VIBRATION ANALYSIS OF TRANSMISSION SYSTEM USING I-LEARN VIBRATION SOFTWARE

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ABSTRACT. Condition monitoring has been widely established to obtain the greatest effectiveness in the predictive maintenance of complex machines and mechanical systems. It has been used to minimise operating faults and overhaul costs without affecting the system's reliability. Vibration analysis is the most favourable technique for monitoring rotating mechanical systems, such as the electric motor, flexible coupling, gearbox, centrifugal pump and bearing. This analysis has been extensively applied in the machinery industry to evaluate the condition of transmission components, identify discrete frequencies, and conduct spectrum analysis. However, vibration analysis often possesses limitations due to the complexity of the data analysis methods and interpretation of the faults. Therefore, transmission system simulation using software emerges as an alternative that eases the vibration analysis process. In this paper, the vibration analysis carried out using Mobius i-Learn vibration software shows no significant deficiency in the transmission frequencies of the machinery parts compared with the results computed from the standard formula. It can be deduced that the analytical results from Mobius i-Learn vibration simulation are reliable for detecting abnormal vibration within machinery parts, providing the optimum frequency readings which efficiently avoid the machine's faults.

KEYWORDS: Condition monitoring; vibration analysis; transmission; frequency

1 INTRODUCTION

Condition monitoring has been widely used to achieve maximum efficacy in the predictive maintenance of complicated equipment and mechanical systems to minimise operating faults and overhaul costs without affecting the reliability of the machines (Vishwakarma et al., 2017). It is usually used on rotating equipment and other machinery such as electric motors, coupling, gearboxes, pumps, shafts, bearing etc. The most favourable technique for monitoring rotating mechanical systems is called vibration analysis. This analysis has been extensively applied in the machinery industry to (1) evaluate the condition of transmission components, (2) identify discrete frequencies and (3) obtain spectrum analysis (Aoki et al., 2022; Jun et al., 1992; Swansson & Favaloro, 1984; Wang et al., 2023; Zhao & Zhang, 2017). An extensive review has been done on time domain vibration analysis techniques used to monitor rolling element-bearing conditions (Prakash Kumar et al., 2022). More recently, Srinivas et al. (2022) proposed a new analytical method of mid-frequency vibration analysis using the augmented distributed transfer function method (DTFM) for complex structures. Studies were also carried out on the vibration characteristics analysis of the complex parallel fluid-conveying pipes system using numerical and experimental methods to collect results of the power flow signal from different positions (Guo et al., 2022). In addition, some researchers performed vibration analysis of a flexible gear transmission system where the spectra accelerations along the *y*- and *z*- directions of bearings were compared (Liu et al., 2023a). Therefore, it is essential to perform the vibration analysis using different approaches to achieve the results' consistency and accuracy. This study compares the vibration analysis of a transmission system between the simulation results produced by the i-Learn vibration software and the computation results.

2 VIBRATION ANALYSIS

In general, vibration analysis is used to identify early detection of mechanical fatigue, obtain high accuracy of machinery monitoring, and reduce manufacturing downtime. The vibration behaviours of a transmission system could be changed by the presence of multi-frequency load excitations (Du et al., 2023). A new approach for the dynamic modelling and vibration analysis of a flexible gear transmission system reduced the vibration compared to the rigid shaft gear transmission system (Liu et. al., 2023b). The vibration analysis is performed on all rotating components, where the signs of wear and damage can be identified before severe machinery breakdown and mechanical degradation (Choy et al., 1996; Leoni et al., 2022). In this study, Mobius i-Learn vibration analysis was carried out based on the following basis:

a) The machine vibrations were recorded by real simulation of sensors, such as accelerometers and tachometers.
b) The simulation of the accelerators imitated the real machine vibrations, which were connected to rotating machinery such as an electric motor, coupling, gearbox, and shaft, to record the vibrations and movements.
c) The recordings were diagnosed using the i-Learn vibration analysis, visually displaying vibration waveforms and spectrum.
d) The simulations were repeated over time and new vibrations that might indicate wear or damage were gradually developed at the earliest stage before failure.

Amplitude and frequency are the main numerical variables for machine vibration, where amplitude describes the severity of vibration, and frequency illustrates the oscillation rate of vibration. The waveforms for vibration analysis represent how the vibration level changes with time. In contrast, a spectrum is a graphical display of the frequencies at which a machine component is vibrating, together with the amplitudes of the components at these frequencies. These individual frequencies efficiently show the cause of the vibration and the condition of the components.

2.1 Identification of Vibration Causes

Signal analysis methods, such as the Fast-Fourier Transform (FFT), have been enormously advanced in diagnosing the rotating machinery vibration causes. The most common causes of excessive machinery vibration related to the transmission modelling in this study are described in Table 1.

Table 1: Descriptions of machinery vibration causes (Adams, 2009)

Causes	Descriptions
Rotor mass unbalance vibration	In a rotor dynamical system, excessive vibration is frequently accompanied by a significant presence of dynamic non-linearity.
Self-excited instability vibration	The most significant group instability mechanisms are oil whip and centrifugal pump impeller forces, originating during the turbo-machinery stages of pumps, turbines, and compressors.
Misalignment	Excessive misalignment causes a high amount of axial vibration and a large twice-running speed harmonic component of the vibration.
Resonance	When a machine’s running speed reaches a critical speed, it causes design flaws, installation problems, component deterioration, and excessive unbalanced-driven vibration.
Mechanically loose connection	Looseness at non-rotating connections, such as bearing caps or bearing mounts, is likely to generate vibration because the bearings and mounts limit the shaft to its rotational centreline. The dynamical characteristics caused by the looseness of these components will add a significant degree of dynamic non-linearity to the vibration system.

3 METHODOLOGY

The machine faults and alarms mode of the i-Learn vibration analysis provides a machine train simulator designed to detect machine faults and diagnose the nature and severity of the defect. It also demonstrates the relationship between the machine structure and the vibration forcing frequencies. Figure 1 shows the transmission modelling of this study. The vibration analysis started with setting the reference speed to 1600 cycles per minute (CPM) in the system. An electric motor of 16 rotor bars and six fan blades was used. A rolling element bearing included 12 balls, a pitch diameter of 29 mm, a ball diameter of 5 mm, and a contact angle of 13° was attached to the electric motor shaft 1. Six coupling elements were also attached to shaft 1. In addition to rolling and coupling, a gearbox with 22 teeth on the input and 57 teeth on the output was attached to shaft 1. Whereas shaft 2 had two stages centrifugal pump. The number of vanes in the first and second stages were 8 and 14, respectively. The vibration analysis was run when the system was completely assembled.

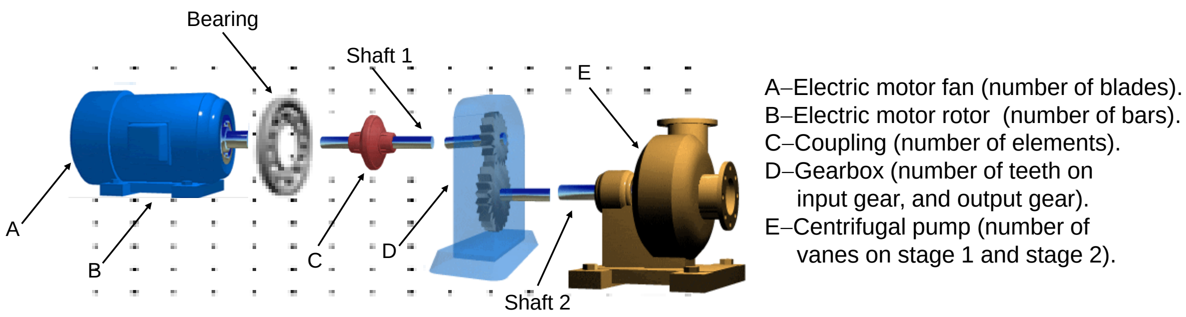

Figure 1: Transmission modelling

4 RESULTS AND DISCUSSION

The time and frequency vibration signal spectrum and readings produced from the i-Learn vibration software are shown in Figures 2 and 3, respectively. Figure 4 shows the band faulty by the machine fault and alarms mode. The dynamic vibration signal spectrum was analysed for the faults with respect to the frequency/peak to ascertain the failure occurrence in the rotating machinery (Khadersab & Shivakumar, 2018).

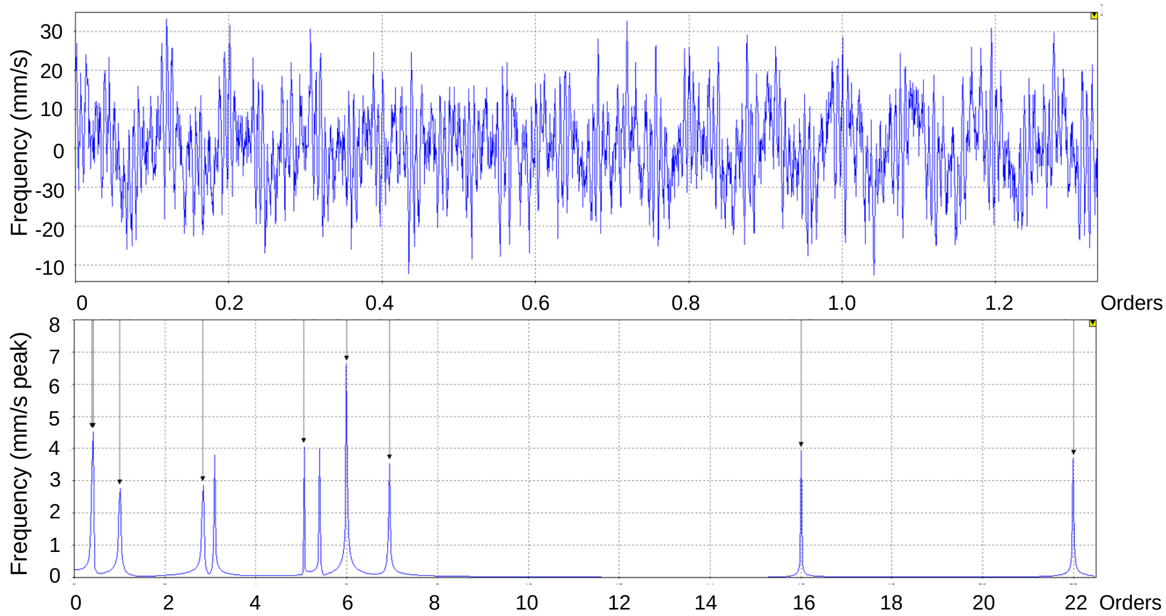

Figure 2: Time and frequency vibration signal spectrum

- Reference speeds:
  - Shaft 1 is at 1X, 1,600 CPM
  - Shaft 2 is at 0.39X, 618 CPM
- Motor: Motor
  - Rotor bar rate: 16X, 25,600 CPM
  - Motor fan blades: 6X, 9,600 CPM
- Bearing: Bearing 1
  - Ball pass outer race: 5.06X, 8,098 CPM
  - Ball pass inner race: 6.94X, 11,102 CPM
  - Ball spin: 2.83X, 4,526 CPM
  - Fundamental train (cage): 0.42X, 675 CPM
- Flexible coupling: Coupling
  - Coupling elements: 6X, 9,600 CPM
- Gearbox: Gearbox
  - Gearmesh: 22X, 35,200 CPM
- Centrifugal: Pump
  - 1st stage vane pass rate: 3.09X, 4,940 CPM
  - 2nd stage vane pass rate: 5.4X, 8,646 CPM

Figure 3: Vibration analysis readings produced from i-Learn vibration software

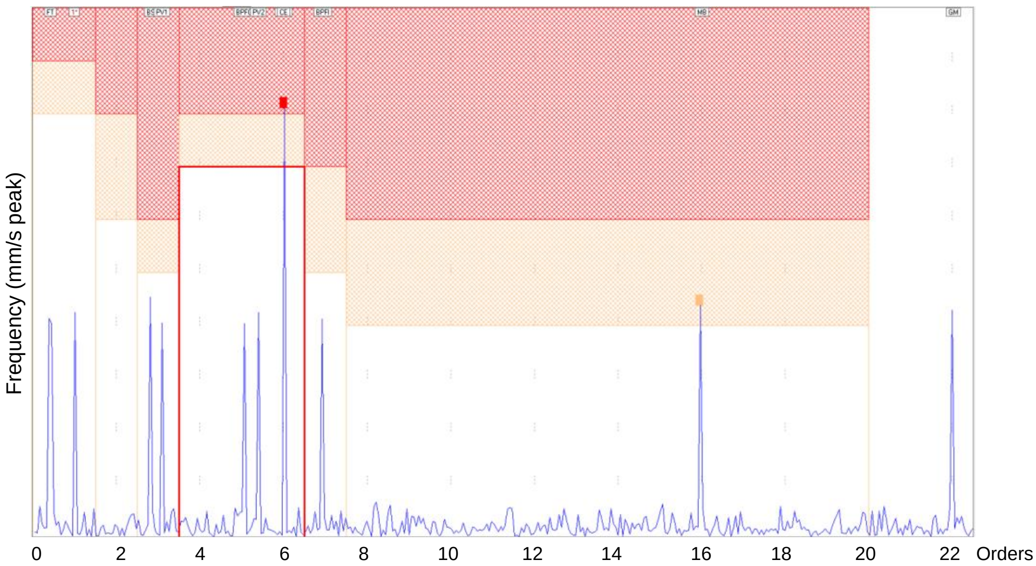

Figure 4: Faulty in band

The computation (using mathematical calculation) was applied to determine the frequencies for the transmission modelling, which comprised an electric motor, flexible coupling, bearings, gearbox and centrifugal pump. The parameters used for the computation are listed in Table 2.

Table 2: Analysis parameters for the computation

A. Motor fan	B. Motor rotor	C. Coupling	D. Gearbox	E. Centrifugal pump		F. Bearing of electric motor			
No. of blades	No. of bars	No. of elements	Teeth	No. of vanes (Stage 1)	No. of vanes (Stage 2)	D_P	d_P	N	ϕ
6	16	6	Z_1=22; Z_2=57	8	14	29	5	12	13°

Table 3 shows the computation results of the transmission modelling.

Table 3: The computation results

1. Reference speeds Shaft 1 is at 1×, 1600 CPM Shaft 2, the output shaft, is based on the reduction ratio of the gearbox. Given that Z_1 = 22 and Z_2 = 57; therefore, the ratio is $\frac{22}{57}\times$ Shaft 2 is at $\frac{22}{57} \times 1600 = 618$ CPM
2. Electric motor The number of blades for the motor fan (A) is given by 6; therefore, blade pass frequency is 6×. The number of bars for the motor rotor (B) is given by 16; therefore, the motor rotor rate is 16×. Based on the reference speed of shaft 1, which is 1600 CPM; Blade passing frequency: 6 × 1600 = 9,600 CPM Motor rotor frequency: 16 × 1600 = 25,600 CPM
3. Flexible coupling The number of elements for coupling (C) is given by 6; therefore, the coupling rate is 6×. Based on the reference speed of shaft 1, which is 1600 CPM; Coupling frequency: 6 × 1600 = 9,600 CPM
4. Gearbox The number of teeth for the input gear is Z_1 = 22, and the output gear is Z_2 = 57. The gearbox (D) frequency is based on the number of meshing teeth of the input gear; therefore, gear meshing frequency is 22×. Based on the reference speed of shaft 1, which is 1600 CPM; Gear meshing frequency: 22 × 1600 = 35,200 CPM
5. Centrifugal pump The number of vanes for the centrifugal pump (E) is given in 2 stages; Stage 1 = 8 and Stage 2 = 14, respectively. Vane passing rate for Stage 1: 0.386 × 8 = 3.09× Vane passing rate for Stage 2: 0.386 × 14 = 5.40× Based on the reference speed of shaft 1, which is 1600 CPM; Vane passing frequency for Stage 1: 3.09 × 1600 = 4,940 CPM Vane passing frequency for Stage 2: 5.40 × 1600 = 8,646 CPM
6. Bearings Bearing 1, which is located on shaft 1. a) Ball pass frequency of outer ring (BPFO) BPFO $= \frac{N}{2}(1\times)\left[1 - \frac{dp}{Dp} COS\ \Phi\right]$ $= \frac{12}{2}(1\times)\left[1 - \frac{5}{29} COS\ 13^\circ\right]$ = 5.06× Based on the reference speed of shaft 1, which is 1600 CPM; BPFO: 5.06 × 1600 = 8,096 CPM b) Ball pass frequency of inner ring (BPFI) BPFI $= \frac{N}{2}(1\times)\left[1 + \frac{dp}{Dp} COS\ \Phi\right]$ $= \frac{12}{2}(1\times)\left[1 + \frac{5}{29} COS\ 13^\circ\right]$ = 6.94× Based on the reference speed of shaft 1, which is 1600 CPM; BPFI: 6.94 ×1600 = 11,104 CPM

c) Ball spin frequency (BSF)

$$BSF = \frac{Dp}{2d_p}(1\times)\left[1-\left[\frac{dp}{Dp}\right].^2 COS^2\,\Phi\ \right]$$

$$= \frac{29}{2(5)}(1\times)\left[1-\left[\frac{5}{29}\right].^2 COS^2\,13^{\circ}\ \right]$$

$$= 2.83\times$$

Based on the reference speed of shaft 1, which is 1600 CPM;
BSF: 2.83 × 1600 = 4,528 CPM

d) Fundamental train frequency (FTF)

$$FTF = \frac{1}{2}(1\times)\left[1-\frac{dp}{Dp}COS\,\Phi\right]$$

$$= \frac{1}{2}(1\times)\left[1-\frac{5}{29}COS\,13^{\circ}\right]$$

$$= 0.42\times$$

Based on the reference speed of shaft 1, which is 1600 CPM;
FTF: 0.42 ×1600 = 675 CPM

The comparison between the simulation results produced by the i-Learn vibration software and the computation results shows no deficiency for the electric motor, flexible coupling, gearbox and centrifugal pump except for bearings, as shown in Table 4. The percentage error for the bearing is minimal, which is 0.02. The computation and simulation results are in good agreement, indicating the accuracy of the proposed model to a certain extent. Decimal point errors could cause the errors found in bearings deficiency. Therefore, these errors could be neglected.

Table 4: Comparison between the simulation and computation results

Component		Rate	i-Learn vibration simulation (CPM)	Computation (CPM)	% error
Electric Motor	Blade passing frequency	6×	9,600	9,600	0.00
	Motor rotor frequency	16×	25,600	25,600	0.00
Flexible Coupling	Coupling frequency	6×	9,600	9,600	0.00
Gearbox	Gear meshing frequency	22×	35,200	35,200	0.00
Centrifugal pump	1st Stage vane passing frequency	3.09×	4,940	4,940	0.00
	2nd Stage vane passing frequency	5.40×	8,646	8,646	0.00
Bearing 1	Ball pass frequency of outer ring (BPFO)	5.06×	8,098	8,096	0.02
	Ball pass frequency of inner ring (BPFI)	6.94×	11,102	11,104	0.02
	Ball spin frequency (BSF)	2.83×	4,526	4,528	0.02
	Fundamental train frequency (FTF)	0.42×	675	675	0.00

5 CONCLUSION

Condition monitoring is a crucial component of reliability-based maintenance analysis. Advanced tools, such as i-Learn vibration software, can provide essential information about the machine's reliability. It can also assist an analyst in interpreting the data, accurately diagnosing the problem, and trending the fault components until it is time to recommend corrective actions. The main contribution of this study is given by the i-Learn vibration software capability to report along with the detected faulty condition at an early stage. While the system has greatly reduced the computation effort, the results produced maintain good accuracy.

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