LUT UNIVERSITY

School of energy systems
Mechanical Engineering

Kojack Kabundi

REVIEWING THE APPROACH ON ESTABLISHING A PIONEER FIRM IN VIBRATION CONDITION MONITORING IN DRCONGO

MASTER'S THESIS

Examiners: Professor Aki Mikkola

Dr. Kimmo Kerkkänen

ABSTRACT

LUT University
School of Energy system
Mechanical Engineering
Master's Programme in Mechatronics

Kojack Kabundi

REVIEWING THE APPROACH ON ESTABLISHING A PIONEER FIRM IN VIBRATION CONDITION MONITORING IN DRCONGO

Master’s Thesis

2021

67 pages, 48 figures, 2 tables, 0 Appendix

Examiners: Professor Aki Mikkola

Dr Kimmo Kerkkänen

Keywords: Modal analysis, vibration analysis, predictive maintenance, business model, pioneers, followers.

The astonishing progression rate in technologies, education, and other environmental aspects, makes the entry order in a market as one of the most decisive factors for business growth and performance in present-day. Pioneering (early entry) is a crucial strategy for competitiveness and dynamic of a firm. Previous investigation has proven that in western markets, pioneers have better profitability and performance over followers. This work mainly focuses on the possibility to launch a vibration monitoring firm in Dr Congo. The conducted survey has shown that a considerable number of companies operating in Dr Congo are affected by the lack of skilled labor. Therefore, a growing concern among investors and entrepreneurs in Dr Congo is mostly oriented to qualified labor which provides business opportunities for those planning to invest in the engineering areas in the future. This thesis examines the technical parts of the business to be implemented by presenting a detailed overview of Finite element method, modal analysis and type of fault problems found in rotating machinery as well as the business model implementation. However, the third chapter discusses the advantages of entering first in the market and the impacts it can have in market share.

ACKNOWLEDGEMENTS

The thesis was the most challenging part of my studies, and I had the feeling that it took an eternity to complete it. I want to thank my supervisors Aki Mikkola and Kimmo Kerkkänen, for allowing me to complete this thesis. I take the opportunity to show my gratitude to LUT University for the knowledge I gained during my studies.

A special thanks go to my family and friends for all their support during my studies.

Kojack Kabundi

Lappeenranta 01.04.2021

Table of Contents

1. Introduction ... 7
1.1. Motivation ... 9
1.2. Objectives and research questions ... 10
1.3. Structure of the thesis ... 10
2. Literature review ... 11
2.1. General principles of establishing pioneering business ... 11
2.2. Special features related to the business in DRC ... 12
2.3. Special features related to the business in the field of vibration monitoring ... 15
2.4. Theory of vibration ... 15
2.4.1. Discrete and continuous systems ... 22
2.5. Experimental methods and equipment used in monitoring of vibration ... 27
2.5.1. Exciter ... 29
2.5.2. Signal Analyzer ... 32
2.6. Condition monitoring and failure prediction by vibration measurements ... 33
2.6.1. Vibration sensor mounting position ... 34
2.6.2. Environmental influence on the vibration sensor ... 36
2.6.3. Importance of dynamic variables in vibration sensor ... 38
2.6.4. Vibration behavior on components ... 38
2.6.4.1. Time waveform analysis on rotating machinery ... 38
2.6.4.2. Time frequency analysis on rotating machinery ... 39
2.7. Importance of using vibration monitoring in industry ... 41
2.7.1. Elements fault monitoring ... 41
2.7.1.1. Bearings ... 41
2.7.1.2. Bearing fundamental frequencies ... 42
2.7.1.3. Damaged inner race of a bearing ... 45
2.7.1.4. Gear misalignment ... 46

2.7.1.5. New generation vibration analyzer 49
2.7.1.6. Vibration severity 50
2.8. Business model literature review 51
3. Methodology 54
3.1. Hypothesis testing 55
3.1.1. Impact of the Order of Entry on performance 55
3.1.2. Impact of the Order of Entry on strategies 55
3.2. Impact of the Order of Entry on performance 59
3.2.1. Impact of the Order of Entry on Strategies 59
3.2.2. Moderating Impact 60
4. Results and discussion 61
5. Conclusion 63
References 65

LIST OF SYMBOLS AND ABBREVIATIONS

A – Amplitude

BFPO – Ball pass frequency outer

BPFI – Ball pass frequency inner

CM – Condition monitoring

DRC - Democratic Republic of Congo

FFT – Fast Fourier Transform

f_n - Frequency

$f(t)$ – Externally applied force

i – imaginary number

k – spring constant

k – stiffness matrix

m – mass

m – mass matrix

p – Principal coordinates

R&D – Research and development

t – Time

T - Period

u – Generalized coordinates

u(t) – Column vector

ω_n – Angular natural frequency

v_0 – Initial velocity

v – Velocity

φ_1 – eigen vector

ϕ – Phase

$\boldsymbol{\phi}$ – Modal transformation matrix

1. Introduction

Vibration is a continuous movement of a body or particle relative to a static frame of reference, and in many cases, vibration can severely damage or affect the structure of engineering designs. The presence of vibration in an engineering system may reduce its performance. Common vibration examples familiar to most include the vibration of a damaged hair clipper, a weak automobile suspension system and a noisy refrigerator. However, while harmful, vibration can be practical for some applications such as concrete vibrator sieve machine, stone/silo vibrating screen machine and many others. Thus, measuring and analyzing vibration knowledge can be useful to control and predict vibration. (Inman 2014.)

Vibration condition monitoring is an engineering applied technique that indicates early signs of malfunction or degradation of a mechanical machine through analysis and observation. Vibration condition monitoring decreases the probability of catastrophic failure, improves safety and machine performance. Many causes result in machine failure such as resonance, looseness, electrical supply, drive belts, gearbox faults, bearing failure, misalignment, unbalanced and motor faults. (ABS 2016.)

Vibration monitoring technique of rotating machinery has been present for decades, and its fundamental principles are still applied to collect vibration data. The development of vibration measuring instrumentation has had a significant effect on actual performance compared to the early days. Generally, a vibration analyzer is used to measure vibration activities inside the machine and allows the operator to collect data through an accelerometer sensor. The devise enables to diagnose vibration amplitudes at different span frequencies; thus, vibration arising at specific frequencies can be tracked and retrieved. Since each machinery problem emits vibration at specific frequencies, it helps the vibration analyzer to identify the machinery faults. In most case, the analyzer is a portable device that allows on-site mobility and provides measurement accuracy with a capacity of storing the collected vibration data for further analysis. The vibration analyzer usually comes with an accelerometer sensor. (Brüel & Kjær 2008.)

The accelerometer sensor is typically attached directly on rotating machinery such as spinning blades, gearboxes, or bearings. The sensor measures the acceleration of the rotating elements as voltage and transfers the information to the vibration analyzer. Therefore, the analyzer converts the data into vibration signals to allow the operator to access it. The three main parameters to measuring vibration characteristics of any rotating system are displacement, velocity, and acceleration.

However, Fast Fourier Transform numerical algorithm is used in many vibration analyses instruments to convert vibration signal from time domain to frequency domain. Thus, a spectral analysis or frequency analysis provides precise vibration signal information in a specific area. The spectral analysis is naturally applied on rotating machinery to detect failures related to geometrical degradation of rotating elements. Traditionally, a collection of data from the machines are done regularly through a sensor to monitor machine performance. Therefore, predictive maintenance can be scheduled whenever a sign of degradation is initiated. In addition, the below picture illustrates a vibration analyzer from Adash company equipped with various features enabling the user to monitor vibrations of rotative machines.

Figure 1.1. Vibration analyzer and an accelerometer sensor. (Adash 2020.)

In rotating machinery, maintenance is responsible for approximately seventeen percent of quality problems and production interruptions based on studies of equipment reliability problems. The cost allocated to maintenance in the heavy industry represents up to sixty percent of the overall production costs. (Mobley 2002.)

Nowadays, the condition monitoring system shows a significant growth in the global industrial and manufacturing industries, mostly in the western regions. However, referring to the forecast of the global market, the optimistic prediction of the CM will increase by 39 per cent in 2022. Predictive maintenance could be simply described as a way of boosting productivity, profitability, product quality of manufacturing and production plants. Unfortunately, very few companies in developing countries utilized these advanced techniques, especially in Dr Congo. (Berger 2018.)

1.1. Motivation

As vibration condition monitoring techniques are gaining ground across the globe, bringing predictive maintenance techniques to Dr Congo will be very beneficial for companies using heavy rotating machinery. However, the purpose of this work is to study the possibility of implementing a pioneering firm offering services in vibration condition monitoring and engineering training. The Democratic Republic of Congo will be the starting point. The Dr Congo has been chosen because of its strategical geo-localization and advantages. It is the second biggest country in Africa with a population of over 84.000.000, sharing boundaries with nine neighboring countries and with the most abundant natural resources of the world. Dr Congo is an Eldorado for mining companies and other firms.

Although setting up a company in Dr Congo gives an excellent perspective for growth, this thesis focuses on the technical aspects and challenges involved in establishing predictive maintenance and technical training in an unpredictable environment. Comparative data analysis is used to measure the advantage of pioneer over followers in the country.

1.2. Objectives and research questions

The researcher aims at finding out answers related to the implementation of pioneering firm that will contribute literally to the reinforcement of education and quality engineering service in vibration condition monitoring techniques in Dr Congo. Research questions help to specify factors that impact significant decision-making regarding the type of business to establish, service to provide, and the type of data analysis to apply for the research.

Hence, the associated research questions of this thesis are:

- What factors influence pioneering advantages of firms?
- What is the appropriate vibration measuring techniques to propose in Dr Congo?
- How vibration analysis can be applied to solve engineering problems?

1.3. Structure of the thesis

To achieve this significant task, the work requires a literature review in pioneering advantages, in the field of vibration analysis, and mechanical engineering.

The literature review is done systematically to compare various information collected from the internet and available books discussing this matter. This review aims to construct adequate questions and provide an overview of this work for potential readers.

Chapter 2 covers the literature review of pioneering business, and vibration monitoring aspect. The work presents some approach regarding the utility of the vibration measurements, methods used to find the results, and the reason why vibration condition monitoring is chosen over other methods. Chapter 3 presents the results obtained throughout the research, followed by Analysis and Discussion in chapter 4.

2. Literature review

In this chapter, a detailed overview of pioneering business and vibration measurement techniques are discussed to introduce technical aspects. Information obtained from various sources concerning pioneering business, and vibration measurements are explored to provide a deep understanding of methods used to detect and solve problems related to vibration.

2.1. General principles of establishing pioneering business

The Cambridge learner's Dictionary refers to a pioneer as someone who is among the first to undertake activities and also who develops methods, approaches or new ideas. The expression pioneer is used to describe activities and field of human interest as various as geographical discoveries, scientific innovation and so forth. If humans did not have the attitudes of trying new things, the world would remain primitive. In the business context, the term pioneer and innovator are, to some extent synonyms. Both terms indicate the aspiration for new managerial practices, futuristic strategies, and new operating procedures. (Kürzdörfer 2013.) Choosing the right time to launch new technology/products and entering new markets is one of the most crucial questions that face business leaders in the strategic management process. There are two possible options to choose, which are to be a pioneer or a follower and both options have risks and advantages. Generally, pioneers have a more significant market share, higher profitability, and extended business life. Still, the relative success of each strategy relies on multiple factors. (Kalicanin 2018.)

2.2. Special features related to the business in DRC

With the slow economic growth in developed countries, firms are looking at emerging markets such as DRC to expand their business. (Mittal and swami 2004.) They are attracted to emerging markets for many reasons; one is the vast potential for sales; firms with solid reputations can easily acquire new clients due to the impact of their brand names. The emerging market economic growth is another reason, and the maturation of developed markets plays an important role. The world bank approach in 2018 shows that the DRC economic grew by 5.8 per cent. When using comparative analysis, as illustrated in figure 2.2, DRC is among countries with the highest annual GDP growth. Picture in figure 2.1 shows a comparative Per Capita Income and Average Annual Economic Growth, by Province. The currency used for the analysis is the US dollar. (world Bank 2018.)

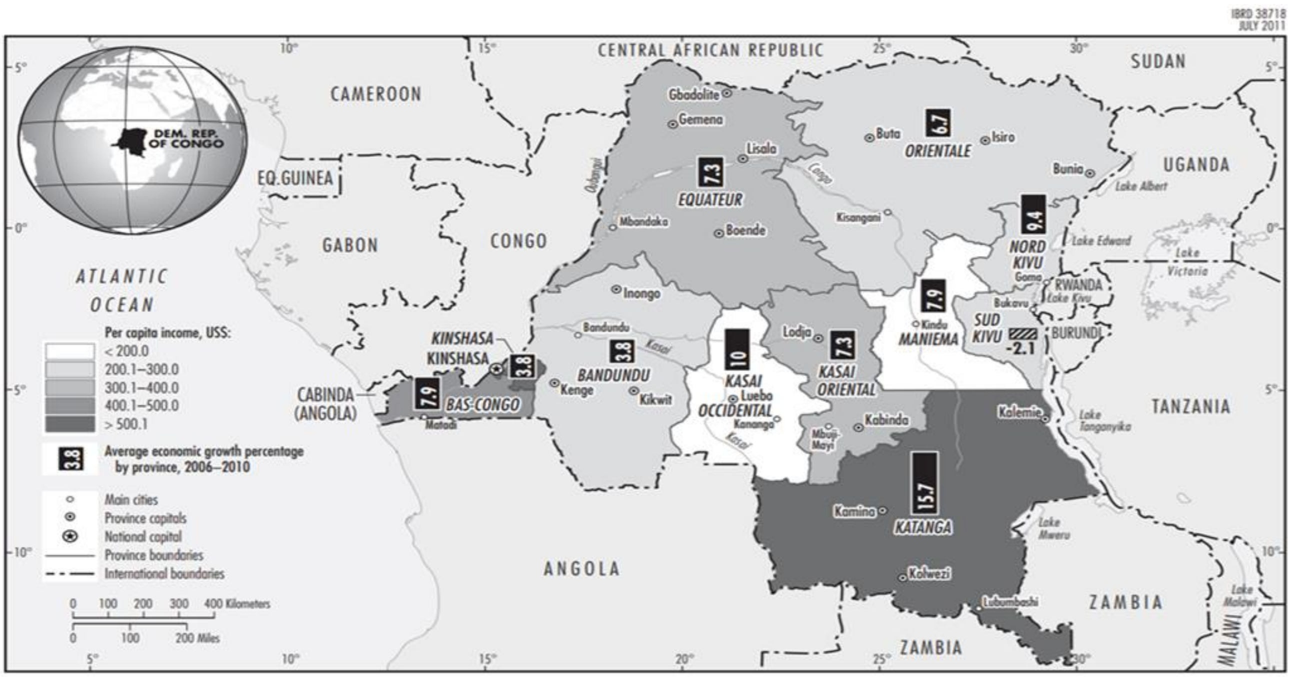


Figure 2.1. Per Capita Income and Average Annual Economic Growth, DRC. (World Bank 2018.)

Chile	2018	4.0
China	2018	6.6
Colombia	2018	2.6
Comoros	2018	3.4
Congo, Dem. Rep.	2018	5.8
Congo, Rep.	2018	1.0
Costa Rica	2018	2.6
Cote d'Ivoire	2018	7.4
Croatia	2018	2.6
Cuba	2018	2.2

Figure 2.2. Selected Countries and Economies. (World Bank 2018)

Katanga has the most considerable economic growth compared with other Provinces due to the intense mining activities happening in that zone, followed by Kasai Occidental and Nord Kivu. The mining sector in only Katanga contributed about fifty per cent to the GDP in 2017. (World bank 2018.) Many international companies operating in these provinces encounter a severe lack of well-trained technicians, causing companies to seek overseas help. The historical context demonstrates that the education sector in DR Congo had been severely affected by the adverse events that took place in the country. Therefore, no education reform has been made for the past 50 years, which led the education to a catastrophic degradation. (Top Congo 2020.) Thus, introducing vocational training school in vibration condition monitoring appears as an avant-garde in the country. Studies indicate that the order of entry, remarkably impacts business performance in the market as pioneers have competitive advantages over latecomers.

An illustrative statistic, shown in figure 2.3 demonstrate that, generally, pioneers consistently outperform followers. In many cases, previous studies indicate that over the years, pioneers 'performance stability is maintained over followers. (Mittal and swami 2004.) statistics also suggest that pioneers average market share is reducing over the years; fortunately, their market share is still higher than followers. Probably, this demonstrates that pioneers have long-term competitive advantage upon their rivals due to their first arrival into the market.

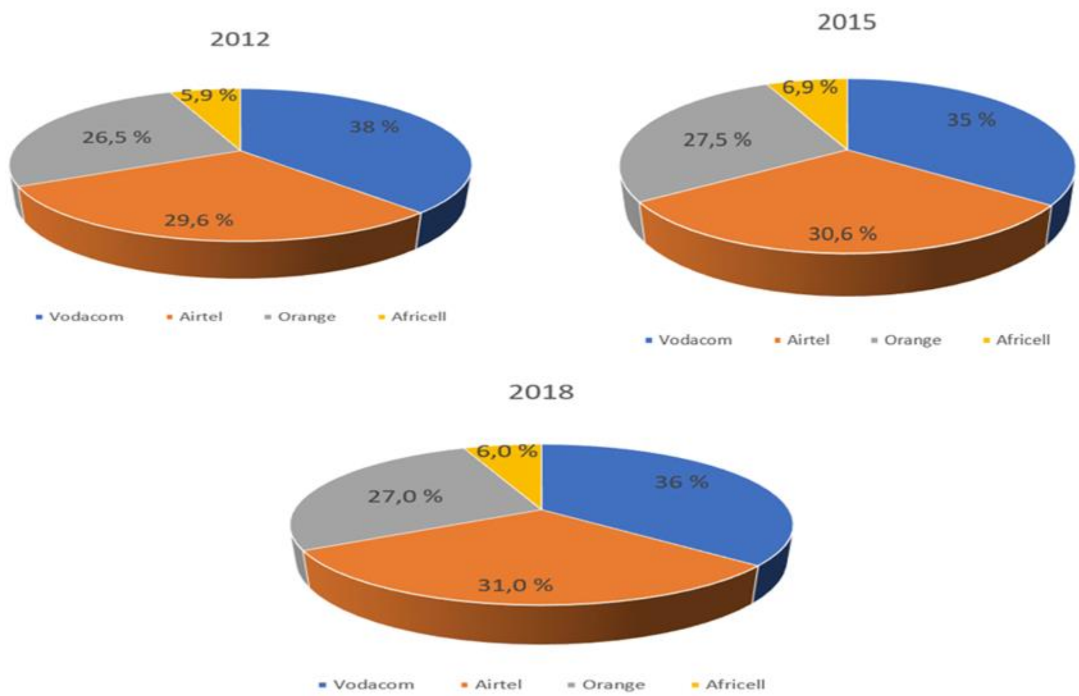


Figure 2.3. Variation in market share. (Office de control Congolais OCC 2018.)

However, to understand the progression of pioneers over followers, an example is given in figure 2.3, illustrating some case on mobile network firms in DR Congo and their results over time. The repartition of percentage reveals the order of entry of each firm in the market. Vodacom launched its company in 2002 a decade before other mobile network firms and its market share performance has been remarkable. A comparative data analysis is necessary to understand the advantage of pioneers over followers in DRC.

2.3. Special features related to the business in the field of vibration monitoring

Nowadays, the impact of technology in most business is noticeable. Technology is progressively changing the way people do business, and this transition sometime can be difficult for some companies to adopt it. Unfortunately, in this modern world, where competition is gaining ground in almost every business sector, the need for optimization is crucial. According to previous research done by Mobius Institute, on average, up to 60% of maintenance costs are dedicated to inspections and planned maintenance. Constant machine condition monitoring is a cost-effective alternative and can cancel up unnecessary inspections while avoiding costly routine inspections by relying on continuous digital monitoring. The company can recover its investment by saving on useless maintenance interventions. (Mobius 2018.)

2.4. Theory of vibration

Vibration or oscillation, as stated previously in the introduction, is an uninterrupted motion. The swing of a bridge due to earthquake or wind and a shaking vehicle due to faulty wheels are typical vibration examples. The concept of vibration deals with the theoretical study of oscillatory movement of an object or body and the associated magnitude forces.

$$x(t) = X \cos(\omega t) \tag{2.4}$$

Where X stands for the amplitude of motion, ω is the motion frequency, and t represent the time. The existence of vibration implicates an alternative permutation of kinetic energy to potential energy and potential energy to kinetic energy. Therefore, an oscillating system must have an element that retains potential energy and an element that retains kinetic energy. The elements retaining kinetic and potential energies are called elastic component or spring and an inertia component or mass. The spring conserves potential energy and leaves it to the mass as kinetic energy, and it goes on inversely in each sequence of motion.

The uninterrupted motion linked with vibration is demonstrated through the movement of a mass on a flatter surface, as illustrated in figure 2.2. Linear spring is attached to the mass and is assumed to be at rest or equilibrium at the position 1. An initial displacement is attributed to the mass m at position 2 and released with zero velocity. The condition of the spring is in a maximum extension at position 2. Thus, the spring potential energy is a maximum one, and the mass kinetic energy is zero since the initial velocity is presumed to be zero. As the spring tends to return to its natural condition, there is a force that obliges the mass m to move to the left. The mass velocity will progressively rise as it displaces from position 2 to position 1. The spring potential energy at position 1 is zero since the spring deformation is zero. Nevertheless, the mass velocity and the kinetic energy will be maximum at position 1 due to the energy conservation if there is no energy dissipation caused by friction or damping since the velocity is maximum at position 1. In that case, the mass will move continuously to the left confronting the resisting force of compression of the spring. As the mass is subjected to an oscillatory motion, its velocity will progressively be reduced until it reaches a value of zero at position 3. The kinetic energy and the velocity of the mass will be zero at position 3. (Rao 2007.) Therefore, the potential energy and the compression of the spring will be maximum. Since the spring tends to return to its uncompressed state, there is a force that pushes the mass m to displace to the right from position 3. Thus, the total spring potential energy will be transformed into the mass kinetic energy at position 1, and the mass velocity will reach the maximum.

As noticed the motion of the spring is a repetitive motion, and when reaching position 2, this finalizes one cycle of the mass movement. The launched excitation could be the initial mass displacement leading to a vibrating system. Thus, the initial excitation places the system into the motion of oscillatory called free vibration. The system will come to rest if only it is given an initial excitation then the initial excitation is called transient excitation, and initial motion will be a transient motion. (Rao 2007.)

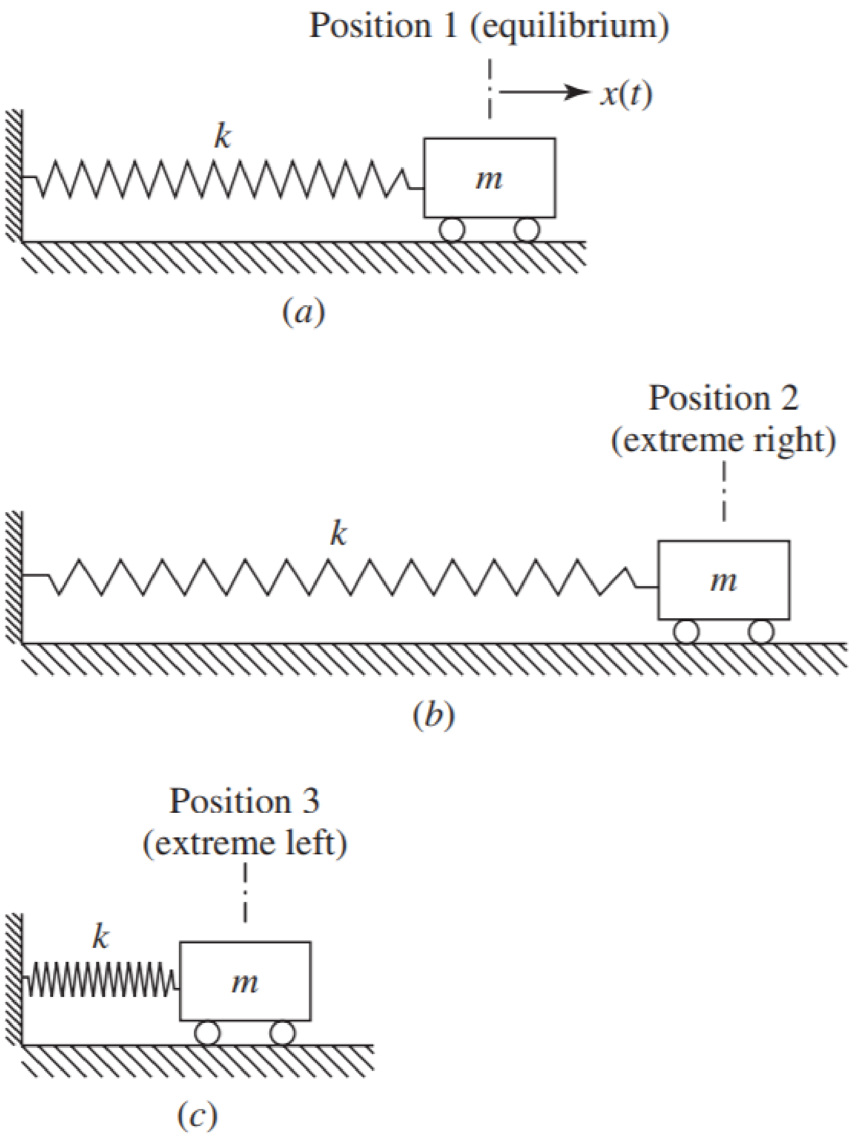


Figure 2.5. Vibratory motion of a spring–mass system. Single DOF: (a) system in equilibrium (spring undeformed); (b) system in extreme right position (spring stretched); (c) system in extreme left position (spring compressed). (Rao 2007.)

The equation shown in figure (2.6), is the equation of motion indicating the dynamics of a simple harmonic oscillation.

$$m\ddot{x} + kx = f(t) \tag{2.6}$$

In the Equation (2.6), m is the mass of the oscillating object, $\ddot{x}$ is the second time derivative of the displacement, x is the displacement from equilibrium position, k is the spring constant and $f(t)$ is the external force acting on the mass m. The externally applied force $f(t)$ triggers the oscillation motion of the system. When neglecting the externally applied force $f(t)$, the free vibration of the system is governed by the equation

$$m\ddot{x} + kx = 0 \tag{2.7}$$

Thus, by neglecting the externally applied force $f(t)$, the inertial and elastic forces located on the left-hand side of the equation (2.7) are studied. The study helps to determine the features of the structure. Therefore, by observing the motion illustrated in figure 2.5, it assumed that the motion is periodic of the form

$$x(t) = A\ sin(\omega_n t + \phi) \tag{2.8}$$

The selection is made because the sine function demonstrates the oscillation in equation (2.8). The constant A is the amplitude of the displacement, ω_n is the angular natural frequency, defines the gap in time during which the function repeat itself; ϕ is the phase, defines the initial value of the sine function. The frequency is measured in radians per second (rad/s), and the phase is measured in radians (rad). As derived in the following equation, the frequency ω_n is defined by the physical properties of mass and stiffness (m and k), and the constants A and ϕ are defined by the initial position and velocity as well as the frequency. To verify if equation (2.8) is a solution to the second-order differential equation, it is substituted into equation (2.7). A successive differentiation of the displacement, $x(t)$ in the form of equation (2.8), yields *the* velocity, $\dot{x}(t)$, given by

$$\dot{x}(t) = \omega_n A\, cos(\omega_n + \phi) \tag{2.9}$$

and the acceleration, $\ddot{x}(t)$, given by

$$\ddot{x}(t) = -\omega_n^2 A\, sin(\omega_n + \phi) \tag{2.10}$$

Substitution of equations (2.10) and (2.8) into (2.7) yields

$$-m\omega_n^2\, Asin(\omega_n t + \phi) = -kA\, sin(\omega_n t + \phi) \tag{2.11}$$

Dividing by A and m yields the fact that this last equation is satisfied if

$$\omega_n^2 = \frac{k}{m} \text{ or } \omega_n = \sqrt{\frac{k}{m}} \tag{2.12}$$

Thus, the solution to the second-order differential equation is the equation (2.8). The constant ω_n describes the spring-mass system, as well as the frequency at which the motion repeats itself, and hence is called the system's natural frequency. The associated units of the notation ω_n are rad/s and to differentiate it from frequency stated in cycles per second or hertz units (Hz), denoted by f_n which is frequently used in discussing frequency. Both are related by $f_n = \frac{\omega_n}{2\pi}$ or $\omega_n = 2\pi f_n$.

Then since $\omega_n = 2\pi f_n$, the frequency f would be given by:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{2.13}$$

Recalling that the period of vibration $T = \frac{1}{f_n}$

$$T = 2\pi\sqrt{\frac{m}{k}} \tag{2.14}$$

Thus, by knowing the spring constant k and the mass m, the period T can be calculated with the Equation (2.14). However, in the equations, the mass m and the constant of the spring k are intuitively dependent. (Lumen 2020.)

Recalling from differential equations that because the equation is of second order, solving equation (2.7) involves integrating twice. Thus, there are two constants of integration to evaluate. These are the constants A and ϕ. These are called initial conditions and when substituted into the solution (2.8) yield

$$x_0 = x(0) = A\, sin(\omega_n 0 + \phi) = A\, sin\, \phi \tag{2.15}$$

and

$$v_0 = \dot{x}(0) = \omega_n A \cos(\omega_n 0 + \phi) = \omega_n A\, cos\, \phi \tag{2.16}$$

Solving these two simultaneous equations for the two unknowns A and ϕ yields

$$A = \frac{\sqrt{\omega_n^2 x_0^2 + v_0^2}}{\omega_n} \quad \text{and} \quad \phi = tan^{-1}\frac{\omega_n x_0}{v_0} \tag{2.17}$$

as shown in Figure (2.15). Here the phase ϕ must lie in the proper quadrant, so care must be taken in evaluating the arc tangent. Thus, the solution of the equation for the spring–mass system is given by

$$x(t) = \frac{\sqrt{\omega_n^2 x_0^2 + v_0^2}}{\omega_n} \sin\left(\omega_n t + \ tan^{-1}\frac{\omega_n x_0}{v_0}\right) \tag{2.18}$$

This solution is called the free response of the system because no external force to the system is applied after $t = 0$. The motion of the spring–mass system is called simple oscillatory motion. The spring–mass system is also referred to as a simple harmonic oscillator, as well as an undamped single-degree-of-freedom system. Figure 2.19 illustrates the phase angle ϕ determined by equation (2.17). This right triangle is used to define the sine and tangent of the angle ϕ.

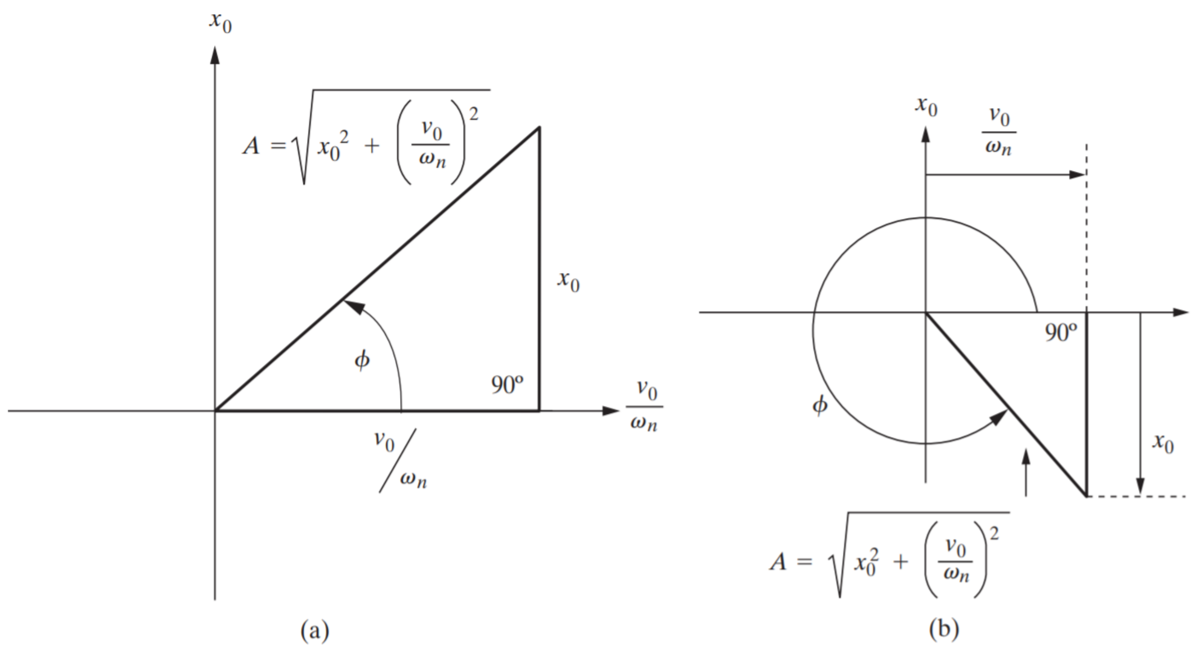
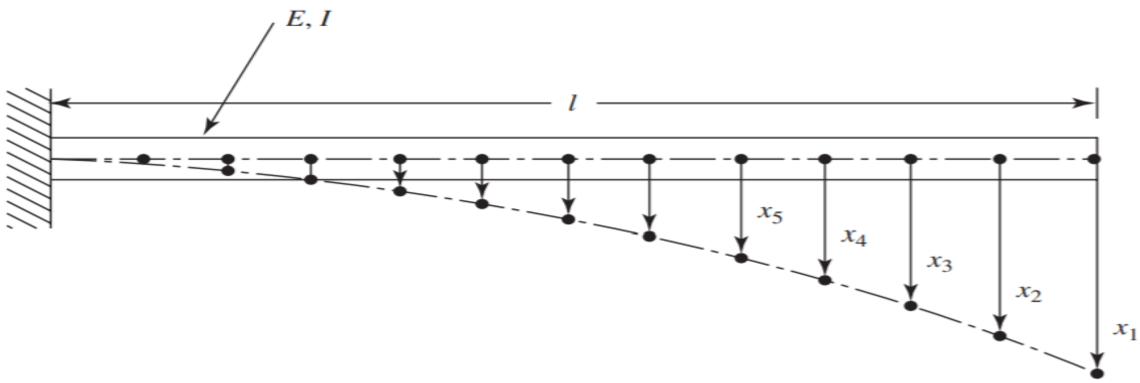


Figure 2.19. The trigonometric relationships between the phase, natural frequency, and initial conditions. Note that the initial conditions determine the proper quadrant for the phase: (a) for a positive initial position and velocity, (b) for a negative initial position and a positive initial velocity. (Inman 2014.)

2.4.1. Discrete and continuous systems

In practice, a significant number of mechanical systems are described using multiple-degree-of-freedom, such as the two-degree-of-freedom shown in figure 2.20.(c). Most systems that involve continuous elastic parts have an N number-of-degree-of-freedom or an infinite number-of-degree-of-freedom as the example of the cantilever beam illustrated in figure 2.20.(a). The cantilever beam has an infinite number of particles and it needs an infinite number of coordinates to define its deflection. Thus, its elastic deflection curve is defined by the infinite number of coordinates. As the cantilever beam, most machines and structures have an infinite number-of-degree-of-freedom since they have elastic parts as well.

Discrete or lumped parameter systems are systems with a finite number-of-degree-of-freedom and distributed or continuous systems are those with infinite number-of degree-of-freedom. Continuous systems are frequently approximated as discrete systems to simplify the solution process. Though processing a system as continuous gives accurate results, analytical methods to deal with the continuous system are narrowed to a few selections of problems, such as rods, thin plates, and uniform beam. However, various practical systems are analyzed as finite lumped masses, dampers, and springs. When increasing the number of springs, dampers, and masses, accurate results are obtained. Automatically, number-of-degree-of-freedom also increase. (Rao 2007.)



(a)

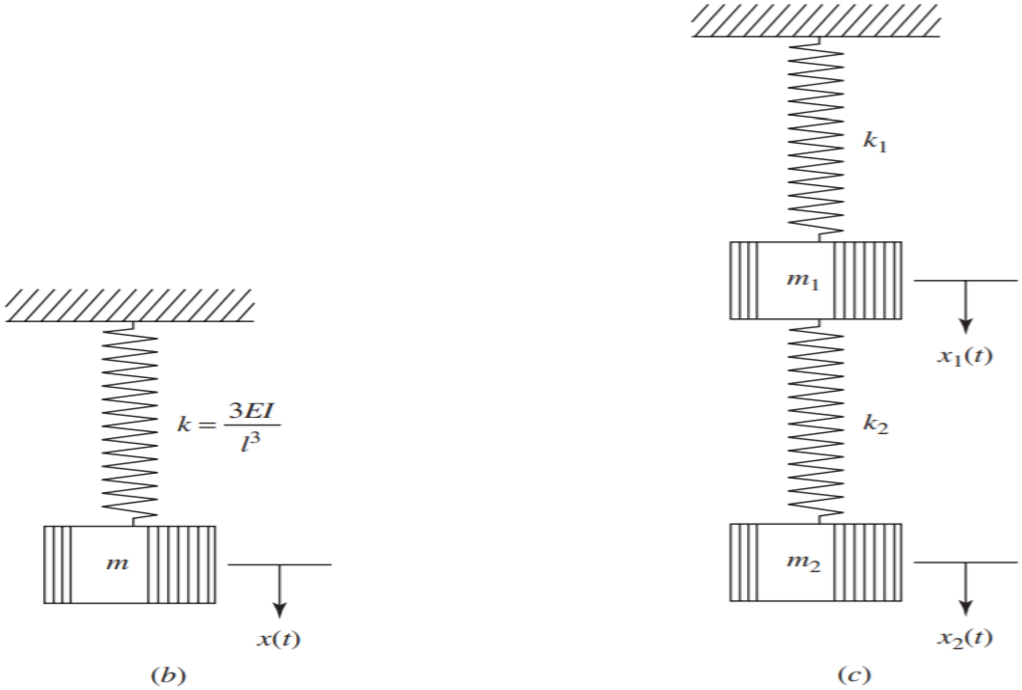


Figure 2.20. Modeling of a cantilever beam as (a) a continuous system, (b) a single-degree-of-freedom system, and (c) a two-degree-of-freedom system. (Rao 2007.)

For instance, the cantilever beam illustrated in figure 2.20.(a) can be seen as a single degree of freedom when assuming the beam mass to be positioned at the free end of the beam. The continuous flexibility to be seen as a simple linear spring, as illustrated in figure 2.20.(b) The accuracy can be improved by using a two degree of freedom model, as illustrated in figure 2.20.(c). The cantilever beam has a series of nodal points aligned across the structure. Each node has at least two-degrees-of-freedom in each nodal location. In general, finite element models consist of N numbers of degrees of freedom which can be excessive and difficult to solve. In a typical N degree of freedom system, the equations of motion are expressed by using matrix notation and the equations of motion describe the vibrational response. Thus, the equations of motion for the FE model is governed by the equation

$$\mathbf{M\ddot{u}} + \mathbf{Ku} = \mathbf{F} \tag{2.21}$$

In the equation (2.21), $\mathbf{M}$ is the mass matrix, $\mathbf{\ddot{u}}$ is the vector of accelerations; thus, the mass matrix and the vector of accelerations describe the inertial force with respect to nodal degrees of freedom.

K is a stiffness matrix, **u** is the vector of displacements and **F** is the externally applied force. The externally applied force is responsible for the dynamics motion of the structure. The features of the structure are studied by neglecting the externally applied force **F.** Therefore, the matrix equation for the FE model is governed by the equation

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{0} \tag{2.22}$$

However, solving vector $\ddot{\mathbf{u}}$ is crucial to have a proper track on the nodal displacement, and with the help of nodal displacement, the displacement at any specific location point can be obtained. On the other hand, a finite element model is generally composed of a large number of degrees of freedom, making it complicated to use direct integration approach. In Finite Element modeling, the number of coordinates is used to define the size of the Finite Element model. Although the use of more coordinates does not necessarily guaranty a higher accuracy of the modelling results, it is often conducive. Therefore, a two degree of freedom system can be described mathematically by

$$\mathbf{u} = \boldsymbol{\phi}\mathbf{P} \tag{2.23}$$

In the equation (2.23), $\mathbf{u}$ is the vector of generalized coordinates, $\boldsymbol{\phi}$ is the modal transformation matrix and $\mathbf{p}$ is the principal coordinates. Nevertheless, when the behavior of the modelled structure at low-frequency range is of interest, a much-reduced mathematical model will be preferred. Such a reduced model can be derived either from a modal model of the structure or from the original FE model using various modelling reduction algorithms. In both cases, the modal model is essential in the process or the evaluation of the final results. (He & Fu, 2001.)

Thus, using modal coordinates allows the number of variables to be reduced without a considerable loss of accuracy. In this stage, an eigenvalue analysis can be conducted. The physical examination of the eigenvalues and eigenvectors represent the natural frequencies and the associated mode shapes. The eigenvalue analysis can predict how the structure can behave, but it does not provide the final responses of the structure. However, the eigenvalue analysis is conducted by neglecting the externally applied force of a given system.

Assume that the solution $\mathbf{u}(\mathrm{t})$ is of the form

$$\mathbf{u}(\mathrm{t}) = \boldsymbol{\varphi}_{\mathrm{i}} e^{i\omega_i t} \tag{2.24}$$

The equation (2.24) is an introduction to the normal mode where $\mathbf{u}(\mathrm{t})$ is column vector, $\boldsymbol{\varphi}_{\mathrm{i}}$ is some constant n-vector, ω_i is the angular frequency and i is the imaginary number. Since the equation (2.24) has an irreducible form, it must be substituted into the equation (2.23) to lead to a standard eigenvalue problem. Thus, the substitution of the equation (2.24) to the matrix equation (2.23) gives this:

$$[\mathbf{k} - \omega_n^2\, \mathbf{m}]\boldsymbol{\varphi}_{\mathrm{i}} = 0 \tag{2.25}$$

In the equation (2.25), ω_n^2 is the eigenvalue (angular frequencies of the vibration) and $\boldsymbol{\varphi}_{\mathrm{i}}$ is the eigenvectors (mode shape of the vibration).

Thus, the eigenvalues are obtained by assuming the first part of the equation (2.25) to be equal to zero

$$|\ \mathbf{k} - \omega_n^2 \mathbf{m}\ | = 0 \tag{2.26}$$

The eigenvectors are characteristic vectors φ_i, which are also known as mode shapes of vibration. The mode shapes and eigenvalues are associated, they are natural properties of the structure in vibration, and they depend only on its mass and stiffness properties. To know the natural frequencies and mode shapes both (ω_n^2, $\boldsymbol{\varphi}_{\mathrm{i}}$) must be solved. The eigenpair (ω_n^2,$\boldsymbol{\varphi}_{\mathrm{i}}$) is solved by iteration, and only one of them is computed by iteration; the other can be obtained without further iteration. For instance, if the eigenvalue (ω_n^2) is obtained by iteration; the evaluation of the eigenvector (**$\boldsymbol{\varphi}_{\mathrm{i}}$)** can be done by solving the equation $[\mathbf{k} - \omega_n^2 \mathbf{m}]\boldsymbol{\varphi}_{\mathrm{i}} = 0$.

Figure 2.27 illustrates four modal shapes of a cantilever beam associated with its natural frequencies. The structure is fixed at the bottom left-hand side.

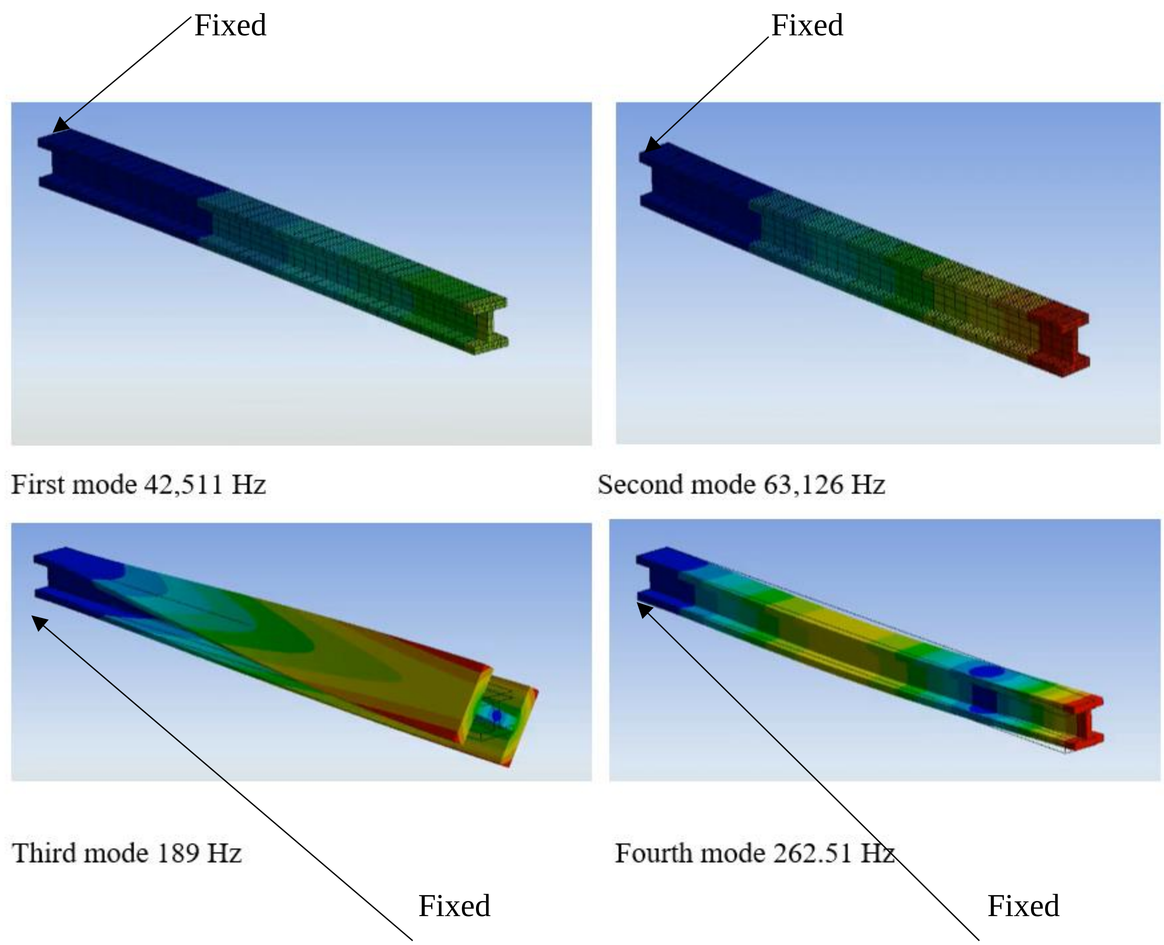


Figure 2.27. Mode shapes of a cantilever beam with some of its natural frequencies. (ANSYS 2019.)

2.5. Experimental methods and equipment used in monitoring of vibration

The fundamental characteristics of vibration scheme are shown in figure 2.28. The motion of the vibrating structure is converted into an electrical signal by a pickup or vibration transducer. The motion is measured by mounting the transducer sensor on a vibrating structure or machine. Then a vibratory motion is measured by finding the displacement of the mass relative to the base on which it is mounted. Typically, a transducer device transforms variation in mechanical quantities such as force, displacement, velocity, and acceleration into variation in electrical quantities such as current or voltage. The most used transducer is the piezoelectric sensor (accelerometer). Since the transducer output signal (current or voltage) is insufficient to be recorded immediately, an instrument converting the signal is utilized to amplify the signal to the needed value. In general, the signal conversion instrument has an embedded display unit for visual inspection and a recording unit that records vibration activities which can be stored in the computer for later use. Then, Data can be analyzed to define the requested vibration characteristics of the structure or machine. Depending on the quantity measured, a vibration measuring instrument is called an accelerometer, a velocity meter, a frequency meter, phase meter, or a vibrometer. In some applications, the structure or machine must be put under vibration condition to find its resonance features. for such applications, electrohydraulic vibrators, oscillators, and electrodynamic vibrators are used.

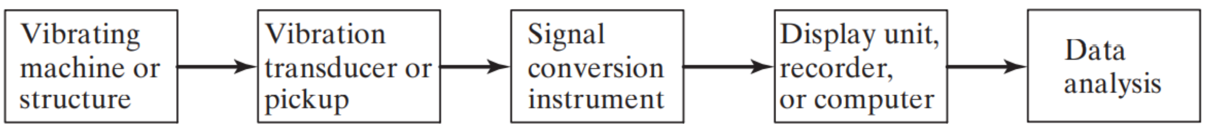


Figure 2.28. Basic vibration measurement scheme. (Rao 2011.)

Thus, the type of vibration measuring instruments to be used in the vibration test are imposed by the following considerations:

1. The expected ranges of the frequencies and amplitudes
2. sizes of the structure/machine involved
3. conditions of operation of the structure/equipment/machine
4. type of data processing used (such as graphical recording or graphical display or storing the record in digital form for computer processing).

The dynamic testing of structures or machines implies finding their deformation at a critical frequency. The dynamic testing can be accomplished using the operational deflection-shape measurements and the experimental modal analysis.

In the operational deflection-shape measurement techniques, the forced dynamic deflection-shape is measured under the operating frequency of the system. The dynamic deflection-shape measurement is done by placing an accelerometer at a certain point on the structure (machine) as a reference. Another moving accelerometer is mounted at multiple other points, and in different directions, if needed. Therefore, the phase differences and the magnitudes between the reference and moving accelerometers at every point under steady-state operation of the system are measured. When the measurements are plotted, the motion of several parts of the structure (machine) relative to one other are fund. The measured deflection-shape is valid only for frequency and forces combine with the operating conditions. Measuring deflection-shape can be crucial. For instance, if a specific location or part has excessive deflection, the location or part can be reinforced.

The experimental modal analysis techniques as shown in figure 2.30, it is also known as modal testing or modal analysis, deals with the determination of mode shapes, natural frequencies, and damping ratios via vibration testing. During the dynamic test, a structure or any system is excited, and its response displays a high peak at resonance when the applied frequency matches the natural frequency. Therefore, requiring hardware to perform vibration measurement is the following:

1. A source of vibration or exciter applying an input force to the machine or structure.
2. A transducer for converting mechanical motion of the machine or any other system into an electrical signal
3. A signal conditioning amplifier to make the transducer features compatible with the electronics input of the digital data acquisition system.
4. The analyzer to execute modal analysis and signal processing tasks with the help of appropriate software.

2.5.1. Exciter

The exciter can be an impact hammer or an electromagnetic shaker. The electromagnetic shaker as illustrated in figure 2.26 can supply high input forces to facilitate response measurement. Also, if is of electromagnetic type, its output can be easily controlled. However, the excitation signal is often of a random type, or a swept sinusoidal input, a harmonic force of magnitude F is applied at several discrete frequencies over a define frequency range of interest. The structure or any system is conceived to attain a steady state before the magnitude and response phase are measured at each discrete frequency. The mass of the shaker will influence the measured response if the shaker is attached to the machine (structure) being tested.

Figure 2.29. An exciter with a general-purpose head. (Bruel and Kjaer Instruments 2011.)

Therefore, proper treatment should be taken to reduce the mass effect of the shaker. In general, the shaker is attached to the machine through a stringer (small thin rod) to minimize the added mass, to isolate the shaker, and apply the force to the machine (structure) across the stringer axial direction. It will enable the control of the force direction applied to the machine (system). To excite a wide frequencies range without generating the problem of mass loading, the machine (structure) is hit with the impact hammer. However, the impact hammer causes nearly proportional impact force to the impact velocity and the mass of the hammerhead, which can be found from the force transducer built-in in the hammerhead.

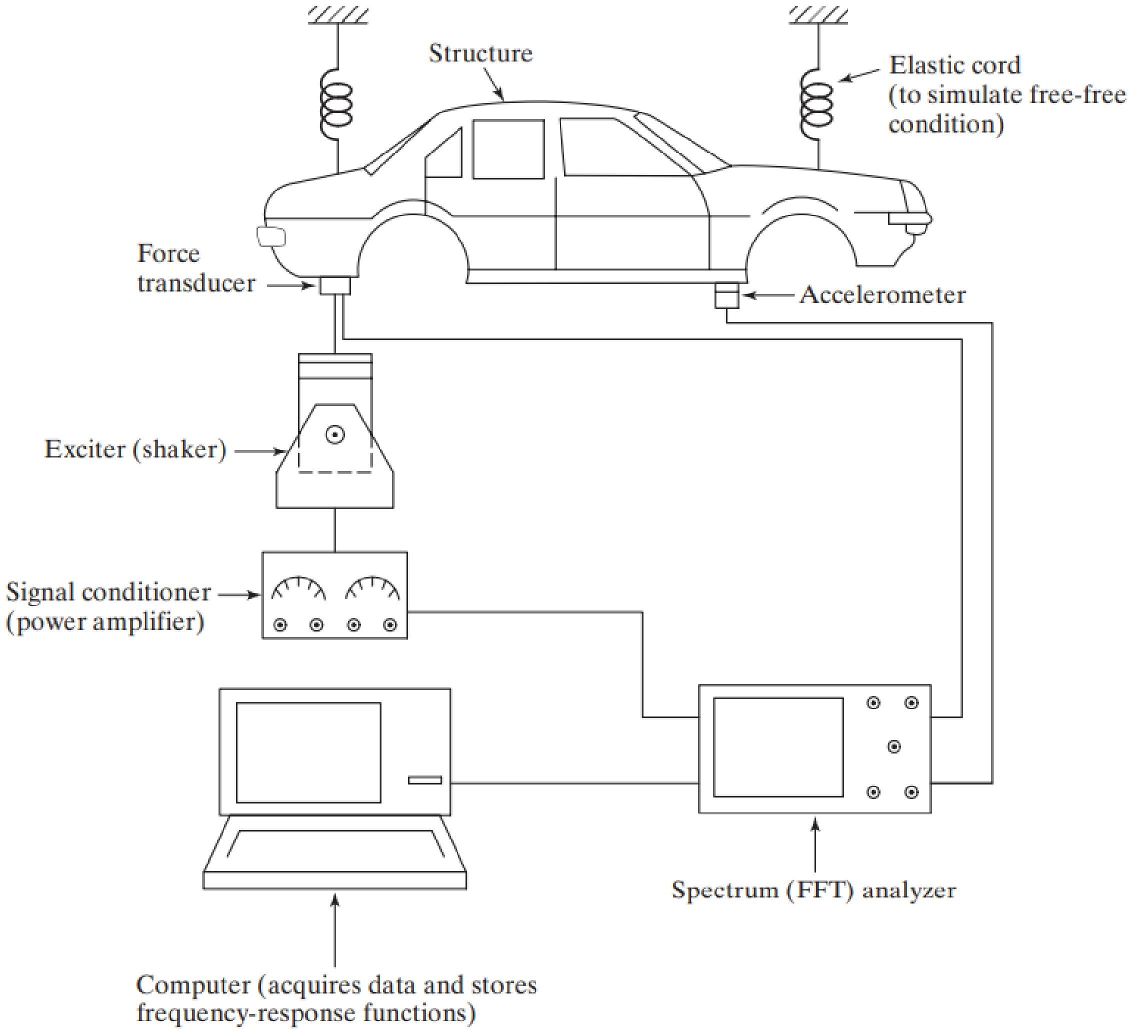


Figure 2.30. Experimental modal analysis. (Rao 2011.)

Though the impact hammer is inexpensive, simple, portable, and more straightforward to use than a shaker, it is usually not able to transmit enough energy to gain sufficient response signals in a frequency range of interest. The typical frequency response of a machine (system) is illustrated in figure 2.32. The frequency shape response depends on the mass and stiffness of the structure (system), and the impact hammer. In general, the excitation frequency range is limited by a cut-off frequency ω_c, which indicates that the machine (system) did not receive enough energy to excite modes beyond ω_c. The impact hammer as shown in figure 2.31 has an embedded transducer in the head, and among transducers, the piezoelectric transducers are most popular. A piezoelectric transducer can be conceived to produce signals proportional to either acceleration or force. In an accelerometer, the piezoelectric material acts like a stiff spring that causes the transducer to have a natural frequency or resonant. Often, the maximum measurable accelerometer frequency is a fraction of its natural frequency. Strain gauges can also be used to measure the vibration response of a machine (system).

Figure 2.31. Impact hammer type 8206. (Bruel and Kjaer 2019.)

2.5.2. Signal Analyzer

After conditioning, the response signal is sent to a signal analyzer for signal processing. The Fast Fourier Transform (FFT) analyzer type is the most used. The analyzer receives the analogue voltage signals (displacement, velocity, acceleration, force, or strain) from a filter, signal conditioning amplifier, and digitizer for computations. The analyzer calculates the discrete frequency spectra of individual signals as well as cross-spectra between the input and the different output signals. The mode shapes, natural frequencies and damping ratios are found by the analyzed signals in either graphical form or numerical form. It is recommended to calibrate all equipment before use. For instance, the impact hammer is often used in experimental stress analysis, since it is faster and practical to use than a shaker. (Rao 2011.)

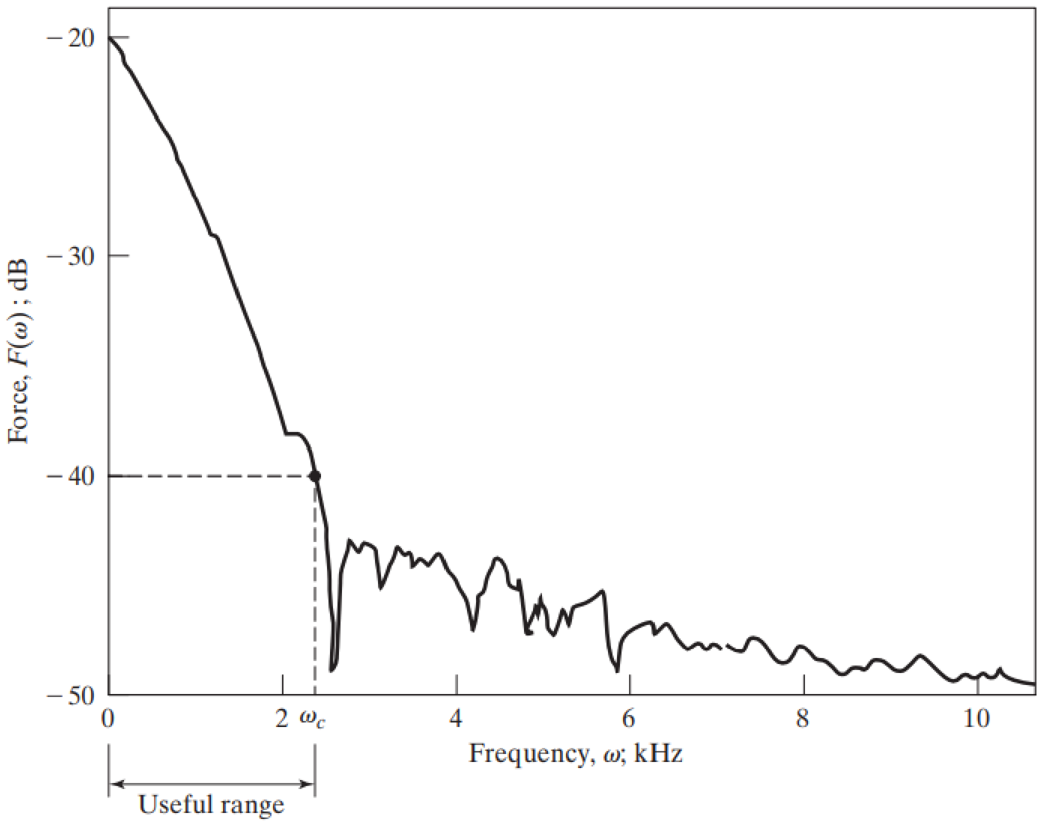


Figure 2.32. Frequency response of an impulse created by an impact hammer. (Rao 2011.)

2.6. Condition monitoring and failure prediction by vibration measurements

Generally, vibration condition monitoring refers to predictive maintenance, an acceptable approach to improve productivity and reliability in many industries. In this context, technology is used to evaluate and measure the condition of machines and equipment, allowing smart decisions in the maintenance process. Several industrial sectors are integrating vibration condition monitoring techniques to reduce the maintenance cost, to increase production efficiency, and industrial safety. Some medium and small-scale industries are implementing preventive maintenance but could not apply predictive maintenance to practice. Vibration condition monitoring is a process of monitoring a parameter of condition in machinery.

With this method, progressive failure tracking of machinery is proceeded by detecting a significant change in the machine behavior that can lead to failure. The vibration condition monitoring techniques enables to schedule the maintenance or to take other actions to avoid failure consequences before the arising of failure, which is generally cost-effective than allowing the machinery to break down. However, predictive maintenance services have been increasing steadily over the past decade, mainly supported by recent technology enabling the collection of data. Many engineering companies have begun to provide predictive maintenance to various companies in need of improving their profit margins, and machine life cycle around the globe. (Mobius Institute 2019.) Some of the predictive maintenances are done manually by mounting sensor transducers on the machine to be measured.

2.6.1. Vibration sensor mounting position

Measuring vibration depends on the way machines are installed in the factory. Nowadays, companies are switching from traditional measuring systems to IoT (Internet of things) for better vibration monitoring. The below pictures illustrate the way sensors can be placed on the machine to measure vibration. The desired measuring direction should coincide with the vibration sensor main sensitivity axis. When positioned in the transverse direction, a vibration sensor can be a bit sensitive to vibrations. But this can typically be ignored as the transverse sensitivity generally is less than 1% of the main axis sensitivity. The picture below illustrates the right position to mount a vibration sensor on a bearing for measuring vibration. In this example, acceleration measurements are being used to monitor the running condition of the bearing and shaft. (Mobius Institute 2019.)

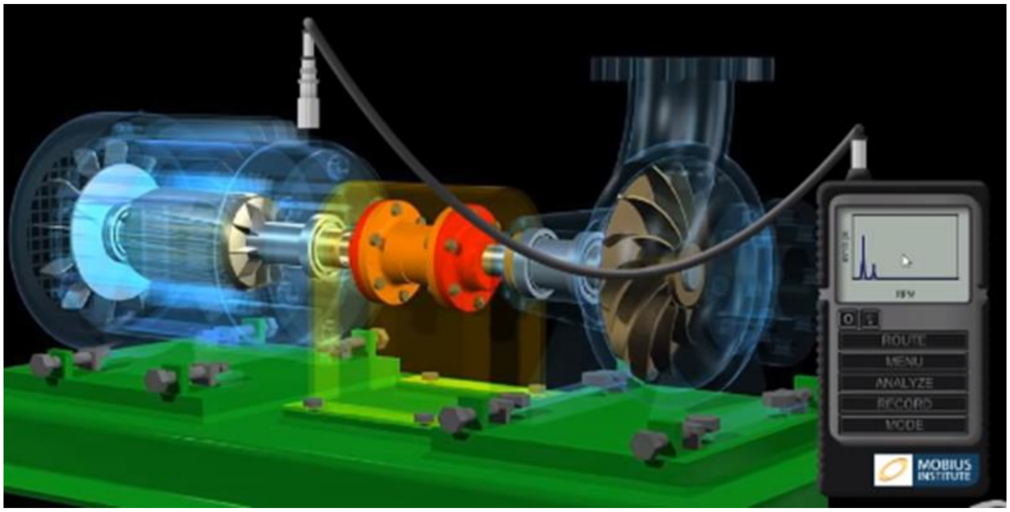


Figure 2.33. Radial vibration measurement. (Mobius Institute 2019.)

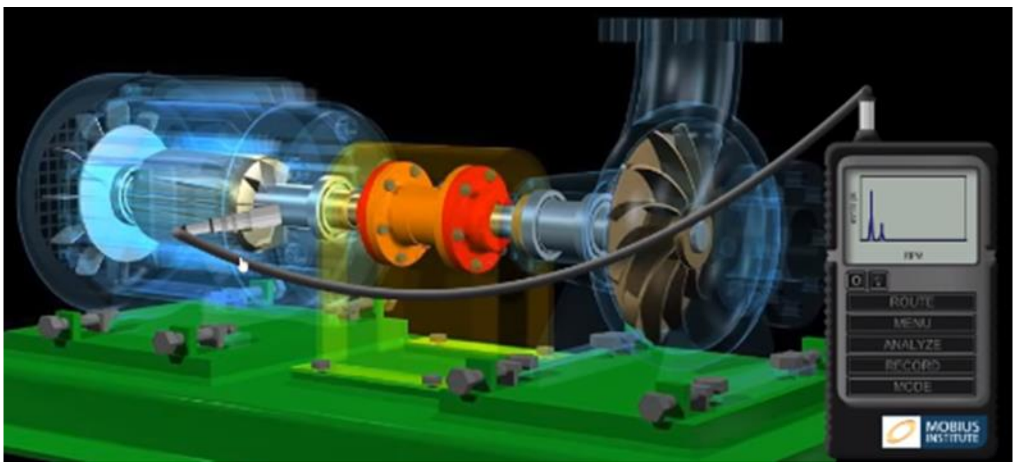


Figure 2.34. Vibration radial measurement. (Mobius Institute 2019.)

The vibration sensor must be mounted to keep a direct path for the vibration from the bearing. At high frequencies, a mechanical response objects to forced vibration can be a complex phenomenon to measure. However, a vibration sensor mounting method to the measuring point is a crucial factor for getting accurate results from vibration measurements.

The device should be mounted onto a smooth and flat surface, as shown in the drawing. If establishing permanent measuring points on a machine, drilling and tap fixing holes are not recommended. Instead, cementing stud can be used. The vibration sensor is attached to the measuring area with the recommended adhesives. Epoxy and cyanoacrylate are preferable than soft adhesives as they can considerably alter the collected frequency information of the v. sensor. (Mobius institute 2019.)

The v. sensor should be electrically isolated from measuring machine. Thus, a mica washer is used for separating the v. sensor body from electrical sources and prevent ground loops. A permanent magnet attachment can also be an effective method to isolate the v. sensor body electrically from measuring objects. These technics reduced the resonant frequency of the v. sensor to about 7 kHz and consequently cannot be used for measurements above 2kHz. The grabbing force of the magnet is enough for vibration levels up to 1000 to 2000 m/s2 depending on the size of the v. sensor. (Mobius institute 2019.)

2.6.2. Environmental influence on the vibration sensor

The v. sensor can withstand temperatures up to 250-degree Celsius. The piezoelectric ceramic will naturally start to depolarize at a higher temperature, damaging its sensitivity permanently. This type of devices can still be operational after calibration if the depolarization is not so serious. V. sensors with unique built-in piezoelectric ceramics are available and can tolerate temperature up to 400 degree Celsius. Therefore, all piezoelectric materials are temperature dependent. An extreme variation of heat will result in a modification of a v. sensor's sensitivity.

Thus, piezoelectric v. sensor also shows a changing output when exposed to low-temperature variations called temperature transients, in the measuring point. This is usually only an issue where very low-frequency vibrations are being measured. When v. sensor is to be mounted to surfaces with a temperature above 250 °C a mica washer and heat sink can be placed between the measuring surface and the base. With temperature fluctuating around 350 to 400-degree Celsius, the v. sensor base temperature can be maintained below 250 °C by this method. (Brüel & Kjær 2008.)

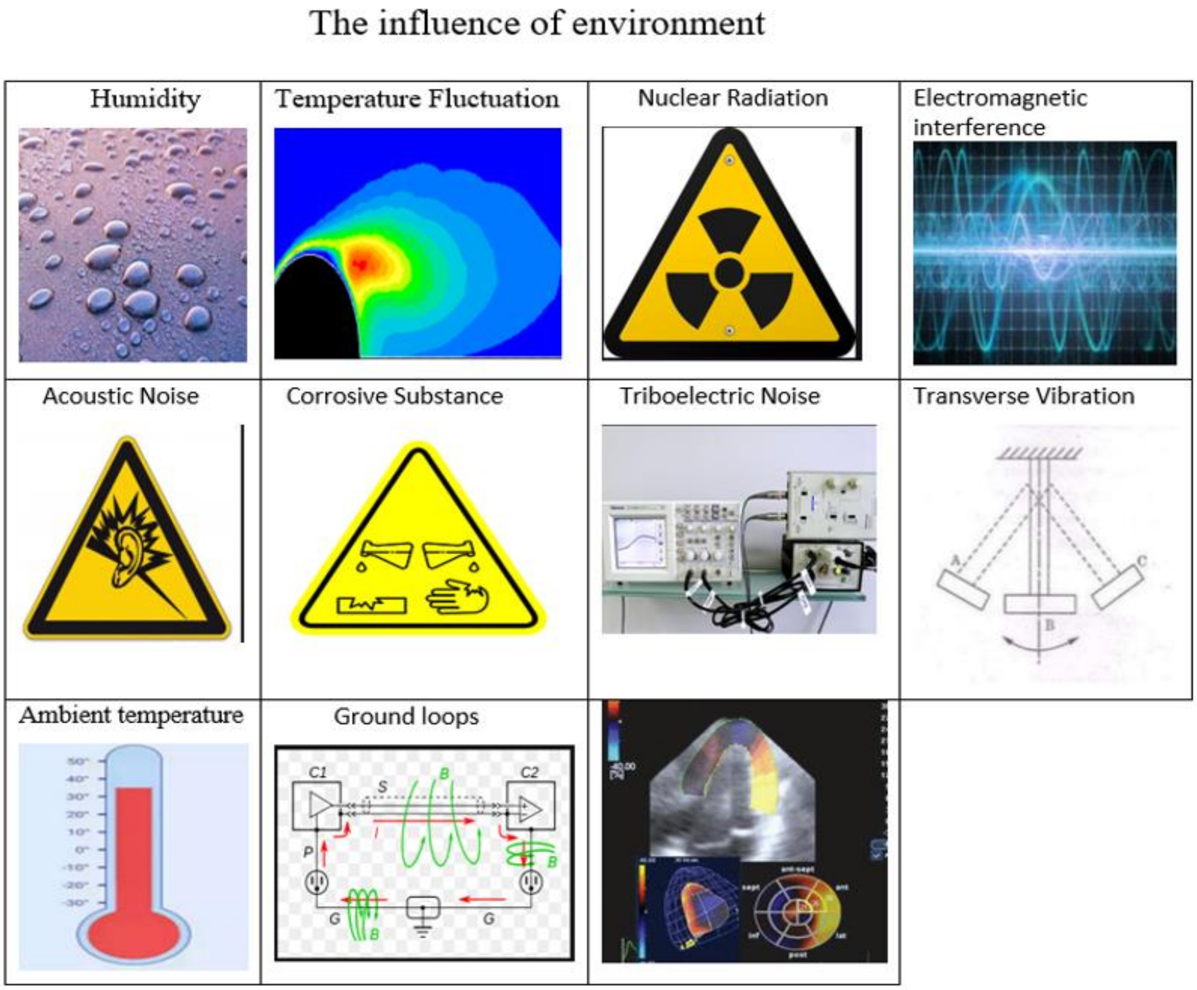


Figure 2.35. influence of environment. (Free google pictures 2017.)

Traditionally, piezoelectric v. sensors have a significant output impedance, and noise signals produce in the connecting cable may sometimes be a problem. These disturbances can arise from ground loops, electromagnetic noise or triboelectric noise. The measuring equipment and the v. sensor are earthed separately. Thus, causing ground loop currents sometimes flow in the shield of v. sensor cables. The noise can also be considered as a disturbing element. Fortunately, the noise levels present in machinery are usually not so high to produce any important error in vibration measurements. Generally, the acoustic vibration produces in the structure on which the v. sensor is placed, it is far better than the air-born excitation. And also, piezoelectric v. sensor is affected by vibration acting in opposite directions that do not coincide with their main axis (Brüel & Kjær 2008.)

2.6.3. Importance of dynamic variables in vibration sensor

The seriousness of the vibration is defined by measuring the displacement, velocity, and acceleration properties; these are frequently present as the amplitude of the vibration. Thus, the vibration amplitude indicates the state of rotational machinery, and usually, higher vibration amplitudes relate to a higher level of a machine fault. However, the connection between acceleration, velocity, and displacement concerning machinery health and vibration amplitude redefines the data analysis techniques and the measurement that should be used.

Typically, motion below 10 Hertz generates minimal vibration regarding acceleration, average vibration concerning velocity, and relatively large vibrations regarding displacement. Hence, displacement is applied in this range. Acceleration values mostly yield essential values in the high-frequency range than velocity and displacement. At frequencies above 1000 hertz, the available measurement unit for vibration is acceleration. These signals picked from the vibration sensor are displayed on the vibration analyzer screen in a sinusoidal form called waveforms. The sinusoidal signals can be converted from time domain to frequency domain with the help of mathematical differentiations called Fast Fourier transform (FFT). (Tom 2015.)

2.6.4. Vibration behavior on components

2.6.4.1. Time waveform analysis on rotating machinery

The time waveform can be confusing and complicated to analyze, but it reveals all type of fault conditions that can be disregarded. Thus, the time waveform resembles a camera recording different sort of activities taking place inside the machine. As the teeth meshed together, the balls rolling inside the bearing and all clashes that happen during machine operation. (Universal technologies 2015.)

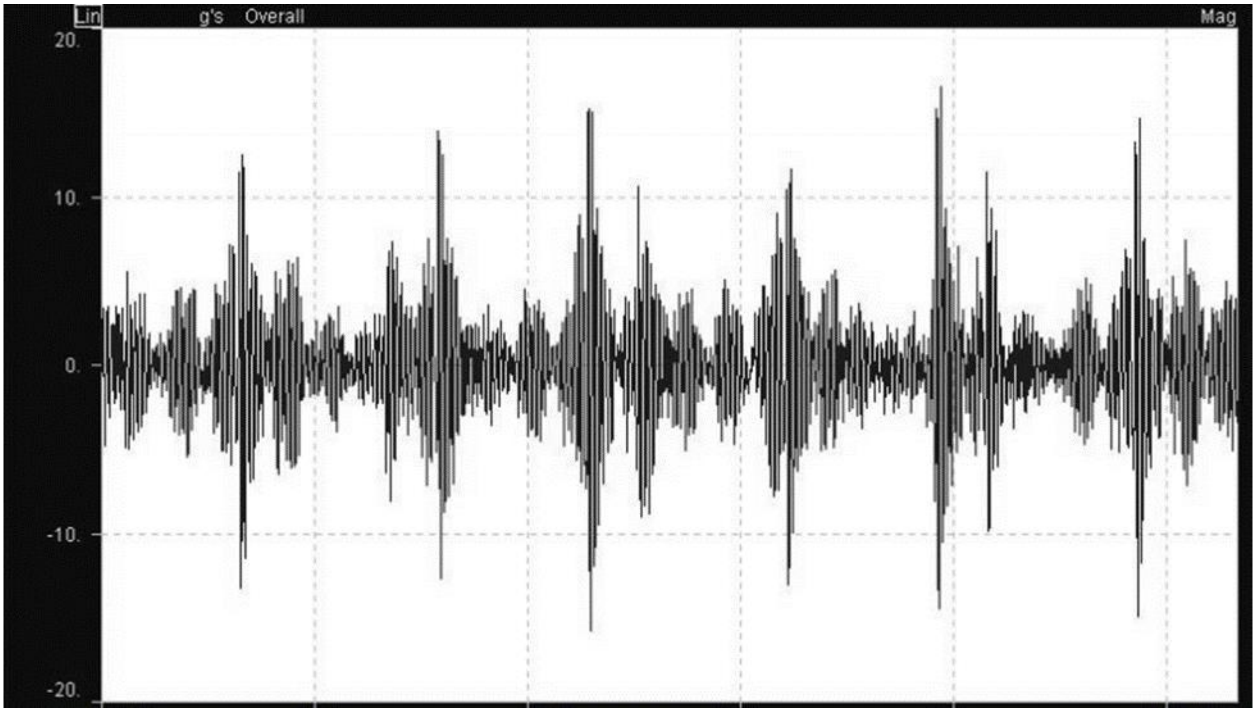


Figure 2.36. Time waveform. (Universal technologies 2015)

2.6.4.2. Time frequency analysis on rotating machinery

The FFT (Fast Fourier transform) was invented in the mid-1960, and it made possible the invention of a modern real-time spectrum analyzer. The vibration analyzer equipped with the FFT algorithm processes time-varying signals from the time domain into the frequency domain. (Adams 2001.) The mathematical foundation for spectrum analysis is the Fourier integral, which was elaborated by the mathematician Joseph Fourier in the early 1800s, century before modern rotating machinery. However, the practical aim of a Fourier transform is that a function can be built from the addition of sinusoidal functions with an uninterrupted distribution of frequency from zero to a suitable cut-off frequency.

Furthermore, some measurements can be challenging to read in the time domain but can be easily understood in the frequency domain. Various harmonic distortion of the sine waves is hard to quantify by looking at the vibration analyzer display. When the same signal is displayed on a spectrum analyzer, the amplitudes and harmonic frequencies are displayed with outstanding clarity. The vibration analyzer collects all sort of vibration activities happening within a dynamic machine and displays them in the form of sine waves. Thus, the sine waves usually look chaotic, and the frequency domain sorts out the sine waves to enable a better understanding. The picture below shows an illustration of a time domain and a frequency domain on a three-dimensional surface area. (Adams 2001.)

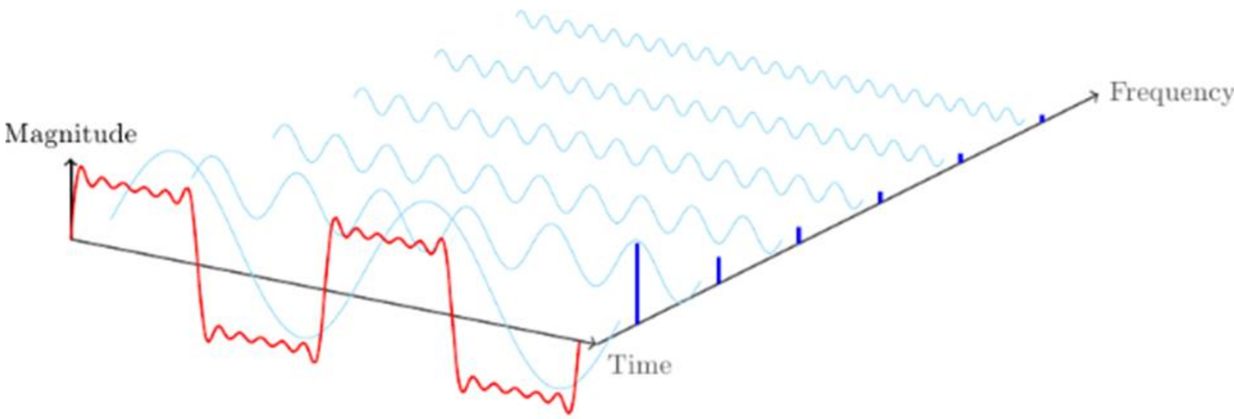


Figure 2.37. time domain vs frequency domain illustration. (Mobius institute 2018.)

Thus, with the Fast Fourier Transform (FFT) algorithm, the vibration analyzer can quickly detect faults in rotating machinery. The following section on “Elements fault monitoring” will develop more about faulty bearing, and other elements of rotating machinery for better understanding of the techniques used to detect faults. (M. Institute 2018.)

2.7. Importance of using vibration monitoring in industry

Some factories still operate with a run to failure maintenance approach. In this method, eventually, actions are not taken until machinery breaks down. The maintenance runs from one issue to another. Production losses and maintenance costs are significant. Many plants have transitioned to calendar-based or preventive maintenance. Actions are scheduled regardless of the actual condition of the equipment. With this approach, fault-free machines can be repaired unnecessarily, leading to higher program costs. With condition monitoring maintenance, machines are measured using vibration analysis, which does not require dismantling a machine to determine its condition. When a machine condition fault comes up, a repair is scheduled when needed - not before and not too late.

2.7.1. Elements fault monitoring

2.7.1.1. Bearings

Rolling elements bearings are widely used in most rotating machinery. From the day Philip Vaughan created the first modern bearing in 1794 until now rolling element bearings are gaining in popularity in various applications such as jet engines, turbines, power plants, aircrafts, robots, and automobiles. However, these components are considered as the most crucial elements playing a significant role in the life of the machinery and its health in the new production method.

Nowadays, the increase in demand for nonlinearity and accuracy required in such systems intensifies the competition in the western environment, and strict requirements on the bearings increase every day. Generally, bearings are system conceived to transmit loads between shaft and housing while providing rotation and relative position freedom. Rotating machineries are sophisticated and have many components that could potentially fail at any time. (Saruhan 2011.)

Eventually, analysis is required to predict bearings defects before damage occurs with the associated costly downtime and the probability to engage failure to other parts of the system. Rolling element bearings emit vibration and noise in the machinery even if they are in good shape. The generation of vibration in the bearings is caused by a phenomenon called variance compliance. The vibration level of the bearing increases when there is a presence of a local defect. The defect zone generates significant vibration when in contact with other elements.

Bearings used under normal conditions will face failure over time caused by the degradation of the material due to rolling fatigue. Typically, the life curve of bearings is expressed as the total number of revolutions or again as a period before failure occurs in the outer ring, inner ring or rolling elements. Lubrication in bearings is the first cause of failure followed by fatigue, installation and contamination. Fatigue occurs when there is an excessive load on the bearing, and when increasing the speed, the load must be monitor carefully to avoid bearings life's reduction. (SarÕdemir 2008.)

2.7.1.2. Bearing fundamental frequencies

Vibrations generated from rolling elements when passing over a defected surface on either the raceway or the roller are called fundamental fault frequencies. The vibrations are a function of the bearing geometry, which is the roller diameter, the pitch diameter and the relative speed between both raceways. At the horizontally oriented machine, for an outer race bearing fault, there are harmonics at the ball pass frequency outer (BFPO). The harmonics are naturally lower than the fundamental harmonic of the ball pass frequency outer. When bearing geometry is known, the formulated below equations can be used to calculate the fundamental fault frequencies. (Rolling bearing analysis).

As the bearing degrades, the amplitude of the harmonics will rise in amplitude to be larger than the fundamental harmonic of the BPFO. For an inner race bearing fault, the spectral frequency content also displays harmonics of the ball pass frequency inner (BPFI) along with sidebands of the shaft turning speed. These sidebands are observed at the fundamental and harmonic frequencies. As the shaft spins, the inner race fault will rise and fall as it moves through the loading area of the bearing.

The sidebands are formed due to amplitude alteration of the inner race bearing fault signal. This phenomenon is known as amplitude modulation (AM). For a rolling element bearing fault, the fault may be observed at the ball spin frequency (BSF) fundamental frequency. Since the fault of the rolling element will impact the inner and outer race per revolution of the shaft, the peak magnitude may be at twice the BSF frequency. Also, there will be sidebands around the BSF harmonics, but the sidebands will be generated at the fundamental train frequency (FTF), also known as the cage frequency. The rolling element bearing fault travels through the bearing load area with the integration of the cage rotation. (Tom 2015.) The illustration of the rolling elements bearing can be seen below in Figure 2.17 and it is just a basic illustration of vibration analysis for machinery diagnosis. In practice, many variables must be considered.

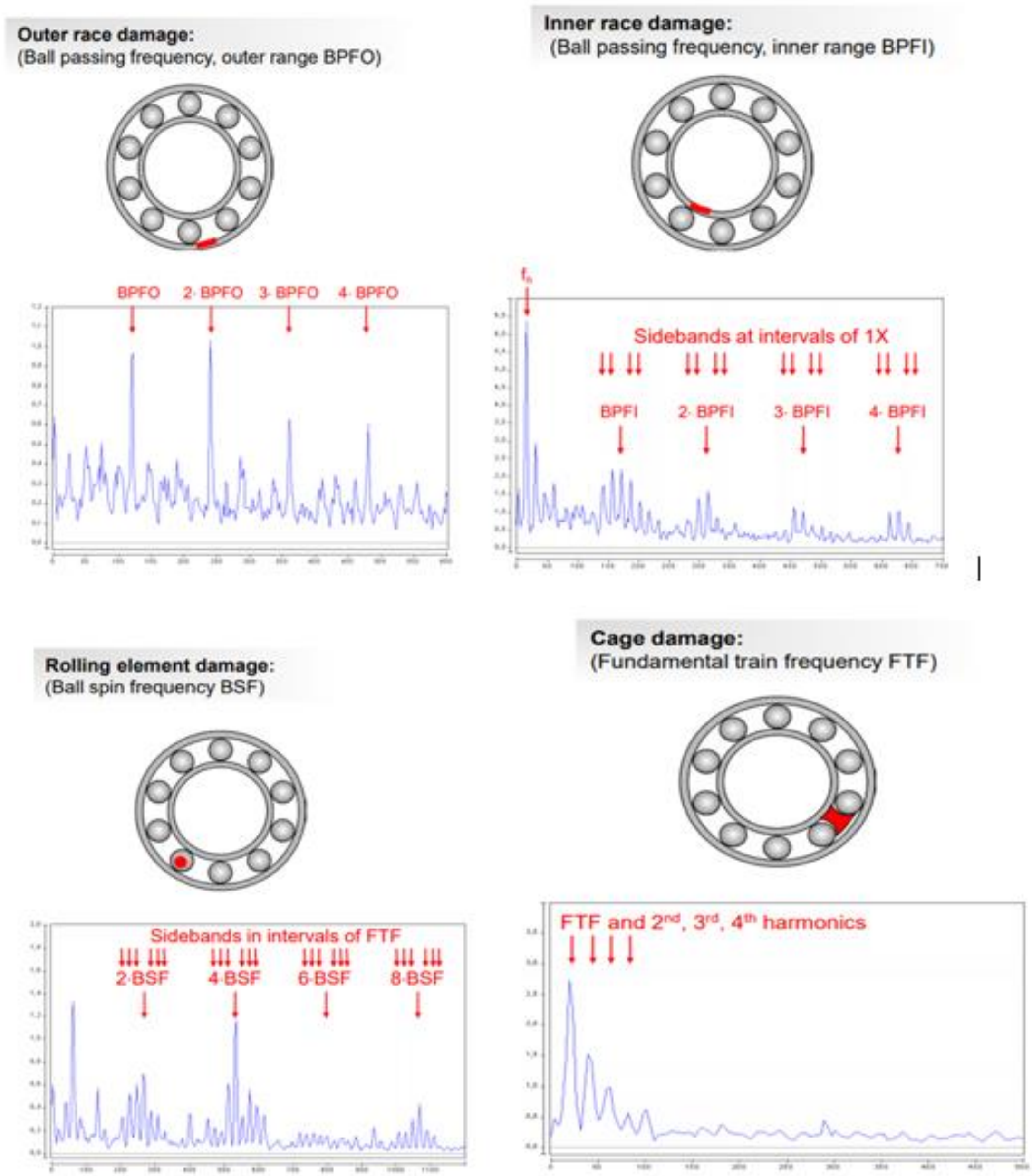


Figure 2.38. Rolling elements bearing damage. (Pruftechnik 2013.)

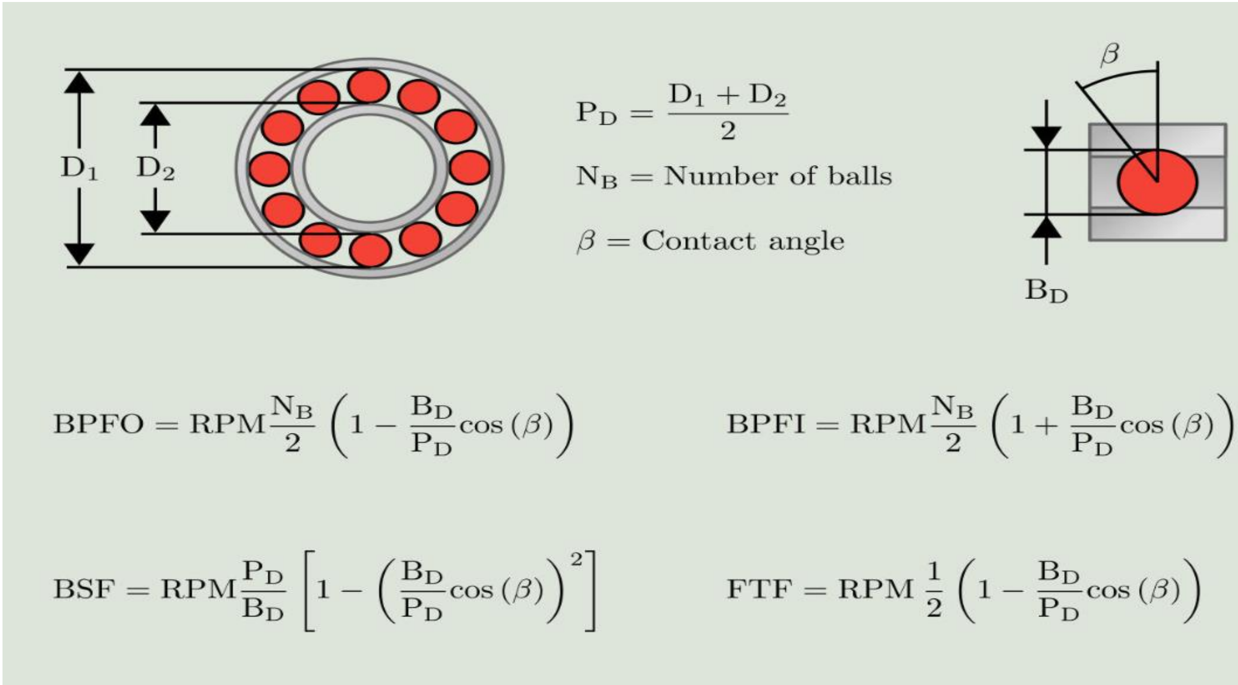


Figure 2.39. Rolling elements bearing failing frequency. (Alfonso Fernandez 2017.)

BD = Diameter of the ball NB = Number of balls BPFO = Ball pass frequency outer

PD = Pitch diameter BPFI = Ball pass frequency inner

BSF = Ball spin frequency FTF = Fundamental train frequency

2.7.1.3. Damaged inner race of a bearing

In rotating machinery, bearing failure is one of the most reason for the breakdown. Such failure can result in a severe financial consequence for a company. The picture below illustrates a damage rolling element revolving out of the load zone and going down into the load zone in the machine and simultaneously, the analyzer displays the reaction produced by this event in time waveform. Therefore, in the load zone is where the amplitudes are the highest, which means at that time, the rolling element takes the weight of the machine. The magnitudes are lower out of the load zone, and the arrow shows the area where the impacts are weaker. Time waveform indicates the nature and the severity of the fault conditions by measuring the acceleration of the vibrations in G's (Pruftechnik Engineers Guide 2017.)

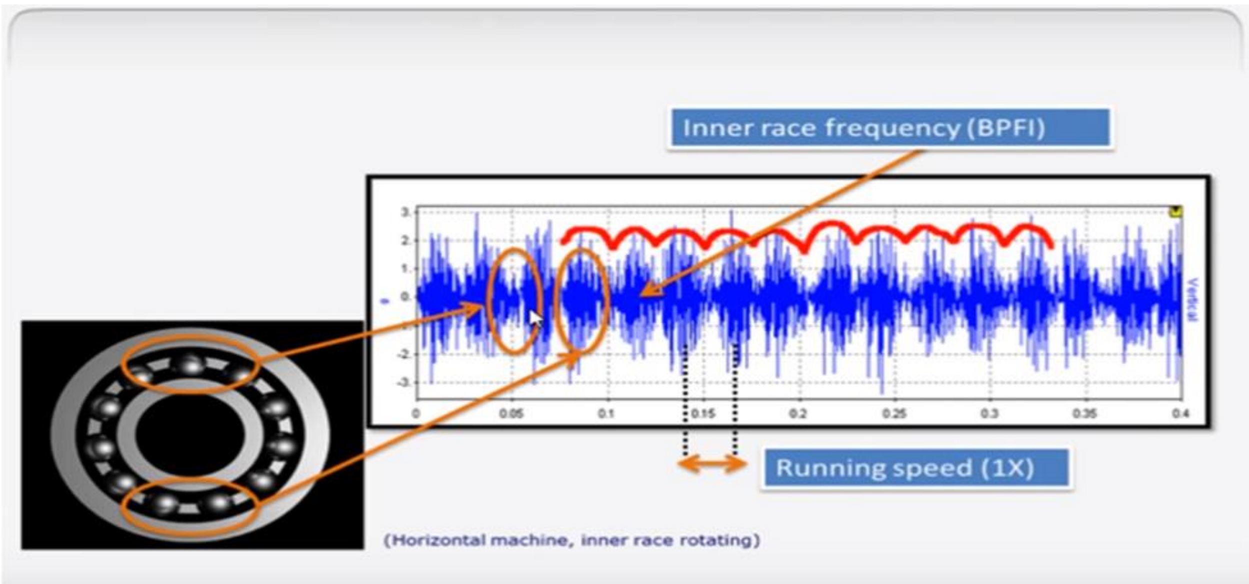


Figure 2.40. Bearing inner race damage. (Mobius institute 2018.)

2.7.1.4. Gear misalignment

Gears are intensively used to transmit power in machines from a shaft to another, generally with a variation of torque and speed. Multiple elements influence the dynamics of gears as the bearing forces, and the gear profile geometry has a decisive impact on the vibration behavior. Consequently, torsional vibration is less considered than flexural vibration since flexural vibrations in the system are immediately transferred to the housing through the bearings.

In reality, the circumstance is not ideal, as the teeth shapes deform under pressure initiating transmission error or meshing error, despite the tooth profiles perfection. Traditionally, gears coupling produce vibration, and when gears are in excellent mechanical condition, the correlating vibration signal could be utilized as a reference signal. If failure arises to one of the gear elements during machine operation, the defective gearbox could result in severe damage. The vibration frequencies variation often indicate that the condition of the pair meshing is changing.

Gearbox misalignment is known among the primary source of gearbox failures. It can reduce machine performance, and lower the operating life of the motor, driven equipment and gearbox. Appropriate coupling between the motor shaft, the gearbox shaft, and driven piece of equipment such as actuator or conveyor indicate that the shafts are collinear because they are arranged in a straight line. Shaft misalignment can be angular or parallel also referred as offset misalignment. Poor gearbox installation and setup often result in misalignment.

If the alignment is within the approved tolerances during installation, probably, the environmental and operating conditions can cause the shafts to shift out of the alignment. There is various phenomenon that can cause shaft misalignment. For instance, the transmission of power through gearbox and load produced during operation can cause deflection of the shafts or other gearbox components. Contraction and expansion of the shafts or gearbox components is due to thermal effects, resulting in shafts misalignment. In some cases, misalignment can be so severe, causing the shafts to bend or break (Abdusslam 2009) as illustrated in figure 2.20.

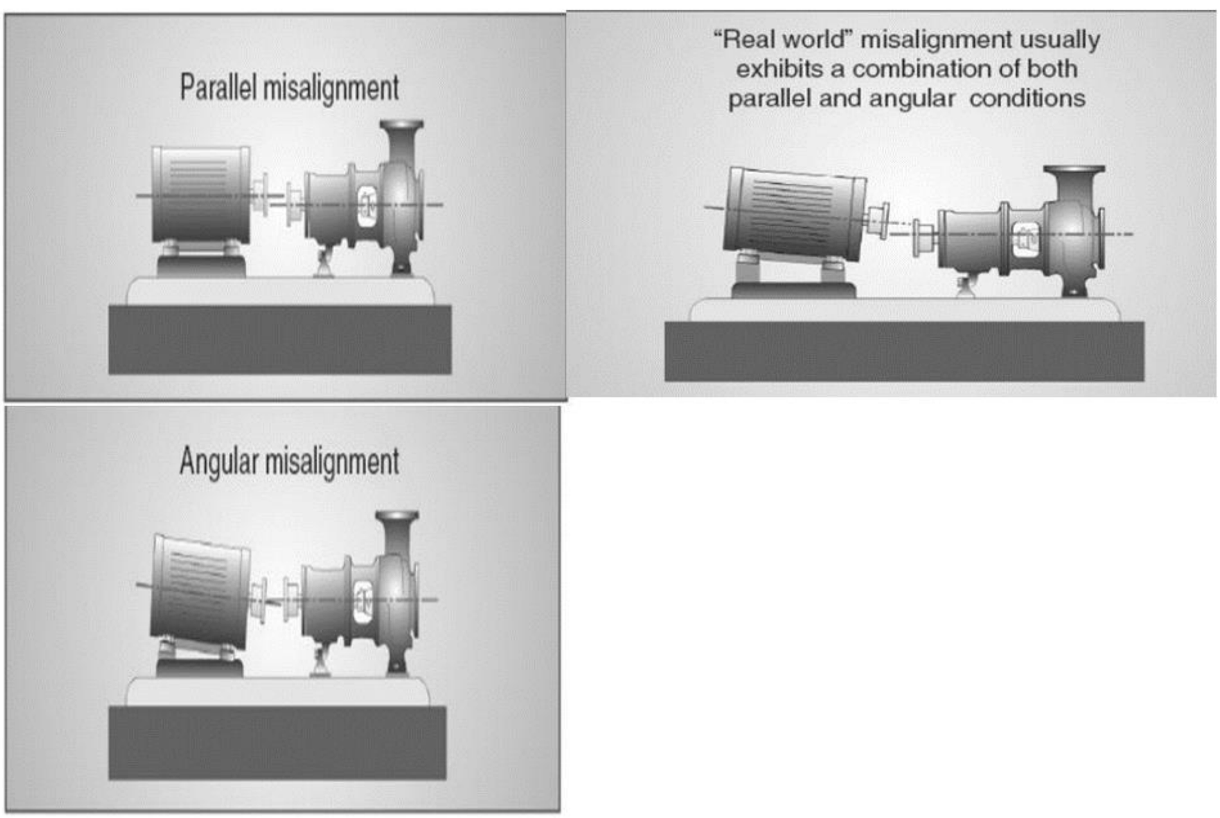


Figure 2.41. Type of gear misalignment. (Flir 2010.)

Also, in the case of gear misalignment, the Vibration analysis method is the most practical technique for measuring vibration occurring in the gearing system. Measurement can be obtained on the machine bearing casings with the help of piezoelectric transducers (vibration accelerometer sensors), and on complex machines, the vibration measurement of the gears can be taken on the axial and radial position of the shaft. Reading vibration signals obtained during measurements requires some advanced knowledge and experience. The frequencies observe, correspond to some specific mechanical components. (Desale 2015.)

The spectrum breaks all frequencies up into their components to reveal false like unbalanced, misalignment, looseness, and foundation problems. Time waveform analysis provides information not found in the spectrum analysis. The picture above shows how the amplitude level of the plot increases each time the gear teeth spin over faulty elements. (Komgon 2007.) Figure 2.21 shows a waveform response due to the Gear vibration failure.

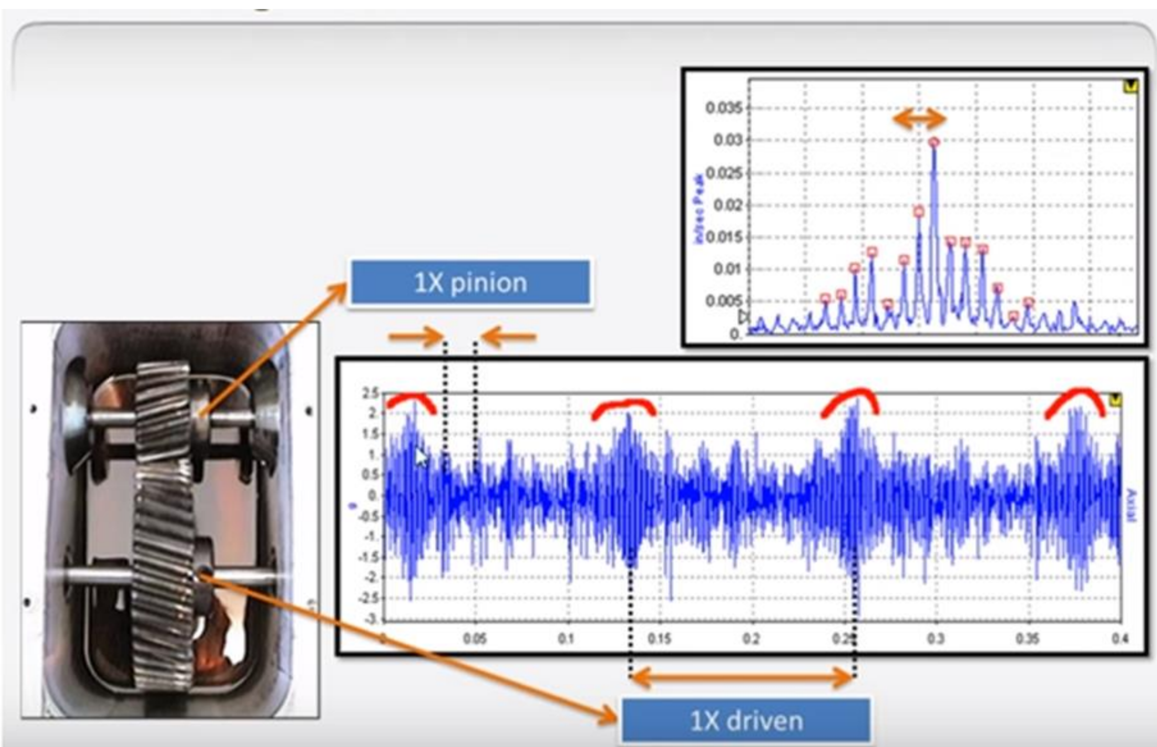


Figure 2.42. Gear vibration response due to failure. (Mobius institute 2018.)

The waveforms as illustrated in figure 2.42, are normally displayed on the screen of a vibration analyzer. The waveforms can be challenging for an inexperienced person to understand; therefore, some new generations of vibration analyzer can be practical to use. (Adash 2020.)

2.7.1.5. New generation vibration analyzer

Currently, many vibration analyzers are designed with multiple and straightforward features to enable both experts and unskilled users to utilize the device without any specific background knowledge in vibration analyzing. (Adash 2020.) With the new generation vibration meter, an inexperienced person can perform the following measurements:

- Speed measurement
- Temperature inspection
- Stroboscope
- Stethoscope
- Time waveform
- FFT spectrum
- Three band spectrums
- Overall vibration measurement

The pictures in figure 2.43 illustrate some features that can be seen on the device's display showing vibration severities of elements.

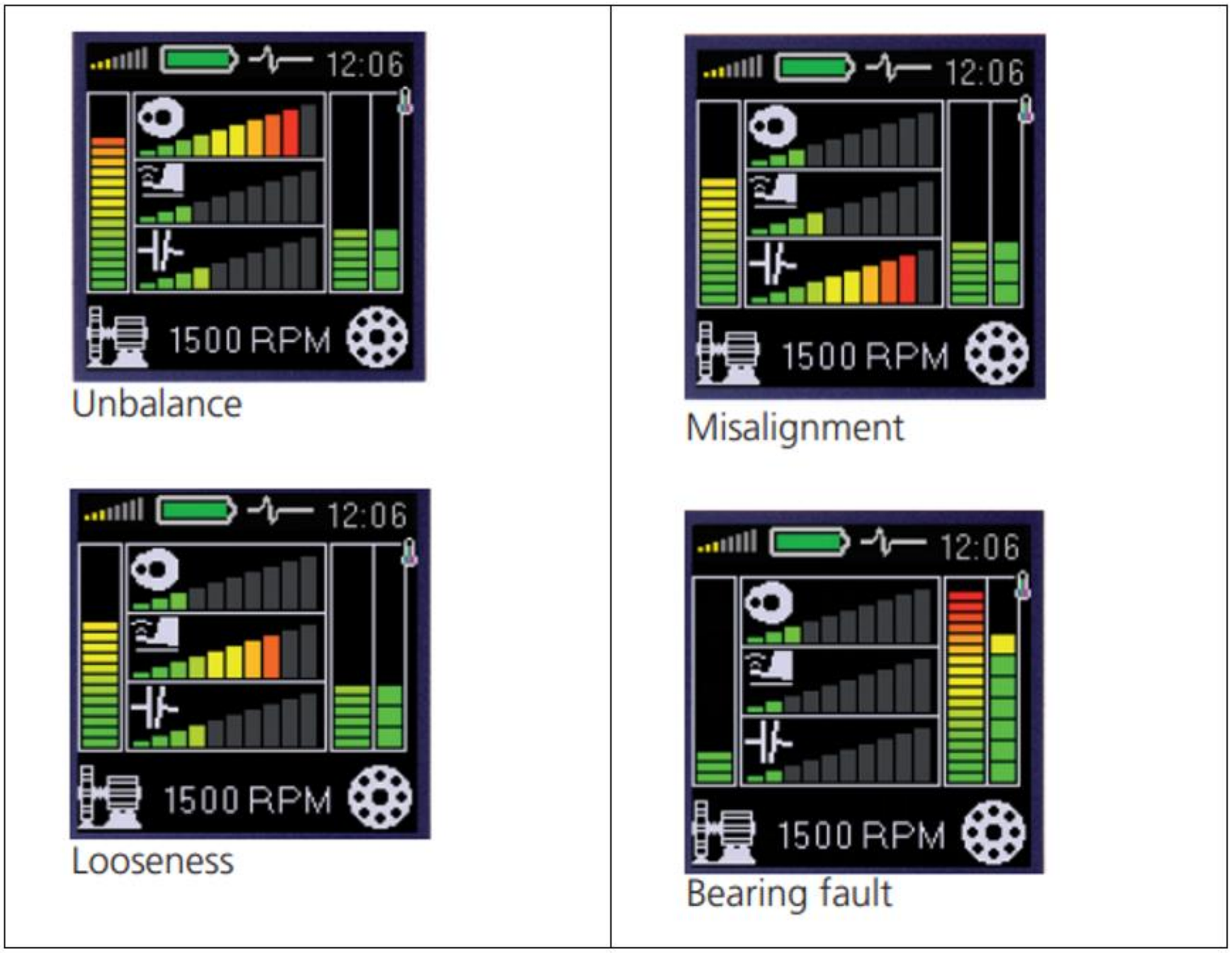


Figure 2.43. Machine fault detection. (CMT Monitoring systems 2016.)

2.7.1.6. Vibration severity

ISO 2372 (10816) Standards provide instruction for assessing the intensity of vibration in machines running from 10 to 200Hz (from 600 to 12,000 RPM) frequency range. For instance, electric motors, pumps, generators, steam and gas turbine, turbo-compressors, turbo-pumps, direct-coupled and fans. Most of these machines can be connected through gears or coupled flexibly and rigidly. Thus, the axis of the rotating shaft can be vertical, horizontal, or inclined. The vibration severity meter helps the user to evaluate the machine condition and adjust the edit alarm threshold switch and select the machine size group. The vibration severity meter is set by default at vibration standards ISO 10816. Some new vibration analyzer devices and software have vibration severity meter integrated features. An illustrative picture in figure 2.23 shows how some vibration severity meter tables are display on screen. (Adash 2020.)

VIBRATION SEVERITY: ISO 10816					
MACHINE	mm/s	CLASS I SMALL MACHINES	CLASS II MEDIUMMACHINES	CLASS III LARGE RIGIFOUNDATION	CLASS IV LARGE SOFT FOUNDATION
	0.28				
	0.45				
	0.71		GOOD		
VIBRATION	1.12				
	1.80				
VELOCITY	2.80		SATISFACTORY		
V RMS	4.50				
	7.10		UNSATISFACTORY		
	11.20				
	18.00				
	28.00		UNACCEPTABLE		
	45.90				

Figure 2.44. Vibration severity: ISO 10816. (Adash 2020.)

2.8. Business model literature review

An examination of the term business models in the literature indicates that there is an extensive range of definitions available. Thus, the implementation of business models as a conceptual tool was not precisely defined in practice as it should be. The perception of business models might be different depending on the organizational background and culture. (Farr 2006.)

Nevertheless, the concept of a business model is widely gaining more attention from practitioners and scholars, underlining the visible interest by both the managerial world as well as the academic side. When going through the literature and profoundly analyzing the business model through various theories, and the diverse opinion given by authors, what seems clear and evident is that no intelligible agreement is given for the business model. Despite the apparent ambiguity on the concept of business models, seven out of ten ventures undertake the risk of creating an innovative business model which was not the case thirty years back. (Alberti 2015.) Competitiveness globalization and market deregulations have pushed firms to come up with new strategies in the market as well as innovative ideas to sustain their Businesses. However, firms can confront environmental conditions with success by using a competitive and innovative business model as a tool. Thus, the business model can be understood as a strategic and systematic tool to enhance the success of a firm. It also used to improve the performance and to increase the turnover of a firm. Pigneur and Osterwalder stated that business model describes the logic of how a firm produces, delivers, and understands value. That means, the business model aims to create value for customers, and the customers decide whether to purchase a product or service if it contributes to their benefit. Nevertheless, in the process of developing the model, both authors created nine elements of the business model, which can be represented as boxes on canvas and thus indicate the most crucial parts of a firm. As a result, each element is linked with other elements which constitute the whole business model jointly.

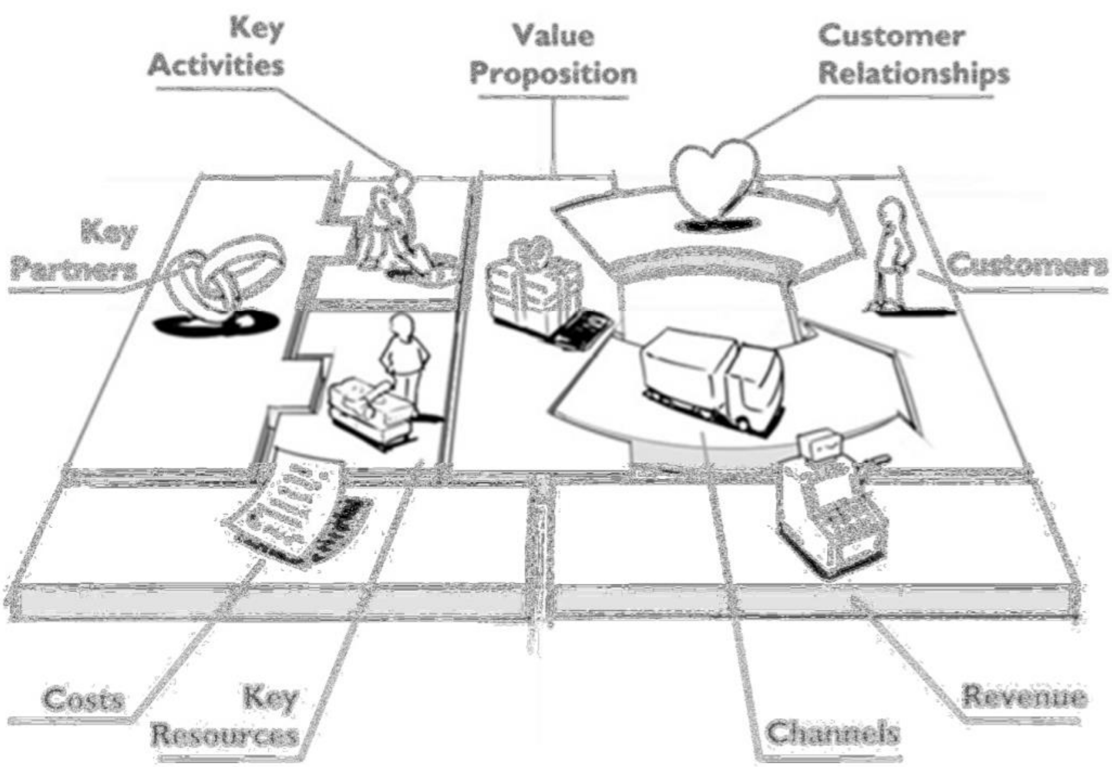


Figure 2.45. Business Model Canvas. (Osterwalder and Pigneur 2010.)

In figure 2.45, the elements key activities, costs, key partners, and key resources are arranged on the firm side and customer, channels, customer relationships and revenue on the market side. The illustration indicates the relations between a single element: partners participate in the resources and key activities of a firm. Traditionally, the procedure represents a template for analyzing existing business models or setting up models with the objective to demonstrate how a firm envisages making money. When applying any business model, the entrepreneur must pay close attention to the cultural aspect, and pioneers usually face severe issues when entering markets in another country. (Kürzdörfer 2013.)

3. Methodology

This chapter presents the comparative approach of the data analysis performed with the Excel sheet. The aim is to study previous firms' performance during some specific years. The year 2012, 2015, and 2018 are taken since they are the years which many innovative firms joined the Congolese market despite the civil war. (Alexis 2020.) Thus, 102 firms are chosen as samples for the study based on their order of entry. The analysis follows a defined procedure which is classifying firms into two categories, pioneers, and followers. The classification of firms is based on their year of integration as given in the official newspaper database in DRC. In each industry section, median separation is used to organize the firms into pioneers or followers' group.

Thus, in each section, one-half of the firms are grouped as pioneers and the rest as followers. For the year 2012, fifty-one firms are classified as pioneers and other as followers. However, some data were not available for some firms in 2012 but available in 2015 and 2018 for the same firms. The sample sizes were reduced in 2012 and 2015 due to the unavailability of certain data.

All average sums were taken on the specific sample sizes corresponding to a determined year. Basically, the category of firms in 2018, its data for 2012 and 2018 are also presented. However, this implies that the firms which were grouped as pioneers in 2012 were considered pioneers in 2015 and 2018.

The following step in the data analysis is to examine variances between means of pioneers and followers' groups on each of the three-step of performance and the three strategic variables. Therefore, One-way analysis of variance (ANOVA) is applied for this reason. The correlation of strategic variables with the market share as a performance variable is studied. In literature, the market share represents the performance in the marketplace. (Mittal and swami 2004.)

Again, ANOVA is applied to analyze variance between the means of two group of pioneers. The analyze is done within the group of pioneers itself; the market share is regarded as an independent variable and strategies as a dependent variable and the above methods are processed to test hypotheses.

3.1. Hypothesis testing

3.1.1. Impact of the Order of Entry on performance in the market

As the analyze of variance has specific rules to follow, the hypotheses to be tested must be defined. Early researchers such as Robinson and Fornell found that frequently, pioneers have a significant market share on average than their rivals. Therefore, the order of entry in the market has a considerable impact on the market share for both growing business and startup business. (Mittal and swami 2004.)

Thus, the formulated hypotheses to be tested are:

Hypothesis A1: Pioneers could probably have a high market share than followers based on the impact of order of entry on performance.

Hypothesis A2: Pioneers could probably have more sales than followers based on the impact of order of entry on Performance.

Hypothesis A3: Pioneers could probably have more profit before tax than followers based on the impact of order of entry on Performance.

3.1.2. Impact of the Order of Entry on strategies in the market

Wilson and Camanor stated that Industries with significant advertising to sales ratio have considerable barriers to entry. They declared that the effectiveness of advertising should depend on the first entrant in the market because customers' experience with the product inevitably influences these responses as well as by the overall volume of competing advertising messages. High advertising cost can benefit pioneers as it creates barriers to entry for late market entrants. Late entrants can experience difficulties with customer response due to lack of experience with their service or product, and they must shout louder to be heard.

The economies of advertising scale can also privilege pioneers if the market is so small for the latest entrants to gain from the economies associated with advertising communication or the purchasing economies. Besides, the capital costs can be particularly high for advertising expenses since there is no salvage value if late entrants fail. If buyers of a new product type have not yet developed loyalty of the brands as stated by consumers; the pioneer offering right quality products boosted by a severe advertising campaign can obtain more significant market share and defend it from the competition. So, to create obstacles to entry for followers, pioneers could invest excessively in promotion and advertising. (Mittal and swami 2004.) Thus, the following hypotheses are:

Hypothesis B1: Pioneers could probably invest more in advertising than followers based on the impact of order of entry on strategies.
Hypothesis B2: Pioneers could probably invest severely in promoting their services or products than followers based on the impact of order of entry on strategies.
Hypothesis B3: Pioneers could probably invest heavily in R&D than followers based on the impact of order of entry on strategies.

The descriptive statistics presented in tables 1 and 2 are represented in figures 3.1 In general, the figures show that pioneers perform better than late entrants, which is coherent with previous research in developed countries. Pioneers have also proven to be stable over the years to maintain their top performance over late entrants or followers. Generally, statistics indicate that although the average market of pioneers decreases over the years, pioneers still have a significant market share than its rivals.

Thus, statistics demonstrate that pioneers likely benefit from long term competitive advantage over late entrants (followers) since they are the first in the market. Nevertheless, followers also seem to narrow the interval between them, and the pioneers based on the average market share. On average, pioneers have a much higher sales volume than followers. The market growth has favored pioneers to increase their sales for last eight years by 58 per cent while followers' sales have grown at 60 per cent during the same period. However, the sales growth rate of followers is higher than the pioneers. This situation shows that the advantage of pioneers cannot remain constant forever; therefore, it is probable that followers overtake them in the future.

Entry order	Market Share (%)			Average Sales (US $ Billion)			Average Profit before tax (US $ Billion)		
Years	**2012**	**2015**	**2018**	**2012**	**2015**	**2018**	**2012**	**2015**	**2018**
Pioneers	63,06	69,31	62,63	1,15	1,63	1,82	0,17	0,21	0,25
Followers	37,24	30,69	37,37	0,68	0,72	1,09	0,016	0,03	0,055

Table 3.1. Average Performance of Pioneers and Followers. (OCC 2018.)

Entry order	Average R&D (US $ Million)			Average Advertising (US $ Million)			Average Promotion (US $ Million)		
Years	**2012**	**2015**	**2018**	**2012**	**2015**	**2018**	**2012**	**2015**	**2018**
Pioneers	8,02	14,52	45,11	11,46	30,62	56,89	104,85	189,21	111,94
Followers	1,09	3,10	9,21	3,92	9,37	20,27	9,59	20,36	39,31

Table 3.2. Average Expenditure on Strategies by Pioneers and Followers. (OCC 2018)

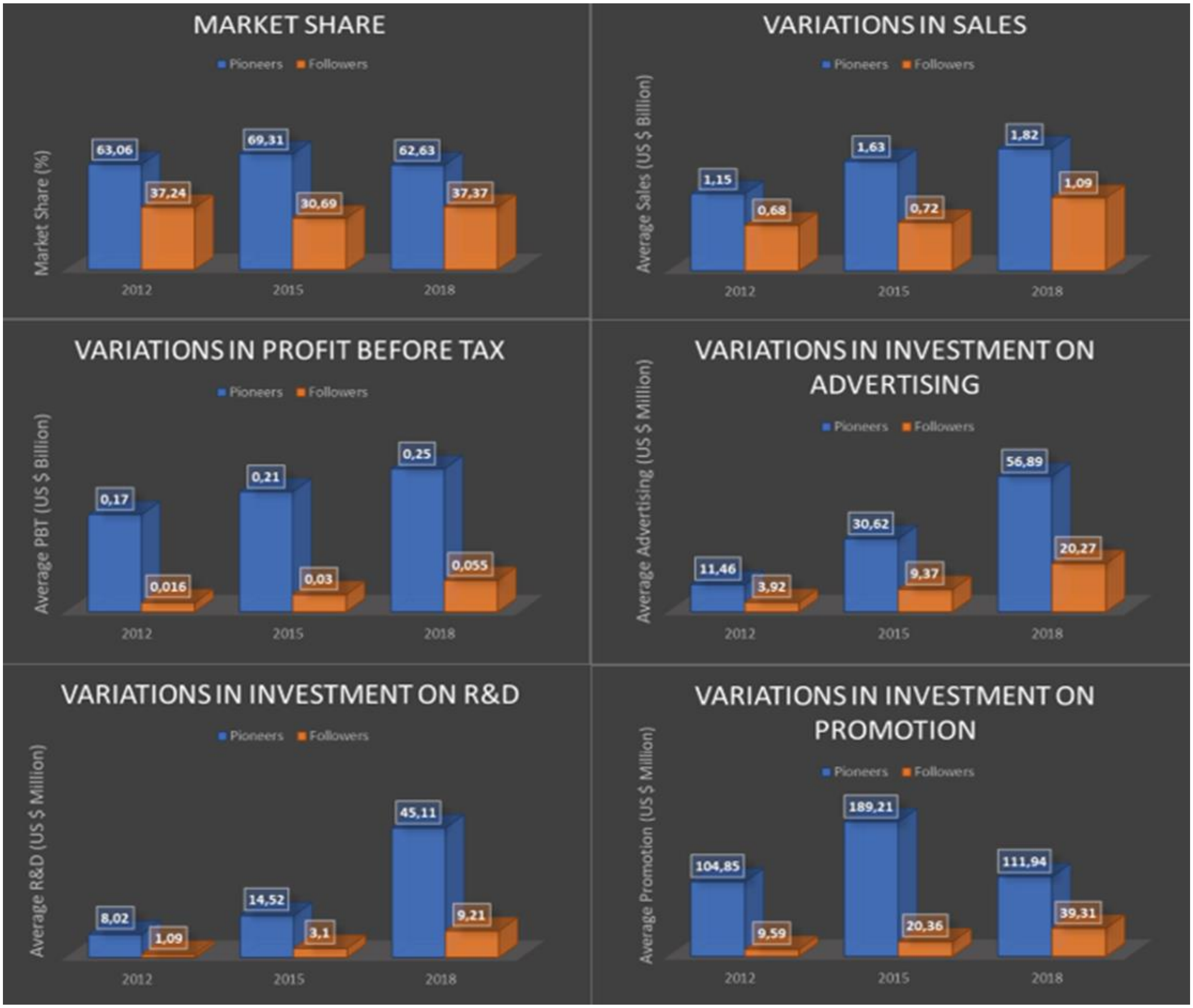


Figure 3.1. Variation charts of Pioneers and Followers. (OCC 2018.)

On average, pioneers made more significant profits than followers, and their profitability increased over the years. In 2012, pioneer profits were 10,6 times higher than those of followers, and in 2018, their earnings were 4.5 times higher than those of followers. Thus, the average sales of the pioneers are slightly higher than that of the followers. During the year 2018, the investment of pioneers in R&D was close to five times that of followers. Nevertheless, follower’s investment on R&D has risen to nine times in the past eight years compared to the pioneer increase of 5,6 times.

During the year 2018, the average investment of pioneers in advertising was nearly double that of followers. Pioneers investment in advertisement increased five times in the past eight years while followers' investments increased by 5.2 times in the same period. It seems that in the early years, pioneers were more aggressive in advertising their products. Followers understood the importance of adverts with time, and they invested more in advertisements in the years later. Similarly, followers seem to catch up with pioneers in promotional spending.

3.2. Classification based on the impact of performance in the market

Assumptions about the effect of entry order on performance (A1, A2 and A3) indicate that pioneers are probably performing better than followers due to their early entry into the market. The median distribution is used to classify companies into two categories: pioneers and followers. However, these performance variables (market share, sales, and profit before tax) are dependent variables, and the entry order is an independent variable. The Analysis of Variance (ANOVA) is performed for each dependent variable. Table 4.1 indicates the average values of performance variables throughout the years for pioneers and followers. Thus, size samples for the years 2012, 2015, and 2018 were 102 (Pioneers-51, followers-51). The samples were evenly taken to analyze the market share, the average sales, and the average profit before tax. Five per cent significant level was applied to come up with the results.

3.2.1. Hypotheses on the impact of strategies in the market

Hypotheses on the impact of the order of entry on strategies (B1, B1, and B3) show that pioneers are susceptible to invest tremendously on strategies (Promotion, Advertising, and Research and development (R&D)), which prevent potential companies from joining the market by creating barriers to entry. Many strategies are regarded as dependent variables, and the order of entry is regarded as an independent variable. Table 4.2. indicates average expenses on several strategies for pioneers and followers across the years with the results of ANOVA. The results prove that with the growing competition tendency in the market, both rivals understood the influence R&D, promotion, and advertising.

3.2.2. Moderating Impact

To obtain the above results on performance and strategies presented in table 4.1 and 4.2, the null hypothesis test H0: ß1 = ß2, and the alternative hypothesis test H1: ß1 ≠ ß2 were carried out to verify the homogeneity of the groups using the ANOVA approach with the following equations.

Sums of squares formula

$$SS_{total} = \sum_{j=1}^{p} \sum_{i=1}^{n_j} (x_{ij} - \bar{x})^2$$

$$SS_{between} = \sum_{j=1}^{p} n_j \, (\bar{x}_j - \bar{x})^2$$

$$SS_{within} = \sum_{j=1}^{p} \sum_{i=j}^{n_j} x_{ij} - \bar{x}_j)^2$$

Mean squares formula

$$MS_{between} = \frac{SS_{between}}{df_{between}}$$

$$MS_{within} = \frac{SS_{within}}{df_{within}}$$

F Formula

$$F = \frac{MS_{between}}{MS_{within}}$$

Figure 3.2. Analyze of Variance (ANOVA) formula (Mittal and Swami 2004)

The above formulas help to find the null hypothesis, or the alternative hypothesis based on the observation samples. Before calculating the F-value, the means must be calculated, followed by the sum of squares. The total sum of squares (SST) is computed, followed by the sum of squares within groups (SSW) and the sum of squares between groups (SSB). Along with the calculations, the degree of freedom (DF) in groups are also calculated. Where xij are the group means, x is the grand mean, and n (column) and p (row) are the number of items in each group.

4. Results and discussion

Therefore, the results show evidence that pioneering advantage exists in the Congolese marketplace. Still, the advantages cannot only be linked to the order of entry as other elements such as competitive environment and strategies also influence a company's performance.

Although some benefits may increase or be endowed on pioneers, being a market pioneer on its own might not directly generate a sustainable competitive advantage and dominance in market share. The pioneer of the market creates opportunities to gain market share dominance and positional advantages. Unless a company has the resources, creativity, and expertise required to utilize these opportunities, thus, being first to the marketplace will generate sustainable desired performance results neither competitive advantage.

However, political influence is predominant in the Congolese market, and policymakers tend to favor firms that bribe the most. Thus, corruption practices affect market competition severely, and other factors also are involved, such as a firm's size, technology, and social awareness. When considering these influences, companies can somehow measure the viability of first entry rather than claiming that first is always the best. On the other hand, being the first in the market gives the advantage of creating a large network among decision-makers—an example of Bralima. This brewing company has a monopoly in Congo due to the strong connection the company has with decision-makers.

The second question concerning the appropriate vibration measuring techniques to propose to DR Congo in section 1.2 indicates That traditional vibration measuring methods are the proper techniques to present to Congolese customers. This decision results from studies and surveys done in many regions of the country where factories are located. Different aspects have been considered, such as infrastructure, electricity, and internet accessibility. Internet access is limited in many parts of the democratic republic of Congo. Currently, many western countries integrate IoT into their vibration monitoring system for accurate results, an advanced technique for monitoring machinery. Unfortunately, setting an IoT system in DR Congo will be too expensive due to the internet cost.

This part will discuss mainly the last question in section 1.2 regarding the application of vibration analysis to solve engineering issues by presenting the benefit of the vibration analysis techniques to solve engineering problems related to cost. In chapter 2, some of the vibration analysis techniques have been illustrated, and vibration condition monitoring was selected due to the need in the DRCongo. Thus, the part will focus on the vibration condition monitoring benefit. The principal goal of a factory is to generate income by manufacturing products that could be easily sold. Therefore, production is maximized when downtime in machines is minimized.

Reactive maintenance is widely used in DRCongo, reactive maintenance on non-critical machinery, the failure of which does not directly affect production. Preventive maintenance is also applied on the more sophisticated machine where failure can impact production. Research has shown that routine maintenance on some types of machines can reduce the machine's reliability rather than improving it, throwing into question the assumption that regular maintenance should be used when reliability is essential. The best solution so far for complex machines is condition monitoring, where machines' health is monitored frequently. However, maintenance is only achieved when a machine's condition shows that maintenance is necessary because of measurable degradation in one or more machine condition indicators such as increased vibration, noise, or temperature. (Movus 2020.)

Therefore, the thesis aim was also to identify the advantage of being a pioneer in a market. After intensive surveys and interviews conducted in DRCongo in different factories and governing institutions, the result revealed that any company willing to invest in condition monitoring might be a pioneer. Pioneering comes with multiple advantages and disadvantages. However, analyzing the probabilities of being successful in business in a new market is crucial for a company.

5. Conclusion

The pioneering advantage concept is a multi-dimensional notion that depends on a range of ingredients. The combined effect of these ingredients defines the company's performance in the market. However, a proper understanding of these factors would help companies to distinguish their products from rivals and stay competitive in the marketplace for an extended period. This thesis presents a conceptual framework for an informed decision concerning the moment of entry into the market under ruling environmental conditions.

Two fundamental strategies have been proposed, Pioneering, and following, and diverse strategic elements have been discussed. This framework provides information about a company's performance in the market—an attempt to analyze the Congolese context the broadly approved belief that pioneers excel better than followers. Previous researchers demonstrated that in developed markets across the world, pioneers have higher profitability and performance than followers. (Mittal and Swami 2004.)

The results of this thesis indicate that, in general, pioneers outperform followers, and companies that enter the market early have more significant market share and profits than followers. In the presented sample for the year 2018, the pioneers had a market share of 62,6% and the followers 37,7%. It has also been discovered that companies entering first in the market are usually more aggressive in embracing several strategies such as promotion, R&D, and advertising.

Thus, companies invest in strategies to create barriers to entry for competitors who might find it hard to compete with the established companies as the requirement of resources are extremely high in this scenario. The Pioneer Advantage appears to be a long-term competitive advantage for businesses, as the performance of Pioneers is continuously more elevated than that of the latecomers over the years. Though the effect of pioneer begins to diminish over time in terms of market share, the profit margins of pioneers are significant even after an extensive period.

The results indicate that the strategic variables and market share performance are connected and interdependent. They also affirm that strategies have a differential effect on the chances of performance within the group of market pioneers. Besides, moderating an inconstant competitive environment changes the relationship between company performance in the market and the order of entry. This preliminary investigation of the pioneering benefit in the Congolese market environment which analyzes a finite set of hypotheses.

The database used may not represent all business categories. It is probable, for instance, that there is an upward bias in the business performances analyzed in this thesis since they are all large productive companies published in the top 200 list.

Taking into account new competitive environments and strategies would offer exciting avenues for future research. Likewise, the complete analysis of each industry segment will provide a better understanding of the order of entry impact in the different sectors. Additionally, if the data were available at a more detailed level, a division-level view of parameters such as profitability or advertising would give a more detailed analysis of the pioneer advantage.

References

ABS, April 2016 Equipment conditions monitoring techniques. [Referred 02.08.2019]. Available at: https://maritimecyprus.files.wordpress.com/2016/05/abs-equipment_condition_monitoring.pdf

Adash 2020, User manual. [Referred 04.09.2019]. Available at: https://adash.com/documents/DDS/Adash-DDS-software-manual.pdf

Alfonso Fernandez. June 2017. Rolling elements bearing failing frequency. [Referred 27.04.2020]. Available at: https://power-mi.com/content/rolling-element-bearing-components-and-failing

Amit Desale. May 2015. Detection of Fault in Gearbox System Using Vibration Analysis Method. [Referred 16.06.2020]. Available at: https://www.ijeas.org/download_data/IJEAS0205054.pdf

Brüel & Kjær 1984, Mechanical vibration and shock measurements. [Referred 02.10.2019]. Available at: https://www.bksv.com/media/doc/bn1330.pdf

CMT monitoring systems 2015, Vibration monitoring, Available at: https://www.cmtechnologies.de/Downloads/Documents/Vibrationbrochure/EN/files/assets/common/downloads/publication.pdf
[Referred 10.11.2019]

Crystal instruments. July 2017. Basics of modal testing and analysis. [Referred 10.11.2019]. Available at:
https://static1.squarespace.com/static/5526e8e7e4b0356ed20c43fe/t/5af39a57562fa7f1ebed5964/1525914254131/Basics+of+Modal+Testing+and+Analysis+07.2017.pdf

Djordje Kalicanin 2018, Improving business performance through brand management practice. [Referred 10.11.2019]. Available at: https://www.researchgate.net/publication/301944673_Improving_business_performance_through_brand_management_practice

Daniel J. INMAN 2014 Engineering vibrations fourth edition. Introduction to vibration and the free response, Pages 14-15.

Giacomo Alberti. 2015. Business Model: a Structured Literature Review. [Referred 16.06.2020]. Available at: http://dspace.unive.it/bitstream/handle/10579/7996/821790-1192410.pdf?sequence=2

HE & Fu. 2001. Modal Analysis. [Referred 07.04.2020]. Available at: https://www.mobt3ath.com/uplode/book/book-32791.pdf

Kwok F. Torm. March 2015, A primer on vibrational ball bearing feature generation for prognostics and diagnostics algorithms. [Referred 23.01.2020]. Available at: https://apps.dtic.mil/dtic/tr/fulltext/u2/a614145.pdf

Komgon, N.C. Mureithi, N. Lakis, A. Thomas, M. 2007, On the Use of Time Synchronous Averaging, Independent Component Analysis and Support Vector Machines for Bearing Fault Diagnosis, 1st International Conference on Industrial Risk Engineering, CIRI, Pages 610-624
PCE Instruments, March 2012, User manual vibration analyzer. [Referred 06.11.2019]. Available at: https://www.pce-instruments.com/english/slot/2/download/2200563/manual-vibration-analyser-pce-vm-25.pdf

Maurice L. Adams, JR. 2001, Rotating machinery vibration. [Referred 08.11.2019]. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.475.2979&rep=rep1&type=pdf

Mobius Institute 2018, Online learning. [Referred 19.11.2020]. Available at: http://mobiuslearningzone.com/

Movus 2020, 5 Advantages of Condition-Based Monitoring. [Referred 23.03.2021]. Available at: https://www.movus.com.au/2018/08/29/5-advantages-of-condition-based-monitoring/

Office de control congolais 2018. [Referred 19.11.2020]. Available at : http://occ.cd/2019/07/17/participation-de-locc-aux-travaux-devaluation-de-la-conduite-en-douane-et-du-transit-des-marchandises-entre-la-republique-democratique-du-congo-et-la-republique-du-congo/
‘

Pruftechnik Engineers Guide 2017, An engineer’s guide to shaft alignment, vibration analysis, dynamic balancing and wear debris analysis. [Referred 08.11.2019]. Available at: https://0201.nccdn.net/1_2/000/000/190/be5/Pruftechnik-Engineers-Guide-2017.pdf

R. keith Mobley 2002, An introduction to predictive maintenance. [Referred 11.11.2019]. Available at http://www.irantpm.ir/wp-content/uploads/2008/02/an-introduction-to-predictive-maintenance.pdf

Roland Berger, April 2017 Predictive maintenance. [Referred 04.09.2019]. Available at: https://www.rolandberger.com/fr/Publications/Predictive-Maintenance.html

Richard Farr. January 2006. Business Model Tools and Definition - a Literature Review [Referred 16.06.2020]. Available at: https://www.researchgate.net/publication/272813909_Business_Model_Tools_and_Definition_-_a_Literature_Review

S. Mittal and S. Swami. 2004. What Factors Influence Pioneering Advantage of Companies. [Referred 05.08.2020]. Available at: https://jonals.sagepub.com/doi/pdf/10.1177/0256090920040302 [

Singiresu S. Rao 2007, Mechanical vibrations [Referred 06.11.2019]. Available at: https://www.u-cur-sos.cl/usuario/427b3901a2f307e5b7b06efd5a13b744/mi_blog/r/Rao_Mechanical_Vibrations_5th_txtbk.PDF

Tamara Katharina Kürzdörfer. May 2013. Cultural Influence on the Success Factors of Business Models. [referred 10.11.2019]. Available at: http://www.divaportal.org/smash/get/diva2:623202/FULLTEXT01.pdf

Top Congo, August 2020 un projet de plan pour booster le numerique en RDC. [Referred 10.11.2019]. Available at: https://topcongofm.net/un-projet-de-plan-pour-booster-le-numerique-en-rdc-remis-au-president-felix-tshisekedi/

Worldbank 2018, Doing business. [Referred 14.11.2019]. Available at: http://documents1.worldbank.org/curated/en/498991541069119764/pdf/131620-WP-DB2019-PUBLIC-Congo-Dem-Rep.pdf