DEVELOPMENT AND ANALYSIS OF ROTORDYNAMICS SYSTEM

MOHAMMAD IKHMAL FITRI BIN MOHD HAYZIR

UNIVERSITI SAINS MALAYSIA

2021

DEVELOPMENT AND ANALYSIS OF THE ROTORDYNAMICS SYSTEM FOR JOURNAL BEARING

By:
MOHAMMAD IKHMAL FITRI BIN MOHD HAYZIR
(Matrix no: 137832)

SUPERVISOR:
PROF. DR. ZAIDI MOHD RIPIN

July 2021

This dissertation is submitted to
Universiti Sains Malaysia
As a partial fulfillment of the requirement to graduate with honours degree in
BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School of Mechanical Engineering
Engineering Campus
Universiti Sains Malaysia

DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled Development and Analysis of Rotordynamics System. I also declare that it has not been previously submitted for the award of any degree or diploma or other similar titles of this for any other examining body or University.

Name of student: Mohammad Ikhmal Fitri Bin Mohd Hayzir
Signature:

Date: 12/7/2021

Witnessed by,
Supervisor: Prof. Dr. Zaidi Mohd Ripin

Signature:
Date:

ACKNOWLEDGEMENT

For the sake of Allah, The Most Kind and Most Merciful. I am exceptionally thankful to Allah the Almighty, who gave me with great wellbeing, solid soul, and direction to finish this research project effectively.

At first, I would like to thank the School of Mechanical Engineering, Universiti Sains Malaysia for giving me the opportunity to acquire the knowledge and comfort to pursue knowledge since my first year in school. In addition, I would like to extend my sincere appreciation to the staff and scholastic technicians especially in the field of mechanics. They shouldered their duty to guide and help me since I have been here so long.

Then, I might want to truly thank my supervisor, Prof. Dr. Zaidi Mohd Ripin for his help and direction all through the undertaking. He gave numerous valuable advice and useful thoughts for my undertaking. He additionally shared all his insight and quietly guided me when I experienced challenges in my project.

At long last, I am exceptionally thankful to my folks Mr. Mohd Hayzir Bin Ibrahim and Ms. Suyati Binti Mamon for their commitment, supplication, care and penance to give instruction and plan to my future. They put forth a valiant effort to shape my existence with energy and eagerness. Without them, I could never be who I am today.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF SYMBOLS

Rpm	Rotational per minute
ω_n	Natural frequency of the system
ω_c	Critical speed of the system
k_{xx},k_{yy}	Stiffness coefficient of the bearing element
$C_{xx,}C_{yy}$	Damping coefficient of the bearing element
mm	millimeter
kg	kilogram
N/m	Newton per meter
GUI	Graphical user interface

ABSTRAK

Faktor utama yang perlu dipertimbangkan untuk mencapai konfigurasi optimum ciri respons dan prestasi perkhidmatan adalah tingkah laku dinamik sistem pemutar. Penentuan frekuensi semula jadi struktur, bentuk mod untuk memperkuat kawasan yang paling fleksibel atau mencari lokasi yang ideal di mana jisim harus dikurangkan atau redaman harus ditingkatkan, dan faktor redaman untuk mengelakkan kesulitan umum yang disebabkan oleh getaran. Pusaran minyak adalah masalah yang berlaku ketika galas jurnal pada mesin yang juga mempunyai sistem pelinciran tekanan dan berlaku pada kelajuan tinggi. Penyelidikan ini menjalankan eksperimen untuk mengkaji fenomena ketidakstabilan yang disebabkan oleh bendalir dalam sistem galas jurnal dengan menggunakan sensor anjakan laser untuk menentukan gerakan orbit poros berputar. Penyelidikan ini juga melakukan pengiraan menggunakan persamaan pesongan statik dan simulasi analisis modal menggunakan perisian ANSYS untuk menentukan kelajuan kritikal sistem. Bentuk mod sistem akan diperhatikan dari analisis modal dalam perisian ANSYS untuk mengkaji tingkah laku galas pada kelajuan operasi yang berbeza. Dalam penyelidikan ini menunjukkan fenomena putaran minyak dan cambuk minyak ditentukan dalam analisis modal masing-masing pada 550.9 rpm dan 2000 rpm. Bentuk mod poros berputar juga dapat mengenal pasti menggunakan analisis mod yang lembap. Dari hasil itu, kelajuan kritikal poros berputar adalah 1101 rpm, dan bentuk mod semasa kelajuan kritikal berada di bawah jenis mod silinder.

ABSTRACT

A major factor to consider for achieving the optimal configuration of response characteristics and service performance is the dynamic behaviour of the rotor system. Determination of the natural frequencies of the structure, the mode shapes to reinforce the most flexible regions or locate the ideal locations where the mass should be reduced or damping should be enhanced, and the damping factors to avoid large vibrations. Oil whirl is a problem that occurs when journal bearings are implemented on machines that also have pressure lubrication systems and occur at high speeds. This research is to study the fluid-induced instability phenomenon in the journal bearing system. A static deflection and simulation of modal analysis are carried out using ANSYS software to determine the critical speed of the system. The mode shape of the system of the damped system in the ANSYS software to study the bearing behaviour at different operating speeds. In this research shows the oil whirl and oil whip phenomenon are determined in the damped modal analysis is at 550.9 rpm and 2000 rpm respectively. The mode shape of the rotating shaft also able to identify using the damped modal analysis. From that result, the critical speed of the rotating shaft is 1101 rpm, and the mode shape during the critical speed is under the cylindrical mode type.

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Rotor dynamics is to study the behaviour and analysis of rotating structure such as a hydrodynamics bearing-rotor system. The stability in the rotor vibration in journal bearing is an important element in rotor dynamics characteristics. In a rotating structure, the interaction of the lubrication fluids will develop a significant sub-synchronous self-excited vibration of resonance when the hydrodynamics bearing-rotor system rotates at the critical frequency of the system (Luo et al., 2018).

This kind of phenomenon can make the rotor dynamics system especially for journal bearing to become unstable. Failure in turbo machineries is due to vibration can increase the maintenance costs can be dangerous (Shubham & Prashant, 2013). The major effect of unstable rotating rotor system can lead to the catastrophic failure.

In the case of plain bearings supporting a high-speed rotor, even if there is no other external force acting on the rotor, whirling vibration can be generated. Below twice the first critical speed, the fluctuating lubricating pressure will rotate at a speed equal to half the rotation speed (Batrak, 2006). It is called oil whirl or half speed whirl. The oil vortex is excited by the circulating force in the lubricating film.

If the rotor is subjected to some sudden external disturbances, it may instantly deviate from its equilibrium position. When this happens, the additional oil film pressure will drive the shaft into the rotating path around the bearing in the bearing clearance. Due to the damping force, the shaft can return to its stable position. Otherwise, the shaft will continue to rotate forward at a constant speed equal to the critical speed. This self-excited rotational vibration is called an oil whip. The oil whip starts at twice the critical speed and continues to exist at that critical speed (Robbersmyr et al., 2014). When the rotational speed is increasing, the whirl smoothly transforms into whip, and at a certain speed, the whip may disappear and the second-mode whirl starts again (Tůma, 2014).

It is generally believed that the main advantage of fluid film bearings is the lack of contact between rotating parts, so the theoretical service life is unlimited. During the start-up process, there will be brief contact between metals, and foreign objects in the lubricant or excessive vibration will limit the life of the liquid film bearing.

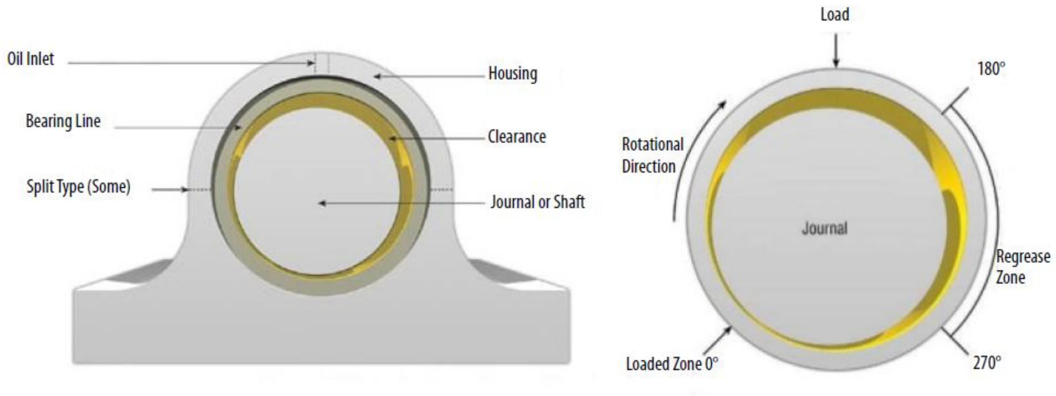


Figure 1.1: The diagram of the fluid film bearing system.
(https://www.machinerylubrication.com/Read/243/sleeve-bearing-lubrication)

For these reasons, special care must be taken when selecting and implementing a lubrication system, and special vibration monitoring techniques must be used. The most important aspects of the health and longevity of liquid film bearings are proper selection, installation, lubrication, and the alternating hydrodynamic load imposed on the bearing surface due to the relative vibration between the shaft and the bearing (Malcolm, 2001).

The dynamic behaviour of a rotating system is studied under the oil whirl and oil whip phenomenon, considering the influence of unbalance, rotor arrangement (vertical and horizontal rotor) and bearing parameters on the instability threshold. (Robbersmyr et al., (2014) investigated the mechanism of oil whirl and whip in fluid film bearings and the problems caused by oil whirl and whip, and (Luo et al., (2018) studied the function of a single-oil wedge hydrodynamic bearing-rotor system as a test platform, and used ferromagnetic fluid as a lubricant that can be controlled by a magnetic field to improve its performance.

The experimental results show that the external magnetic field will increase the stability threshold condition of the bearing, and the rigidity of the magnetic fluid will also increase. This experiment helps understand the occurrence of oil whirl and oil whip phenomenon in fluid film bearings. The equipment at different shaft speeds can be conducted for studying the effect of speed on the vibration level in oil whirl. The orbit motion analysis is implemented in this experiment to explore further understanding in fluid induced instability issues.

1.2 PROBLEM STATEMENT

Development of a hydrodynamic bearing-rotor system requires the investigation of oil whirl and oil whip phenomenon. Oil whirl and oil whip are the most common cause of instability for the journal bearing that can give a strong impact on the vibration characteristic of machinery application. Most of the research published just focuses on how to prevent the existence of the oil whirl and oil whip phenomenon. In this work, the modal analysis simulation and experimental setup carried out to study the relation of critical speed of shaft with oil whirl and oil whip phenomenon.

A small lab scale motor driven rotor system is used in the analysis of the effect of the oil whirl and oil whip are very important characteristics by determining the point when the critical speed, oil whirl and oil whip begins. The knowledge of fluid induced instability in fluid film bearing is important to optimize the performance of the journal bearing.

1.3 RESEARCH OBJECTIVES

The main objective of this research is to study the rotor dynamics behaviour in the rotating shaft driven by a motor. The investigation on the oil whip and oil whirl phenomenon are required to gain further information about the failure in rotor dynamics system. Therefore, the objectives of this research are:

1. To stimulate the oil whirl and oil whip phenomenon from the experiment setup.
2. To conduct the modal analysis of journal bearing to study the shaft behavior by using ANSYS simulation software.

1.4 SCOPE OF RESEARCH

The main idea of the project is to discuss the details of how the oil whirl and oil whip occurs. There are many possibilities and reasons that may cause oil whirl. The boundary focus of this research paper is the speed parameter, which is about the objective function of the oil whirl. An experimental system will be introduced to study the oil whirl phenomenon and determine the oil whirl behavior in journal bearings.

1.4.1 Flow Chart of The Project

The flow chart below shows the project's flow of the progress to set up this research paper.

FLOW CHART OF THE PROJECT

Researching and Analyse the Project Title and Objective

↓

Gathering all Information and Resources to Create the Concept

↓

Literature Review of the Journals and Outsources

↓

Design the Experiment System and Measurement Simulator

↓

Analysis Data Collection and Discussion

↓

Conclusions, Recommendations and Future Work

1.5 THESIS OUTLINE

This thesis covers five chapters that consists of:

Chapter 1:

Introduction to the study background, problem statement, research objectives, research scope and thesis content.

Chapter 2:

The literature review of every journal with similar objective relevant to this project title.

Chapter 3:

The methodology section which introduced requirements and specifications of the experimental system and experiment procedure to carry out the simulation study on the operating parameters with respect on objective functions.

Chapter 4:

Important part of research that is results and discussion sections. The results section is the results obtained from measurement using laser displacement sensor.

Chapter 5:

The conclusion and recommendation sections. This chapter will conclude the whole research results and discussion and recommend on preventing the oil whirl phenomena.

References:

A list of references used in this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Basis of oil induced instability

Fluid induced instability or known as oil whirl and oil whip is a phenomenon that represent the most major characteristics in the frequency which is resonances. Both are characterized as a sub synchronous frequency in an orbital motion (Al-Shurafa, 2010). The way to investigate the existence of whirl or whip vibrations is by using orbit analysis and frequency spectrum. The point of whirl and whip existing is at the journal bearing where these instabilities develop. The interaction between rotating shaft, oil film and bearing are the major aspects that involve stability based on the theory of *Complex Dynamic Stiffness*.

Oil whip can exist in the rotor system due to influence of journal bearing design, misalignment of the shaft or sudden shock to the system (Alok et al., 2012). Dislocation of rotating shaft from center position in the machine caused by misalignment, load or eccentricity will give effect in clearance of the bearing. This is the reason for Alok and Somnath (2012) came out with the idea to develop the experiment to investigate the misalignment of the shaft and its effect on journal bearings. They believe that the factor of affecting instability is due to oil whirl, oil whip and misalignment.

Most of the bearings in large critical machines are hydrodynamic liquid film bearings. The rotational interaction with the surrounding fluid in the bearing always eventually results in a certain degree of vortex in the direction of rotation of the fluid. When the shaft is displaced from the centre of the bearing, the converging fluid forms a pressure wedge that look like in the figure 2.1. The support force generated by the pressure wedge (profile) can be divided into two parts: a radial spring force, which points to the centre of the bearing and is balanced with the load; and a tangential force, which is 90% to the force of the bearing, °angle, radial force and direction of rotation.

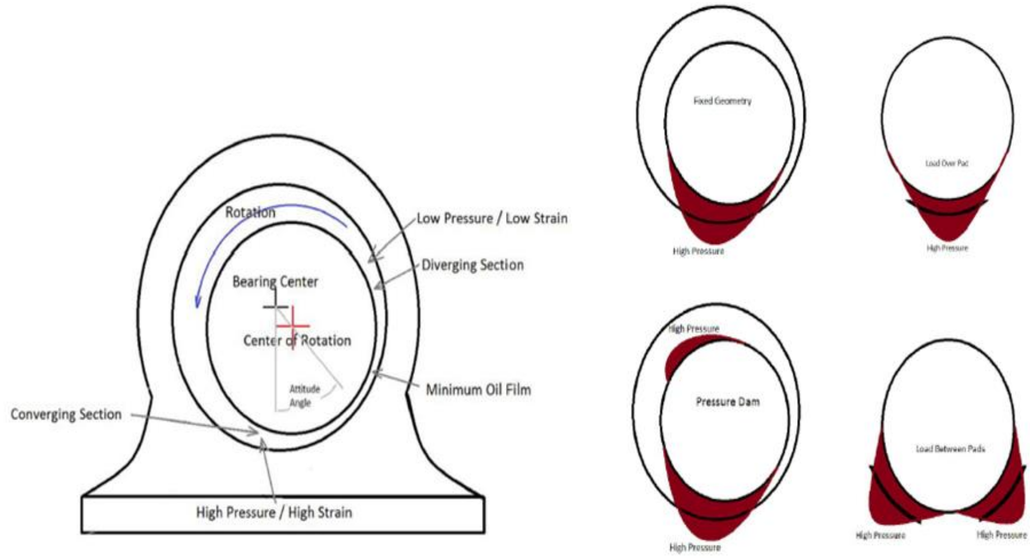


Figure 2.1: The prediction of oil wedge geometry for all bearings type (Loon, 2020).

2.2 Effect of fluid induced instability

If the oil whirl caused by fluid-induced instability occurs in the journal bearing, it is a major problem. This instability is a serious failure in rotating machinery, because if the machine runs unimpeded, it may cause catastrophic failure. Even though, a single bearing failure alone, it can lead to a machine breakdown resulting in costly lead time and production loss. The occurrence of oil whirl and oil whip phenomenon will influence the temperature rises due to effect of localized heating.

By nature of the mechanism, oil whirl will involve friction of the rotor at the point of contact due to metal interaction in the journal bearing (Fan et al., 2011). The friction of the rotor at the point of contact will generate heat then causes the temperature rises in the rotor system. The increase in fluid film temperature is due to mechanical work done by the shaft. In turn, the friction caused by the shaft shear lubricant generates a drag torque on the shaft and consumes mechanical power. This friction loss is closely related to the bearing size, clearance, shaft speed and oil viscosity (He & Byrne, 2018).

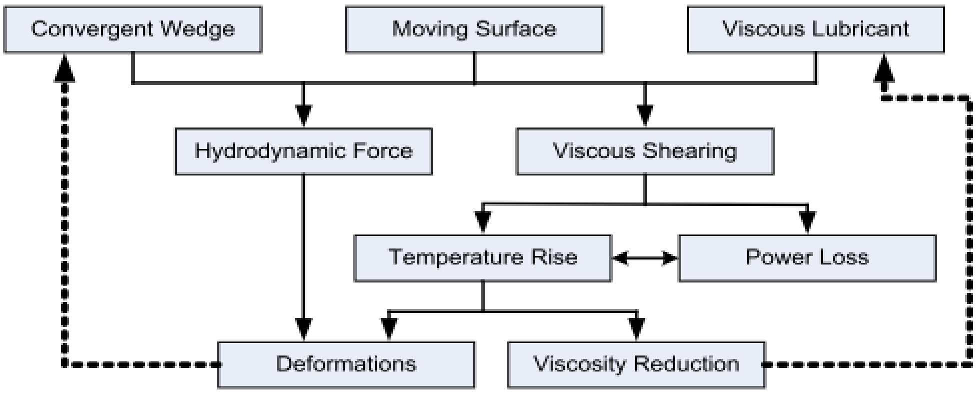


Figure 2.2 The flow of steady state operation of the fluid film journal bearing(He & Byrne, 2018)

The Figure 2.2 summarized of the principle for steady state operation in the fluid film bearings. Basically, there are three elements are required to stimulate a fluid film hydrodynamic forces which is convergent wedge, moving surface and, viscous lubricant to support when the load was applied. The accompanying phenomenon is viscous shear, which causes temperature rise and power loss. Temperature rise and power loss are related because the energy used to heat the film is converted mechanical energy from the shaft. The increase in temperature causes the oil viscosity to decrease and the bearing deformation. Conversely, deformation will also change the geometry of the bearing, thereby changing the wedge shape.

2.3 Critical speed analysis in ANSYS

2.3.1 Modal Analysis

ANSYS finite element software is frequently used for static and modal analysis. ANSYS Workbench is a new generation of ANSYS software designed to help you solve real-world problems. It inherits classical ANSYS's sophisticated analysis features and adds more sophisticated solutions tools (Li et al., 2014). This is the reason why we chose ANSYS Workbench to study about the shaft behaviour. It can transmit parameters directly with CATIA, Pro/E, and other CAD systems, as well as establish seamless connections across them, allowing ANSYS Workbench to start up quickly. Automatic assembly relationships and construct contact components may be available in ANSYS Workbench without the requirement for user involvement throughout the assembly process.

Modal analysis may also be used to determine the inherent frequencies and mode shapes of a construction. The proper natural frequencies are difficult to compute since they change with various factors, as discussed in the rest of this paragraph. Because the journal bearings are rotationally speeding dependent, the natural frequencies change with the rotational speed.(Analysis, 2001). Viscosity, oil temperature, and load are three parameters of a journal bearing that are affected by rotating speed. To make matters even more challenging, natural frequencies might shift at constant rotational speed owing to changes in load, mass imbalance, temperature changes, or rotor misalignment (Samuelsson, 2009).

- During the shaft operation, it does not remain fixed at the axis of rotation; instead, it revolves around it in a circular motion. Whirling is the term for this motion. The centrifugal forces that cause the rotor to bend are one factor that causes the spinning motion. It also is potential that the rotor is not completely axis symmetric.

Forward and backward whirling are the two different forms of whirling.

- When the whirling rotation occurs in the same direction as the rotational speed, it is called forward whirling. This form of whirling is the most harmful because forward whirling in resonance is simpler to excite the rotor than backward whirling.

- Backward whirling happens when the whirling rotation occurs in the opposite direction of the rotational speed. A Campbell diagram may be used to indicate which type of whirling motion the rotor has, with forward whirling increasing natural frequency as rotational speed increases and backward whirling decreasing natural frequency as rotational speed increases.

2.3.2 Campbell Diagram

The Campbell Diagram illustrate the oil whirl frequencies based on the critical speed estimated under various operating conditions. This diagram consists of rotational speed of the rotor that represents as x-axis and the mode frequencies as y-axis. The Campbell diagram also the most important tools to study and understand the behaviour of the rotational equipment. In the Ansys modal analysis, a Campbell diagram are plotted to obtain the required critical speeds correspond to forward frequency and backward frequency speeds of the various modes of the simple rotor system (Samuelsson, 2009). The intersection between excitation line or 1X frequency of the modes line in the diagram is represents as critical speed of the shaft.

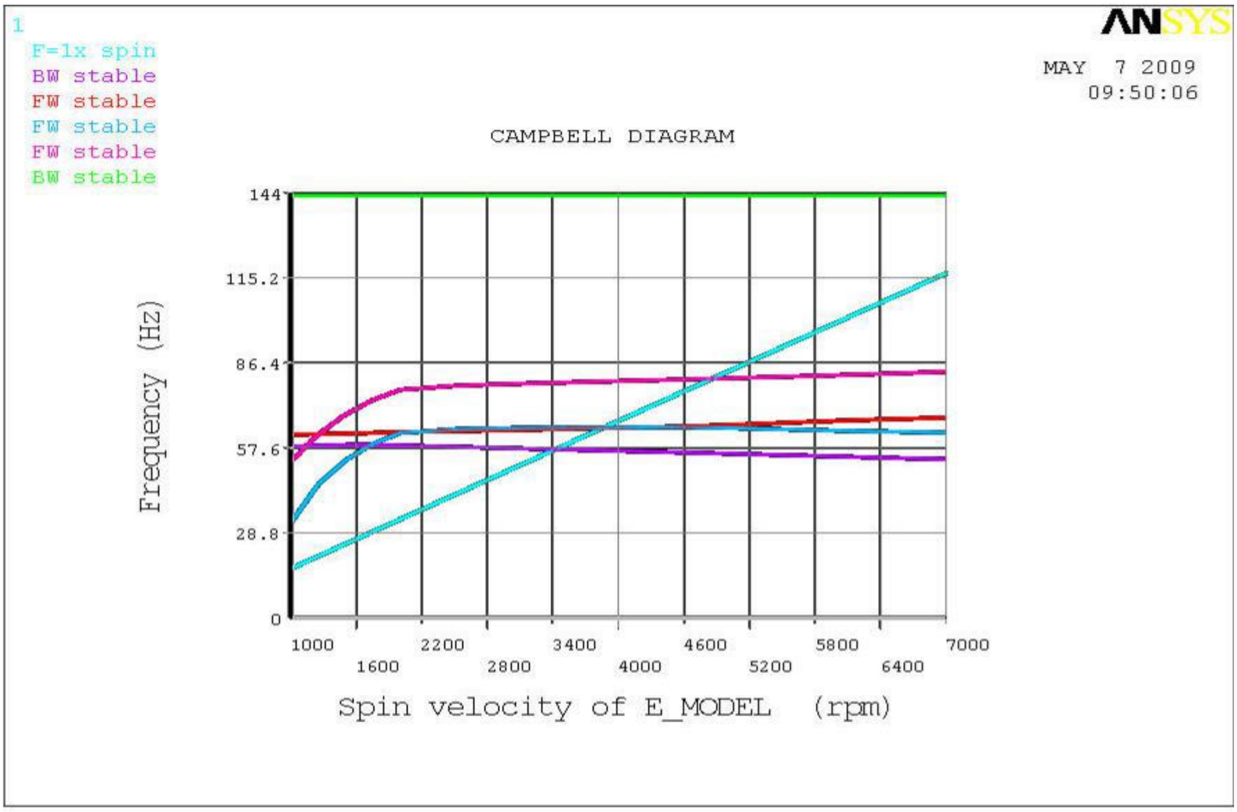


Figure.2.3: Example of Campbell diagram from the modal analysis (Samuelsson, 2009).

Figure 2.3 shows the example of Campbell diagram that indicates frequency as y-axis and whirl velocity as x-axis. This illustration gained from the modal analysis in ANSYS simulation software. From the figure above, we can identify some important information about critical speed of the system.

- The diagram has the rotational speed of the rotor on the x-axis and the mode frequencies on the y-axis.
- The modes are plotted with a different rotational speed.

- The frequencies are not constant over the rotational speed range because most of the modes will be increased or decreased with higher rotational speed.

- Forward whirling modes are increase and backward whirling modes are decreasing which is shown in the diagram in Figure 3.

- The excitation line, which is blue and directly proportional to the rotational speed, indicates natural excitations occurring on the rotor.

- In the diagram above, the excitation line is synced with the rotating speed.

- When the excitation line crosses any of the mode lines, the critical speeds are obtained.

- Therefore, there are four critical speeds in the figure above.

2.3.3 Mode shape

Understanding structural vibration requires an understanding of the modal domain. The structure vibrates or bends in a certain shape termed a mode shape when aroused at its natural frequency. The structure will vibrate in a complicated arrangement of all modes under normal operating circumstances. Engineers, on the other hand, can identify all potential variations of vibration by studying each mode of vibration (Hansen, 2018). The identification of the natural frequency, modal damping and mode shape of the structure based on Frequency Response Function measurement is called modal analysis. The movement of the system begins to move in a certain pattern at natural frequencies, and all elements of the system move simultaneously. This is referred to as a pattern. When dealing with the rotor, the issue is that the mode changes with speed and is influenced by the bearing and stator.

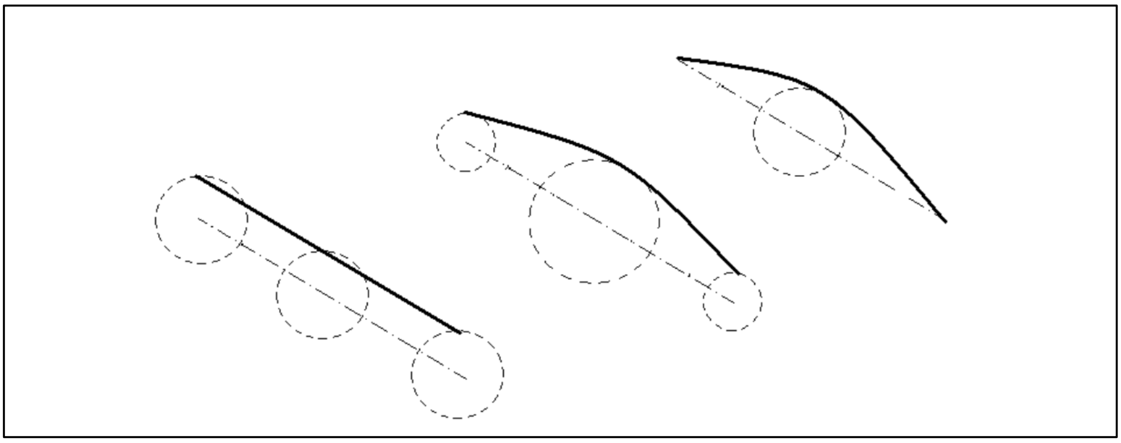


Figure 2.4: Different cylindrical modes by applying various stiffness of the shaft (Samuelsson, 2009).

Figure 2.4 shows cylindrical shape of the mode shape from the modal analysis. The left side of the figure 5 shows the shape and movement of the bearing for the soft bearing. The right one has a very stiff bearing, whereas the middle one has an intermediate bearing. Furthermore, cylindrical modes are the initial modes, and they are also known as rigid modes since the rotor does not flex unless the bearings are extremely strong (Samuelsson, 2009). The cylindrical modes are depicted in the diagram above. The rotor appears to be simply bouncing up and down from the front.

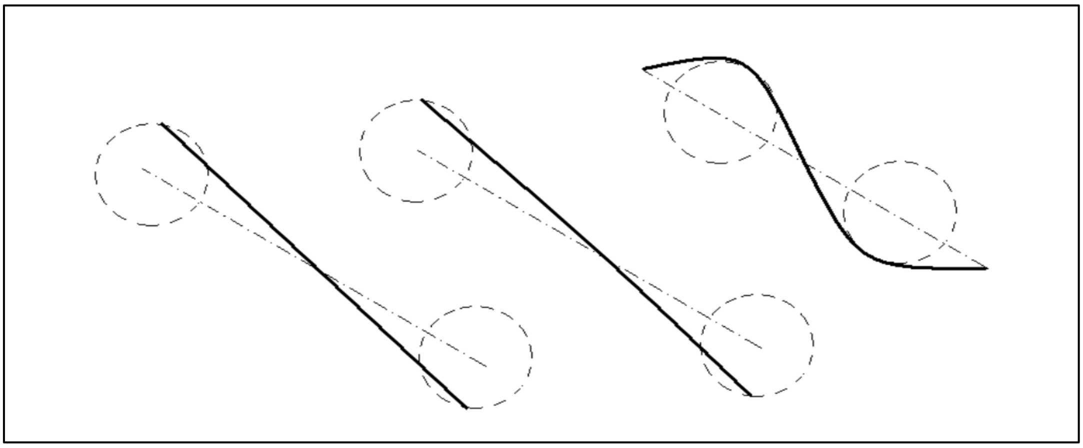
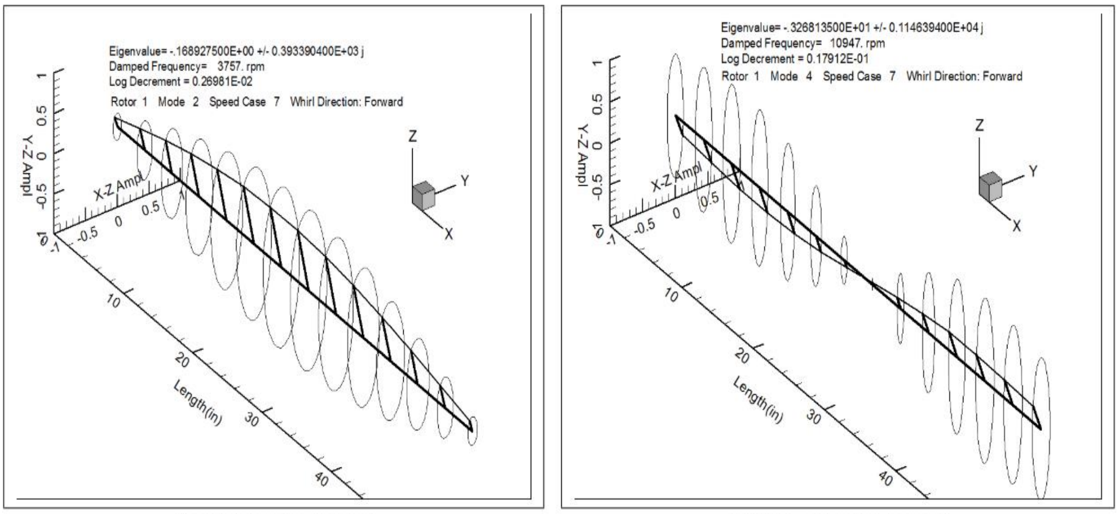


Figure 2.5: The conical modes shape with different stiffness of the bearings (Samuelsson, 2009).

Figure 2.5 shows the second type of lateral modes is conical modes. The modes look like somebody is holding the centre of the rotor still and the ends are moving in circles. The left side shaft shows the conical shape for soft bearings. The middle one is with intermediate bearing and the right one is with very stiff bearing. Viewed from the side, the shaft seems to swing up and down around the centre, and the left and right sides are out of phase. Therefore, this mode is sometimes called "rock" mode or "pitch" mode(Swanson et al., 2005).



(a) First Bending, Forward (b) Second Bending, Forward

Figure 2.6: Example of Damped Mode Shapes at 3500 rpm (Dimond et al., 2013).

2.3.4 Monitoring oil whirl phenomenon

One of the methods can be applied to determine the occurrence of the oil whirl and oil whip phenomenon in the rotating machine by using laser displacement sensor or uncontacted proximity sensor. This kind of method very useful because the displacement probes can monitor the shaft vibrations and shaft alignment by implementing orbital plots. The displacement probe (using the orbit diagram) measures the relative movement of the shaft relative to the machine housing. This means that if the machine and the shaft move together, the displacement will be measured as zero, although in reality the machine may vibrate violently (Brancati et al., 1995).