Evaluation of Torsional Vibration on Vertical-type Centrifugal Pump Shaft

*Hendri Chandra**
Muhamad Indra Luthfi
Department of Mechanical Engineering,
Faculty of Engineering,
Sriwijaya University,
Palembang, South Sumatera, 30662, Indonesia
**hendrichandra09@gmail.com*

Fauziana Lamin
Ahmad Kamal Ariffin
Centre for Integrated Design for Advanced Mechanical System (PRISMA)
Faculty of Engineering and Built Environment,
Universiti Kebangsaan Malaysia,
43600 Bangi, Selangor, Malaysia

ABSTRACT

A reliable procedure for malfunction detection due to excessive vibration is required especially for equipment that works in a continuous operation. In this paper, an analytical model to describe the vibration level of a vertical-type centrifugal pump shaft was developed. Based on the developed model, vibration characteristics of the pump was simulated. It was found that the pump vibrates at its natural frequency of 15.9 Hz with the amplitude of 0.2903. The tangential forces, as a result of the motor torque, forced the system to vibrate at a higher frequency of 325 Hz with a higher amplitude of 1. Physical vibration measurement revealed that vibration is primarily occurred on the vertical axis, in which point 1 recorded a higher level of vibration as compared to point 2. These procedures allow examination of the vibration level and primary axis of the vibration in the studied pump system for further monitoring application and appropriate maintenance action.

Keywords: *Analytical model; Centrifugal pump; Torsional vibration; Monitoring system; Maintenance*

ISSN 1823-5514, eISSN2550-164X

Received for review: 2017-10-11
Accepted for publication: 2018-06-08
Published: 2018-11-30

Introduction

Pump is one of the fluid flow machinery tools that serve to move fluids from one place to another by increasing pressure of the displaced fluid continuously. This tool is widely used in almost every manufacturing industry, particularly in the production process. The critical demand for pump usage in the industry has led to the investigation of an effective monitoring system as a continuing concern within the industrial practitioner.

According to S. Ebersbach et al. [1], the most common problem encountered in pump operation is caused by excessive vibration. It is primarily caused by resonance, which occurred when the excitation frequencies equivalent to the system's natural frequencies [2, 3]. Improper installation including poor support is another cause of vibration problem [4]. Use of different materials in a pump construction could also produce variation in the vibration as well as noise level [5]. In addition, vibrations level at different operating condition including rotation, different pump characteristics, dynamic or static load exhibits a unique dependency relation [6]. Besides the system itself, it could also be attributed to the fluid instability due to whirl and vortex that occurred while the pump is operating [7].

Numerous studies have been published to investigate this vibration phenomenon using various analytical and technical approaches. T. R. Milind and M. Mitra [8]established the use of multibody dynamics (MBD) and finite element (FE) approach in determining the dynamics and vibration behaviour of an axial piston pump. Natural frequencies and mode shapes have been evaluated by modelling the motor structure of a vertical pumping unit using FE analysis [9]. Experimental measurements using different measurements techniques including Operational Modal Analysis (OMA), Experimental Modal Analysis (EMA) and Operating Deflection Shape (ODS) that have also been incorporated by the previous researcher to locate the source of excessive vibration [2].

Accordingly, effective countermeasures in minimizing the level of vibration have been established. In view of the resonance problem, besides detuning the system by modifying the natural frequency to differentiate it with the excitation frequency, increasing the structure stiffness is among the possible efforts [9]. Realizing the importance of vibration monitoring, recently, S. Oscar and V. Anvar [10] proposed an automated control system of the actual state of the pumping units in real time for early defect detection on a pump system.

The existence of previous literature on characterizing and addressing the vibration phenomena in pump system demonstrates the crucial need of a detailed vibration assessment in a pump. Even though plenty of approaches have been introduced, it is necessary to select an appropriate technique for a specific system. Exploration of vibration characteristic in a system is persistently essential. Therefore, this paper aims to examine the vibration level in a centrifugal pump system and to assess the primary axis of the vibration. This data would enhance the understanding of the vibration characteristics in the pump system and would be beneficial for further vibration monitoring, control and maintenance in the future.

Materials and Methods

This study was conducted in three stages i.e. modelling, simulation and validation. Each procedure was described in the following subsections. The pump used in this study was a vertical-type centrifugal pump with fluid flow. Specification of the pump is listed in Table 1.

Table 1: Specification of the vertical-type centrifugal pump

Parameter	Value
Capacity	1100 m3/hour
Suction	1.033 kg/cm2. G
Discharge	6.03 kg/cm3. A
Total head	50,2 m
Driver	Motor 274 kW/1500 rpm
Mass of impeller	34.5 kg

Modelling and simulation

Model of the pump was initially developed to represent the actual system. It consists of two masses and a shaft that fixed at its one end as illustrated in Figure 1.

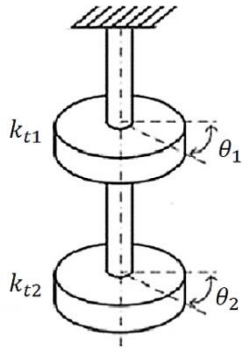

Figure 1: Free body diagram of two mass model

The analytical calculation was performed in order to evaluate vibration in the studied pump system. For that reason, mass moment of inertia for the shaft and impeller was obtained from the multiplication of the density and cross-sectional area of the steel component, as written in Eq. 1 and Eq. 2.

$$J_1 = J_{p1} + J_{i1} \tag{1}$$

$$J_2 = J_{p2} + J_{i2} \tag{2}$$

where $J_{p1} = J_{p2} = \rho J_A l = \pi/2 * r^4$, $J_{i1} = J_{i2} = w\, d^2/8g$, ρ is density of the shaft, l is length of the shaft, d is diameter of the impeller and $w = mg$. Angular velocity, ω_n can be expressed as in Eq. 3.

$$\omega_n = \sqrt{\frac{k_t}{J_T}} \tag{3}$$

where J_T is the total of mass moment of inertia and k_t is the torsional stiffness, which is formulated as in Eq. 4.

$$k_t = \frac{\pi G D^4}{32 l} \tag{4}$$

where G is the Shear Modulus and D is dithe ameter of the shaft. Since $f = \omega/2\pi$, natural frequency of torsional vibration, f_n can be calculated as in Eq. 5

$$f_n = \frac{1}{2\pi}\sqrt{\frac{(J_1 + J_2)k_t}{J_1 J_2}} \quad \text{[Hz]} \tag{5}$$

The amount of torsional vibration amplitudes, A, can be expressed as in Eq. 6.

$$A = \frac{T}{(k_t - (J_1 - J_2)\omega_n)} \tag{6}$$

where T is torsion induced by shaft rotation ($T = P60/\omega_n$, where P is powea r of the motor) and ω_n is the angular velocity, which is equals to $2\pi f$.

Simulation of vibration signals generated by the system was performed using MATLAB software. The generated signals were based on the developed analytical model. The observation was then performed to the generated signals, in terms of its vibration amplitude and frequency.

Validation

Validation process was conducted by performing vibration measurements on the actual physical system of the studied vertical type centrifugal pump shaft. This procedure aims to determine the vibration level and its primary vibration axis. In total, two measurement points at its three-dimensional axes were determined, as illustrated in Figure 2.

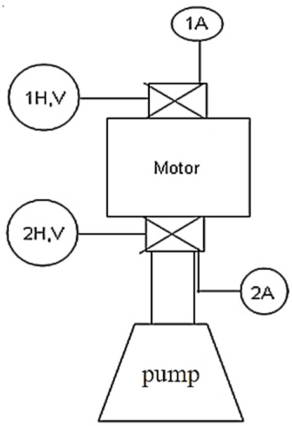

Figure 2: The six measurement points determined on the actual physical system

Referring to Figure 2, the measurement points were labelled as 1 and 2, in which the following letter *A*, *H* and *V* represent axial, horizontal and vertical axis respectively. Detail descriptions of each measurement points are summarized as follows:

1. 1*A*: Axial measurement point towards the direction of the x-axis
2. 1*H*: Horizontal measurement point toward the direction of the y-axis
3. 1*V*: Vertical measurement point towards the direction of the z-axis
4. 2*A*: Axial measurement point towards the direction of the x-axis
5. 2*H*: Horizontal measurement point toward the direction of the y-axis
6. 2*V*: Vertical measurement point toward the direction of the z-axis

Vibration measured at each point and axis was evaluated. The maximum level of vibration was accordingly determined and compared with the simulated results as a validation of the proposed model.

Results and Discussion

Findings of this study will be presented in the following subsections i.e. the simulated vibrations and the actual physical system vibration.

The simulated vibrations

Natural vibration of the studied pump system was simulated by incorporating the system configuration in the developed model. Signal generated as a result of the simulation was then plotted in both time and frequency domain, as shown in Figure 3. Based on the time domain signal (Figure 3a), it can be seen that the pump system vibrates naturally at the amplitude of 0.2903 mm-peak with an approximately constant time for one full oscillation. This is called the natural frequency of the system, which is found to be 15.9 Hz, as shown in the frequency domain in Figure 3b.

Figure 4 shows the changes of frequency versus time. It can be observed that the system vibrates with a frequency range up to 71,679 Hz. This maximum frequency value was referred to as the torsional vibration signal excited on the system.

Besides natural vibration, excitation from internal and external forces also generates additional vibration in a system. Figure 5 shows the signal generated by these excitation signals. In this case study, the additional vibration signal is mainly caused by the tangential forces as results of torque from the motor.

Figure 5(a) exhibits that the tangential forces increase the vibration in the system to 1 mm-peak, three times the natural vibration of 0.2903 mm-peak. The system also forced to vibrate at a higher frequency level, in which a complete oscillation was achieved in a time of less than 0.005s. The spectrum of frequency components revealed a dominant frequency of 325 Hz, as shown in Figure 5b. This finding reveals that there is the occurrence of excessive vibration in the system.

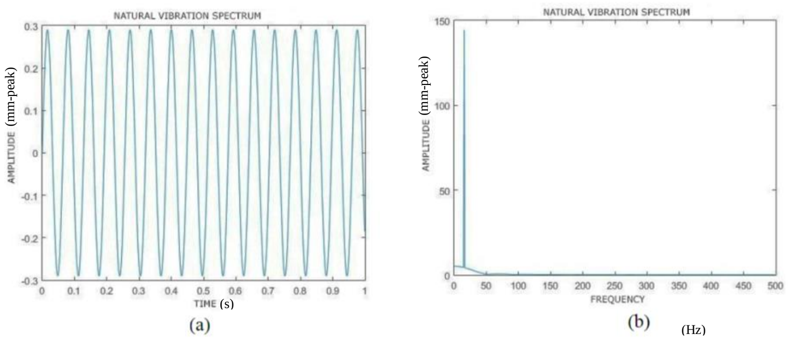

Figure 3: The natural vibration signal: (a) time domain, (b) frequency domain

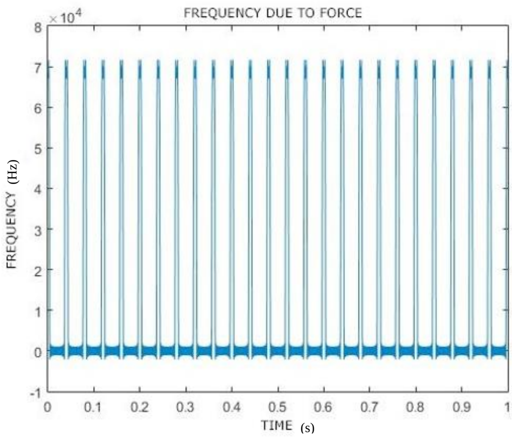

Figure 4: Excitation frequency versus time

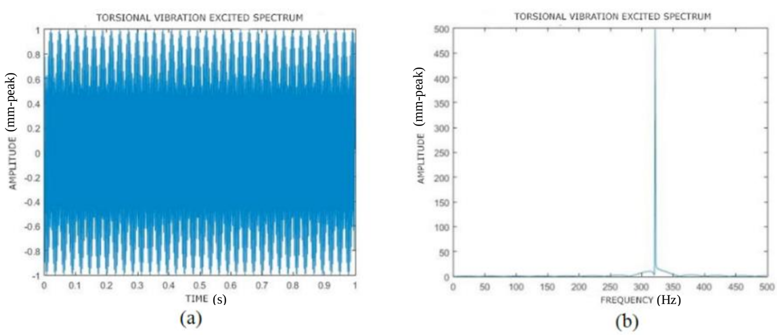

Figure 5: The excitation torsional vibration signal:
(a) time domain, (b) frequency domain

The actual physical system vibration

Vibration measurements were conducted at the six determined points and axes while operating the centrifugal pump. The signals generated at these points were illustrated in Figure 6. The vibration value for each point of measurement is 3.008 mm/s-Peak, 5.254 mm/s-Peak and 9.153 mm/s-Peak at point 1*A*, 1*H* and 1*V* respectively. At this particular point, the vertical axis (1*V*) shows the highest vibration level as compared to the other two axes of measurement, 1*H* and 1*A*.

Meanwhile, at the second point of measurement, the vibration was found to be 1.832 mm/s-Peak, 2.21 mm/s-Peak and 4.553 mm/s-Peak at point 2*A*, 2*H* point, and 2*V* respectively. Similarly, the vertical axis recorded the highest vibration level, which explains the primary axis of vibration in the system. This result is consistent with the vertical-type pump shaft model simulation finding, reported in the previous subsection, which found the occurrence of excessive vibration.

In comparison between both measurement points, point 2 vibrates at a lower level as compared to the point 2. These findings describe that the upper part of the system experience more displacement as compared to the lower part. This might be due to the closer distance between the point 2 and the fixed end support.

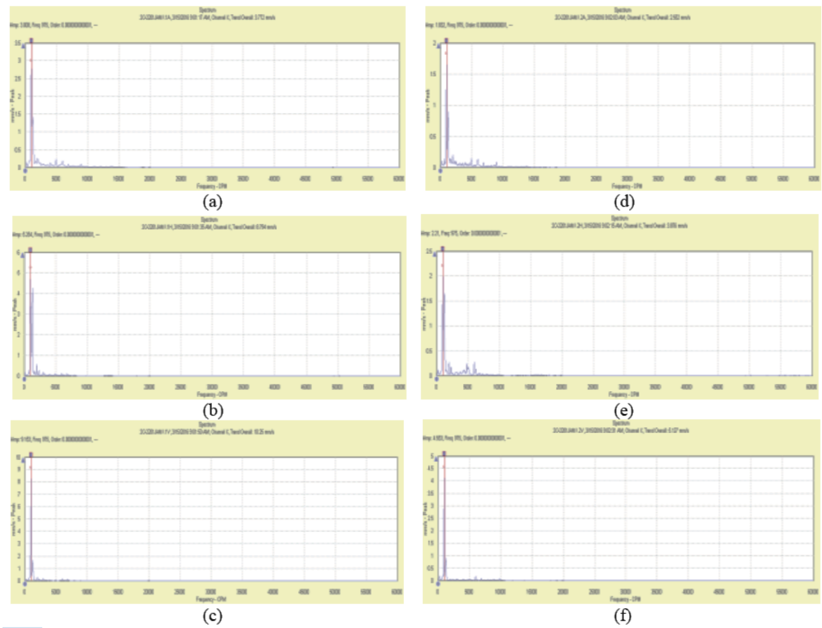

Figure 6: Vibration signals at the different measurement point and axes: (a) 1A, (b) 1H, (c) 1V, (d) 2A, (e) 2H and (f) 2V

Conclusion

This study set out to examine the vibration level in a centrifugal pump system and to assess the primary axis of the vibration. The findings clearly indicate that the pump system vibrates at its natural frequency of 15.9 Hz with the amplitude of 0.2903. The tangential forces as a result of the torque of the motor forced the system to vibrate at a higher frequency of 325 Hz with a higher amplitude of 1, which may cause the excessive vibrations. Furthermore, physical vibration measurement revealed that vibration is primarily occurred on the vertical axis, in which the point 1 recorded a higher level of vibration as compared to point 2. These findings provide a better insight of the vibration characteristics of the vertical-type centrifugal pump shaft. This work contributes to the existing knowledge of such pump monitoring system, especially for monitoring and maintenance purpose. As with all business practices, managing critical equipment requires an effective monitoring and proactive maintenance in order to ensure that operational risk reduction is actively performed.

References

[1] S. Ebersbach, Z. Peng and N. Kessissoglou, "The Investigation of the Condition and Faults of a Spur Gearbox Using Vibration and Wear Debris Analysis Techniques," Wear (260), 16–24 (2006).

[2] J. Grosel, W. Pakos, and W. Sawicki,"Experimental measurements as the basis for determination of the source of pumps' excessive vibration," Procedia Engineering (111), 269–276 (2015).

[3] J. K. Sinha and A. R. Rao,"Vibration diagnosis of failure of mechanical coupling between motor and pump rotors," Int. J. Acoust. Vibr (10), 89–92 (2005).

[4] K. Fetyan and D. M. El-Gazzar,"Effect of motor vibration problem on the power quality of water pumping stations," Water Science (28), 31–41 (2014).

[5] L. Rodionov and P. Rekadze, "Experimental Vibroacoustic Research of a Gear Pump Made of different Materials," Procedia Engineering (176), 636–644 (2017).

[6] S. C. Mustata, D. Dracea, A. S. Tronac, N. Sarbu and E. Constantin, E,"Diagnosis and vibration diminishing in pump operation," Energy Procedia (100): 970–976 (2015).

[7] T. N. Kushwaha, "CW Pump Fluid Induced Vibration Troubleshooting Methodology," Procedia Engineering (144), 274–282 (2016).

[8] T. R. Milind and M. Mitra, "A Study on the Dynamics and Vibration Behavior of an Axial Piston Pump Using Combined MBD/FE Approach," Procedia Engineering (144), 452–460 (2016).

[9] D. M. El-Gazzar, "Finite element analysis for structural modification and control resonance of a vertical pump," Alexandria Engineering Journal (56),695-707(2016).

[10] S. Oscar and V. Anvar,"The Monitoring System of an Actual Technical Condition for Pumping Units with Frequency Analysis," Procedia Engineering (176), 144–149 (2017).