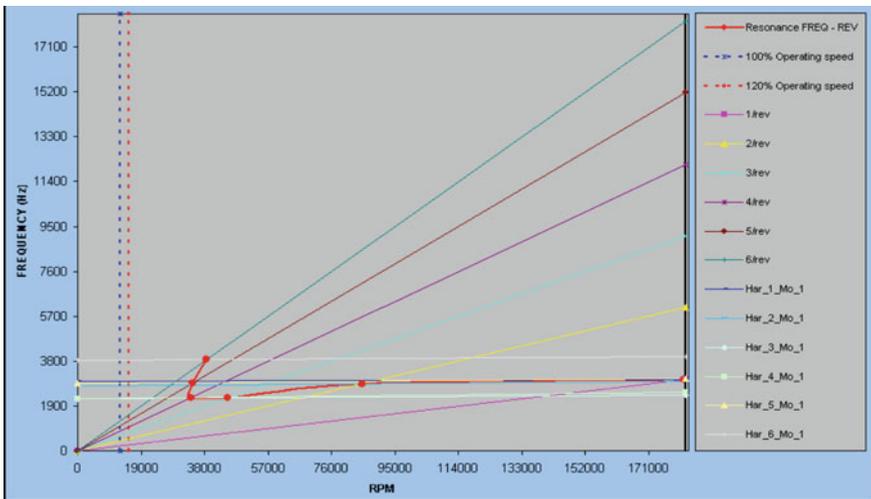
Fig. 12.10 Combined Campbell diagram for forward rotating seal

12.3.2   *CASE 2*: *Addition of Stiffening Shell*

These frequencies were input to the tool developed, and Campbell criteria were evaluated as shown in the figures below.

Figures 12.11 and 12.12 show the frequency versus nodal diameter (f/N) ratio Campbell diagram for forward stationary seal and forward rotating seal, respectively,
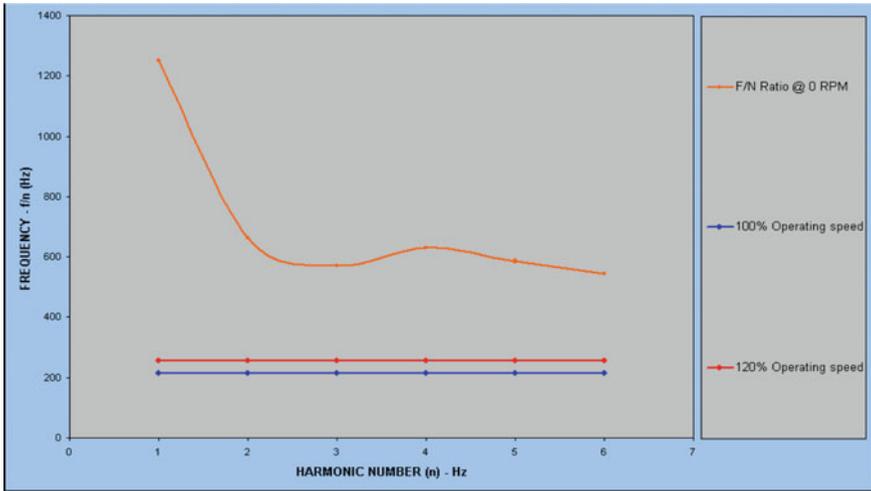
Fig. 12.11 Campbell diagram for forward stationary seal (Case 2)
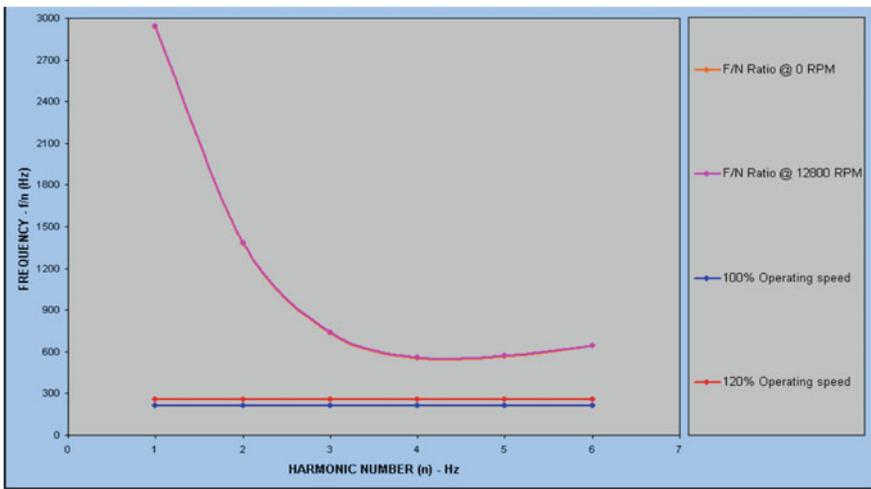
Fig. 12.12 Campbell diagram for forward rotating seal (Case 2)

which indicates that there is no resonance occurring since the f/N ratio curve lies beyond the operating speed and the red line speed.

Figures 12.13 and 12.14 show the combined Campbell diagram for forward stationary seal and forward rotating seal, respectively, which indicates that there is no resonance occurring since the line joining the intersection of per revolution line and the harmonic frequency lines indicated by the red line lies beyond the operating speed and the red line speed.
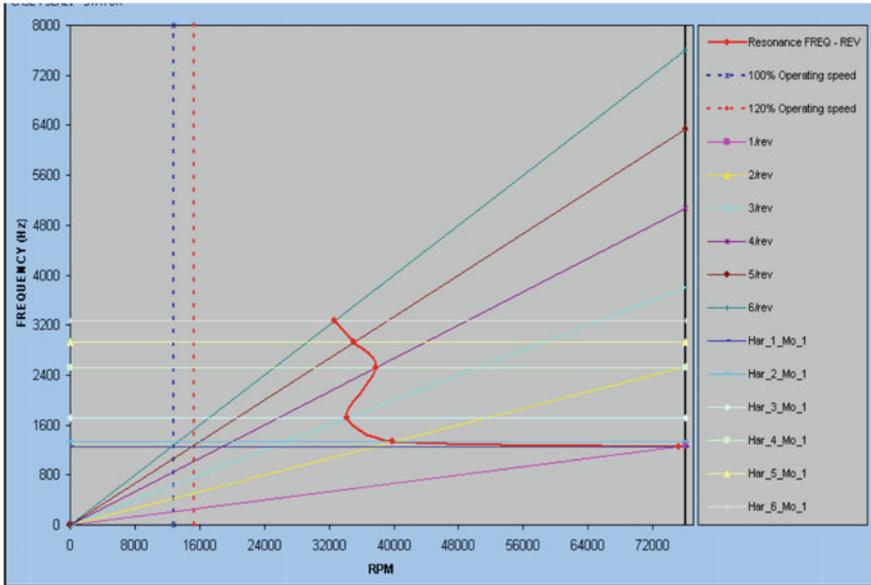
Fig. 12.13 Combined Campbell diagram for Forward stationary seal (Case 2)
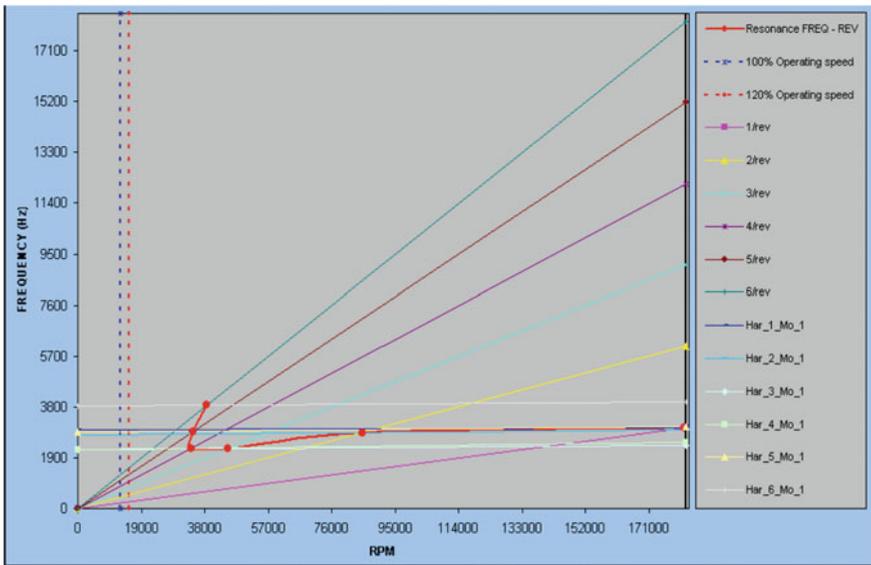
Fig. 12.14 Combined Campbell diagram for forward rotating seal (Case 2)

12.4   Results and Discussion

The various mode shapes obtained from the analysis of the baseline model are as shown in Fig. 12.5. Mode 1 of each harmonic, which is associated with the rub strip, is highlighted in blue color and is important here. The modes that involve the rub strip vibrations which can cause the interactions with the rotating component and hence the frequencies associated with these modes are important.

- By observation of frequency versus nodal diameter (f/N) and combined Campbell plots were obtained; it can be inferred that no resonance was observed with respect to engine rotor speed. The interaction between stator and rotor occurs in harmonic 4 at 3233 rpm, which is within the operating envelope of the engine. Hence, this interaction needs to be eliminated. Stiffening of the rub strip leg to increase the frequency may eliminate interaction. By an observation of frequency versus nodal diameter (f/N) plots shown in Figs. 12.11 and 12.12, and combined Campbell plots shown in Figs. 12.13 and 12.14, it can be inferred that no resonance is observed with respect to engine rotor speed. The interaction between stator and rotor occurs in harmonic 3 at 12,095 rpm and at harmonic 4 at 5052 rpm, which is within the operating envelope of the engine. Hence, these interactions need to be eliminated. Further improvement is needed to shift the frequencies outside the operating envelope.

12.5   Conclusions

This work gives a lot of exposure in the area of dynamic stability of Labyrinth seals using Campbell's criteria. To begin with, the scope of the work was divided into two broad categories and both of them have been successfully completed.

A user-friendly Excel-based tool has been developed. All the requirements of the tool such as plotting of frequency versus nodal diameter curve, the combined Campbell diagram and checking of individual harmonics with the revolution line and also the interaction Campbell diagram are successfully met. This tool was tested with several dry runs for accuracy and user-friendly input and output. The format of the output has been tuned to match the presentation style of the users.

A case study on the design of a stationary Labyrinth seal was also done to show the validity of the tool. The modal analysis was carried out in ANSYS and the tool developed was used to plot the Campbell diagram. By the observation of frequency versus nodal diameter (f/N) plots shown in the respective figures and combined Campbell plots shown in respective figures, it can be inferred that no resonance is observed with respect to engine rotor speed.

The interaction between stator and rotor is also checked and plotted which showed interactions occurring at different frequencies for different cases. The geometry of the stationary part was modified to shift the interacting frequencies within the operating envelope. Thus, this tool significantly reduces the post-processing time and is found to be very user friendly.

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