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Experimental Investigation of Impeller Material on the Vibration Spectrum in a Centrifugal Pump

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Abstract

This study investigates experimentally the effect of impeller material on the generated vibration level from a centrifugal pump under various operating conditions, including normal operation, the onset of cavitation, and fully developed cavitation. Five different impeller materials—plastic, cast iron, brass, stainless steel, and aluminum—were experimentally tested. Cavitation was determined at the separation point on H-Q curve when the head dropped by 3% and by analyzing the vibration spectrum at a pump speed of 2850 rpm with varying suction pressures. The experimental setup included a centrifugal pump equipped with pressure transducers and a turbine flow meter to measure the suction pressure, outlet pressure and water volume flow rate. Vibration acceleration measurements were taken using an accelerometer with bandwidth of 20-20000 Hz, recorded via a data acquisition system using LabVIEW software. Results indicate that the plastic impeller generates the lowest vibration levels in both the normal and cavitation conditions. Furthermore, the vibration spectrum amplitude in the high-frequency range of the vibration spectrum varied significantly between different impeller materials during the normal pump operation. Cavitation can lead to an increase in the vibration amplitude in the high frequency range. This study provides quantitative insights into the vibration behavior of impeller material, suggesting plastic impellers as optimal for vibration reduction strategies.

Keywords: Centrifugal pump, cavitation, vibration, impeller material, vibration spectrum

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Nomenclatures

c_1	Fluid absolute velocity at impeller inlet	m/s
c_s	Flow velocity at the pump suction	m/s
g	Gravitational acceleration	m/s^2
H	Pump head	m H_2O
N	Pump rotation speed	RPM
p_d	Absolute discharge pressure	Bar
p_s	Absolute pressure at the pump suction	Bar
p_v	Absolute vapor pressure at the fluid temperature	Bar
Q	Pump discharge	L/h
R_F	Pump rotational speed frequency	Hz
z	Potential elevation	M
ρ	Density of fluid	kg/m^3

Abbreviations

$NPSH_A$	Available Net Positive Suction Head
$NPSH_R$	Required Net Positive Suction Head
PVC	Polyvinyl chloride
PC	Personal Computer
FFT	Fast Fourier Transform

1. Introduction

Centrifugal pumps play a crucial role in a wide range of industrial applications, including water distribution systems and chemical processing plants. These pumps rely on impellers to transfer energy to the fluid, however under certain conditions, cavitation may occur. Cavitation—a phenomenon involving the formation and collapse of vapor bubbles within the pump—is a major concern as it can reduce pump efficiency, cause material damage, and produce excessive vibration. The study of cavitation, therefore, remains a critical area of research for improving pump reliability and performance [1-7]. Cavitation primarily occurs when the pressure within the pump drops below the vapor pressure of the fluid, causing vapor bubbles to form at the impeller's eye. These bubbles are swept along the impeller vanes and collapse in regions of higher pressure, causing noise, vibrations, and potentially damaging the impeller surface. Prolonged cavitation degrades pump performance, leading to efficiency loss and, in severe cases, mechanical failure. One of the most distinct symptoms of cavitation is the distinctive vibration it produces [8-14].

While earlier studies, such as Albarik et al. [15] studied single-suction, single-stage, end/top discharge, closed impeller and closed-coupled centrifugal pump, which can deliver water at a rate of up to 30 m^3/h at a head of up to 55 m. It is driven by a three-phase electric motor running at 2900 rpm on 9.5A at 380 - 400 V (nominal 4 kW). The results showed that the vibration level increases with increased of flow rate and the pump faults may then be identified using these data/features. In addition, Suhane [16] used single-stage horizontal and diffuser type pump with impeller having eight blades and diffuser having seven blades. Radial clearances of the order 6.8 mm, 3.7 mm, 1.5 mm has been used during the experimentation. It was found that; vibration is dominating at the fundamental frequency. The overall vibration level is minimal at low flow rates and elevated at higher flow rates. The larger radial clearance, the more erratic flow becomes, and the energy with which the fluid impacts the diffuser decreases. Consequently, the total vibration is lowest when the radial clearance is at its maximum.

Other studies have examined investigated the cavitation detection using discrete wavelet transform by classifying the pump vibration signal [17]. Vibration signal acquired from centrifugal pump cavitation test rig carry more information about the cavitation classes. Two classes have been defined namely, no cavitation class and developed cavitation class. This method uses the deviation from zero mean value of detailed components of wavelet coefficients, obtained from five level decomposition of vibration signal to detect the signal belongs to normal class or cavitation class in centrifugal pump. The advantage of this proposed algorithm, more robust results show that this algorithm has better detection response. Furthermore, both the inception and development of cavitation in three different impellers of a laboratory centrifugal pump with a Plexiglas casing, using flow visualization, vibration and acoustic emission measurements have been investigated in [18]. The results showed that the geometrical characteristics of the impeller affect cavitation development and behaviour, while an acoustic emission sensor and an accelerometer can be applied for successfully detecting the onset of this mechanism.

Despite extensive research on cavitation in centrifugal pumps, the specific role of impeller material on vibrational behavior remains underexplored. In addition, a detailed understanding of how different impeller materials affect vibration emissions under both normal and cavitation conditions is still lacking. Therefore, the current study aims to fill this gap by investigating the vibration behavior of five different impeller materials—plastic, cast iron, brass, stainless steel, and aluminum—during centrifugal pump operation under normal and cavitation conditions. By analyzing the vibration emissions due to using plastic, cast iron, brass, stainless steel, and aluminum, a deep understanding of material selection will be explored in pump design and offer insights into vibration reduction strategies in centrifugal pumps.

2. Pump Operation at the Cavitation Condition

Applying Bernoulli's equation (1) along a streamline inside the impeller shows that static pressure decreases as flow velocity increases:

$$\frac{p_s}{\rho g} + \frac{c_s^2}{2g} + z + H_p = constant \tag{1}$$

Where p_s is the absolute pressure at the pump suction, related to the pump centerline, ρ is the fluid density, c_s is the absolute suction flow velocity, g is gravitational acceleration, z is the potential elevation, and H_p is pump head. Figure 1 case (a) illustrates how the pressure within the impeller path decreases to a minimum value at a certain location in the impeller eye and then increases near the impeller blades walls due to the pumping action. When the pressure falls below the fluid's vapor pressure, as shown in Figure 1 case (b), cavitation bubbles form and collapse when exposed to a high pressure at certain location in the way out near the impeller blade walls, producing noise and vibration.

The available net positive suction head ($NPSH_A$) is defined as the available total suction head at the pump inlet above the head corresponding to the vapor pressure at a given liquid temperature.

$$NPSH_A = \frac{p_s - p_v}{\rho g} \tag{2}$$

The cavitation occurs when the required net positive suction head ($NPSH_R$) is greater than the available net positive suction head ($NPSH_A$).

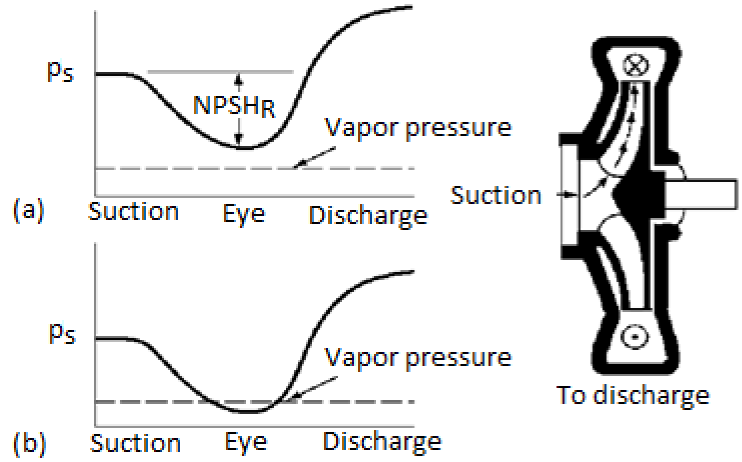


Fig. 1. Schematic distribution of the static pressure along the pump impeller: (a) Normal operating condition, (b) Operating at cavitation condition. [19]

3. Methodology

3.1. Experimental Setup

The experimental test rig (Figure 2) was designed according to ISO 3555 and BS EN ISO 9906/2000 [20] standards to ensure precision and repeatability in performance and efficiency measurements. The system operates as a closed-loop water circuit consisting of a tank, pump, polyvinyl chloride (PVC) pipes, regulating valves, pressure transducers and a turbine flow meter. The water temperature was maintained at 27 ^{o}C using a temperature control unit.

The centrifugal pump tested (JET SJET-100B model) has a rotational speed of 2850 rpm, with a maximum discharge of 55 L/min at a head of 7.5 m. The pump is powered by an electric motor with a maximum capacity of 0.75 kW. The emitted vibration from the pump was tested using impellers made from five different materials: plastic, cast iron brass, stainless steel and aluminum. Each impeller featured six backward-curved blades, with inlet and outlet diameters of 33 mm and 125 mm, respectively.

3.2 Vibration Acceleration and Flow Measurements

There are a set of measuring instruments inside the test rig. Water pressures were measured using both pre-calibrated dial gauges and pressure transducers, with accuracies of 0.5% and 0.25% for both the pump suction and discharge measurements, respectively. The inlet water pressure transducer is of

Holykell HPT200-H type ranging from -1 to 1 bar, while the outlet water pressure transducer is of HolyKeller Pa 21 SR type ranging from 0 to 28 bar. The transducers output signals are 4 to 20 mA to ensure noiseless signal. The water flow rate was measured by a turbine flow meter of accuracy ±2%, and its range is 0 - 60 L/min. A BK 4134 accelerometer with a frequency of 5–20 kHz and ±0.001 m/s^2 attenuation in the range of 5 -10 kHz was used to measure generated vibration. This accelerometer was placed 35 cm from the pump to record vibration levels and ensure consistent measurements during the experiments.

3.3. Data Acquisition

All measured signals were recorded using NI 9234 data acquisition system (DAQ) with a 24-bits resolution and 102 dB dynamic range, with 2 mA signal stabilization, constant current accelerometer. The sampling rate per channel is 51.2 k-sample/s. Both the pump and accelerometer have the same level.

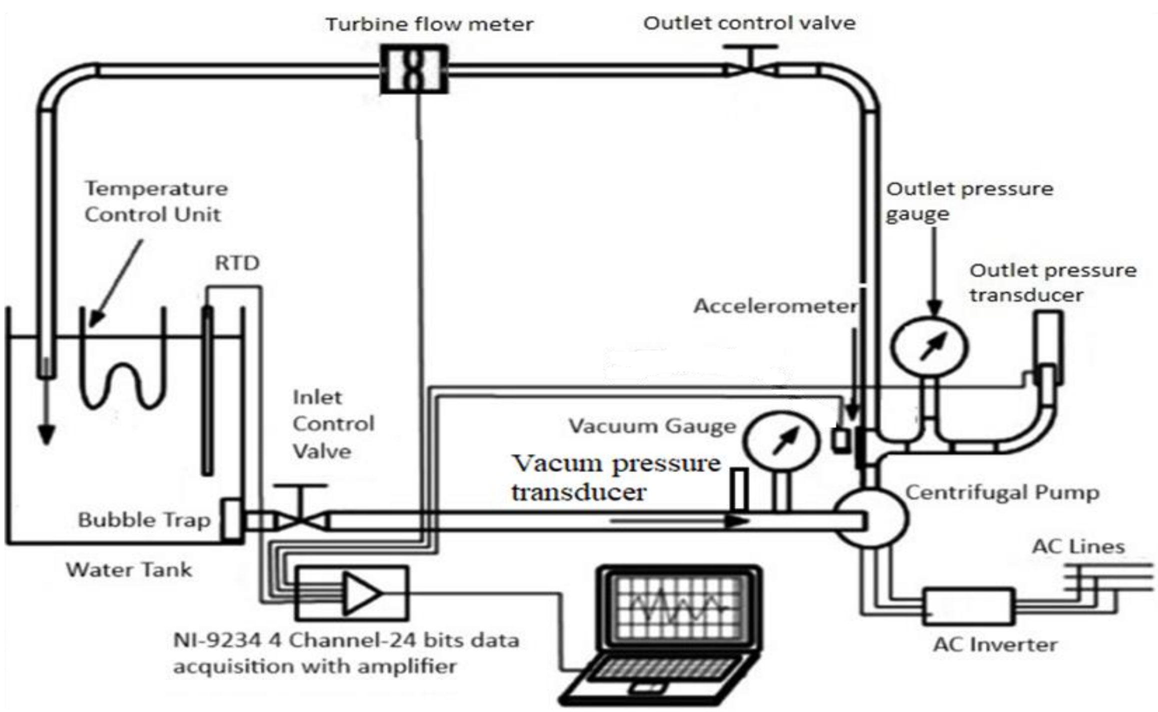


Fig. 2 Experimental test rig.

3.4. Experimental Data Analysis Procedure

LabVIEW software was used to perform real-time data acquisition and produce graphs for all simultaneously measured parameters. The LabVIEW software was used for recording both the upstream and the downstream pressures, the water mass flow rate and the vibration level continuously. The software performs Fast Fourier Transform (FFT) analysis of the vibration signals. The scheme of peak hold is applied for 10 second, and each measurement was repeated 10 times (one second at a time) to ensure accuracy. Meanwhile both the instantaneous volume flow rate and the downstream pressure were continuously acquired and averaged for the 30 second run. Both the raw and processed data were then stored in an Excel sheet file. Figure 3 shows the LabVIEW block diagram of the whole program. It includes the DAQ Assistant toolbox which acquires four analog measurements channels each has 50 kHz sampling rate. The second measurement (acceleration amplitude vs. time). Meanwhile, FFT subroutine was used to convert the pressure-time values to amplitude-frequency values in the range (5-20000 Hz). The process was repeated 10 times and Peak hold scheme was used during FFT analysis. This can be seen from the 10 arrows shown at the left side of this figure. The third and fourth measurements were the vacuum inlet pressure and delivery pressure (pump head) in meters units, respectively. Both these pressures were averaged over a period of one second.

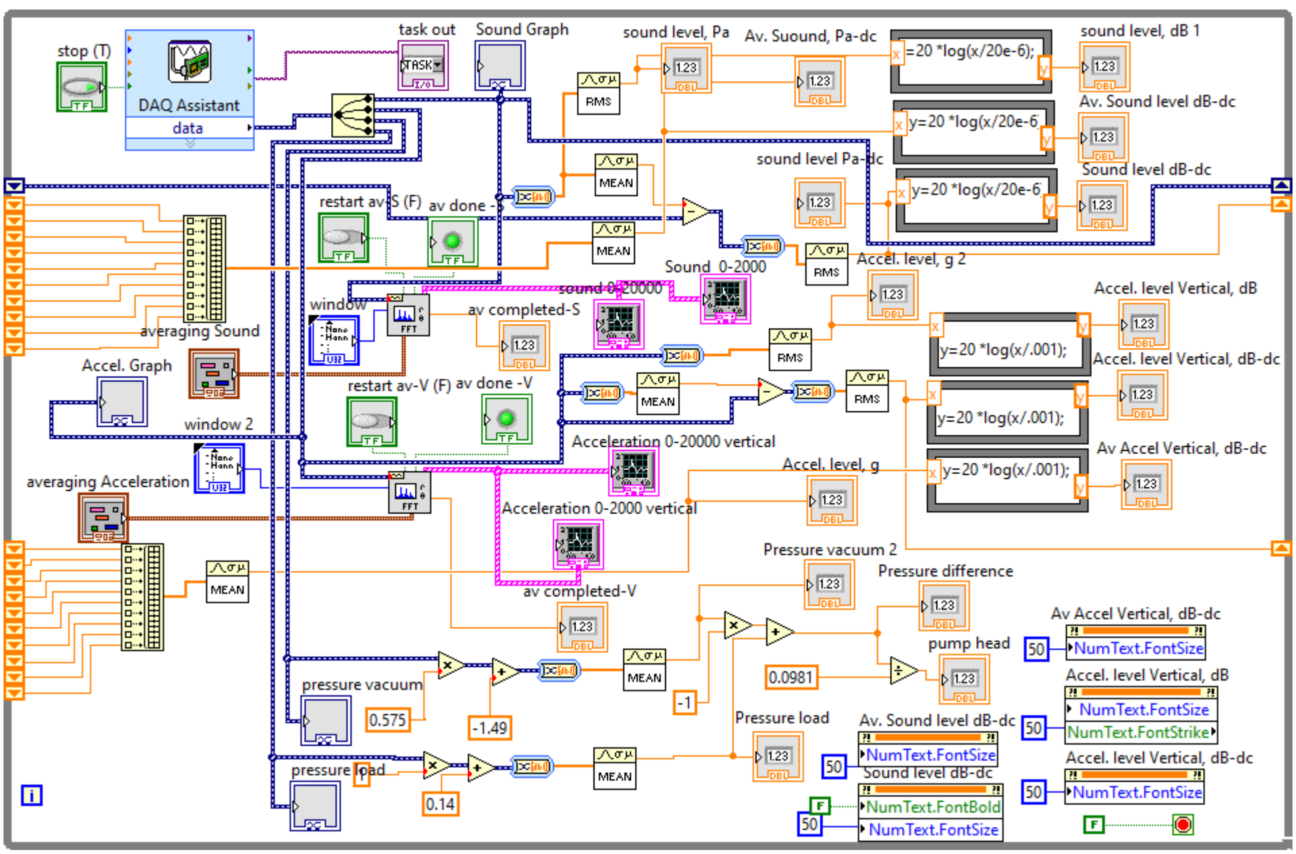


Fig. 3 LabVIEW block diagram of the whole program

4. Results and Discussion

4.1. Pump performance characteristics at variable suction pressures

Figure 4 shows the experimentally measured pump performance characteristic curves (pump discharge versus the pump head). They are almost the same for the five impeller materials at the rotational pump speed of 2850 rpm (47.5 Hz). The absolute suction pressure varies from 0.18 to 0.92 bar absolute. At each suction pressure, there is a certain point where the performance curve breaks away from the normal profile where the head starts to degrade, while the flow is getting choked. The operating point at the beginning of the choked flow is defined as the separation point (practically when the head drops by 3%). These separation points at each suction pressure are indication for the commencement of cavitation. The required Net Positive Suction Head ($NPSH_R$) is also shown to increase with increasing the pump flow rate.

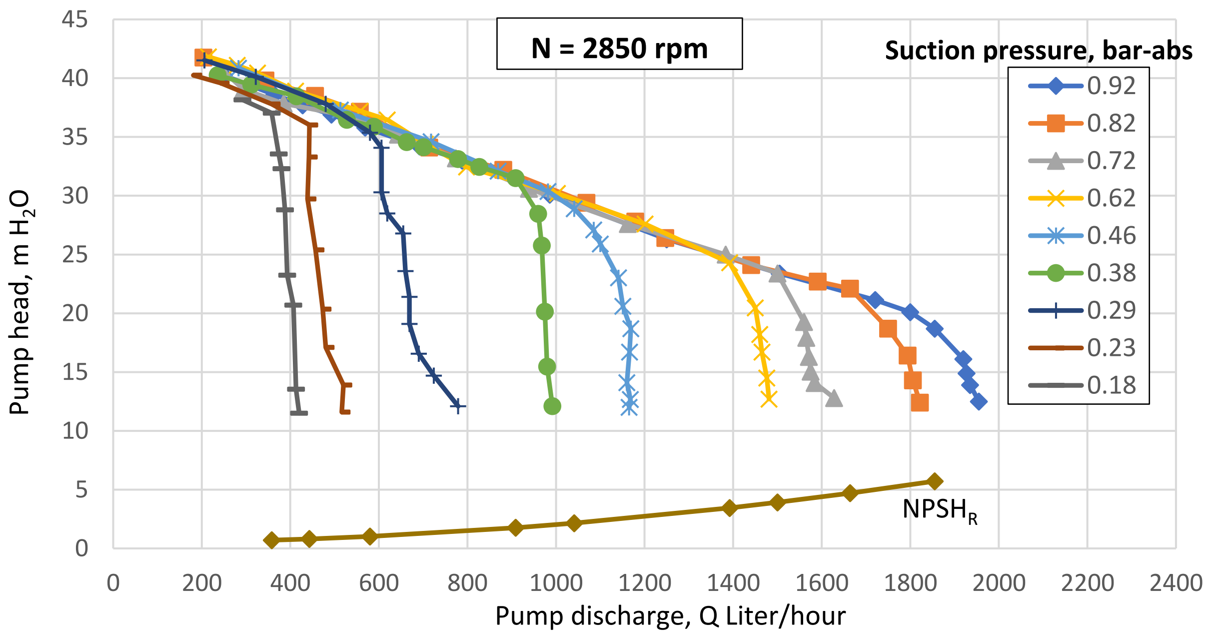
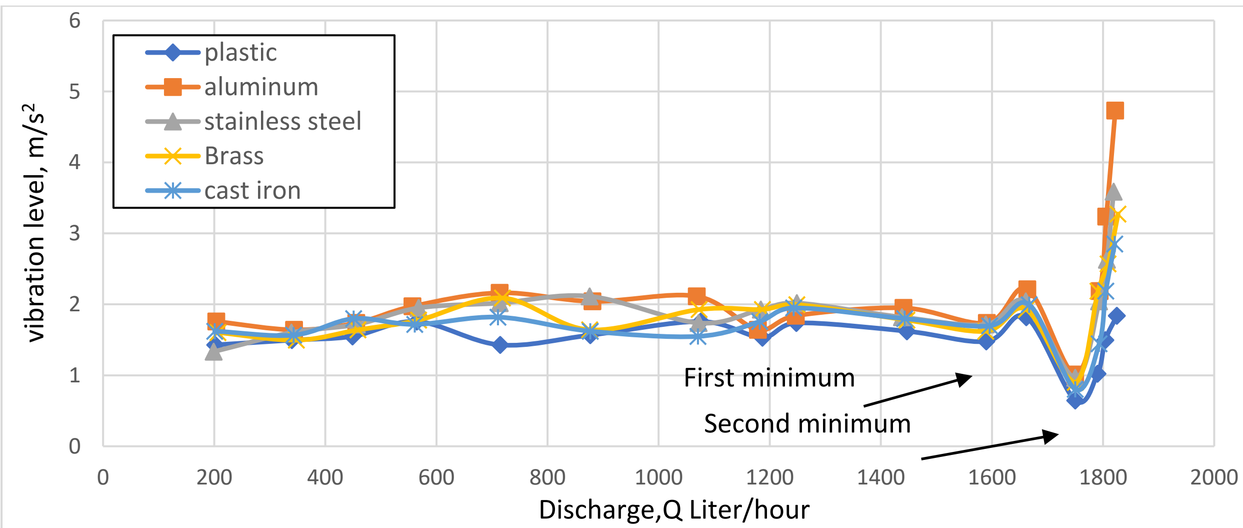


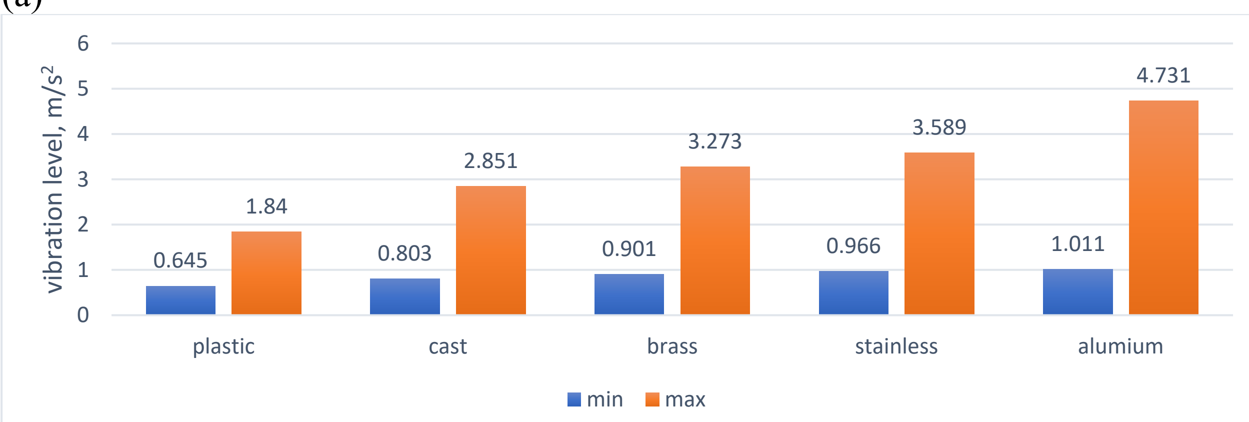
Fig. 4 Pump performance characteristics at variable suction pressures for N = 2850 rpm.

4.2. Vibration levels generated from the pump.

Figures 5–7 present the generated vibration levels from the pump during both the normal and cavitation conditions for the tested five impeller materials at different suction pressures of 0.82 bar, 0.62 bar and 0.38 bar- absolute. At the suction pressure of 0.82 bar absolute, Figure 5-a, as the discharge increases in the no-cavitation range (200 - 1660 Liter/hour), the vibration level is almost constant at 1.6 m/s^2 with a little fluctuation. As the discharge increases beyond 1660 Liter/hour, the vibration level drops abruptly to a minimum value of 0.645 m/s^2, then it increases sharply to 4.7 m/s^2 at 1820 Liter/hour. This Figure also shows two points of minimum vibration level. The first point lies in the normal operation range while the second minimum occurs during the cavitation condition. Figure 5-b shows both the minimum and maximum vibration levels for the five impellers. It is clearly shown that the plastic impeller produces the lowest vibration level. Under normal pump operation (suction pressure of 0.82 bar absolute).



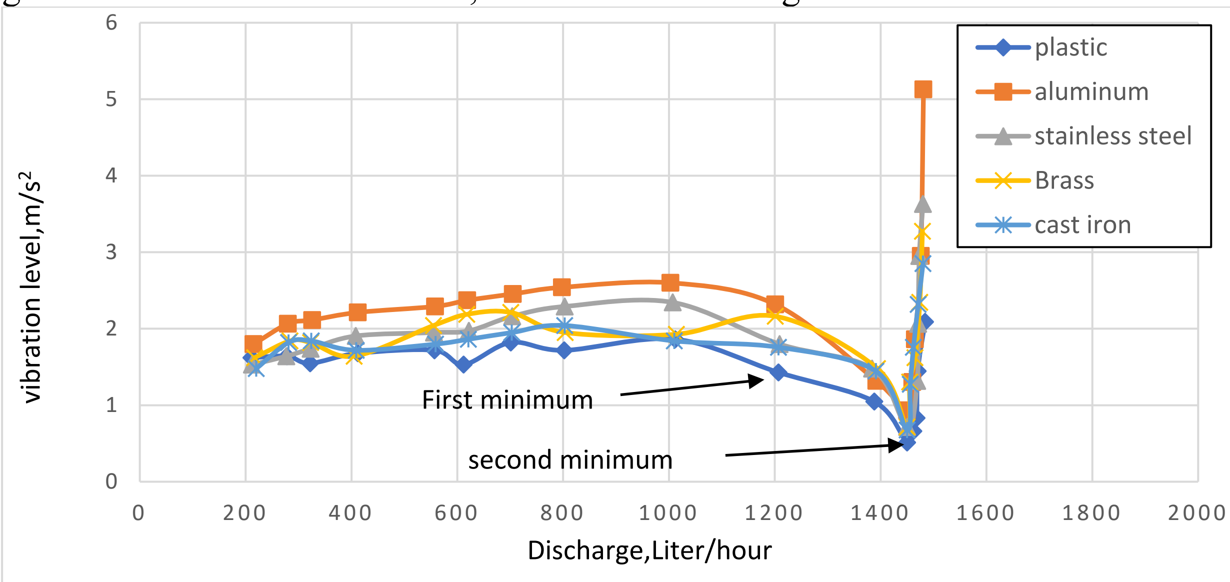
(a)



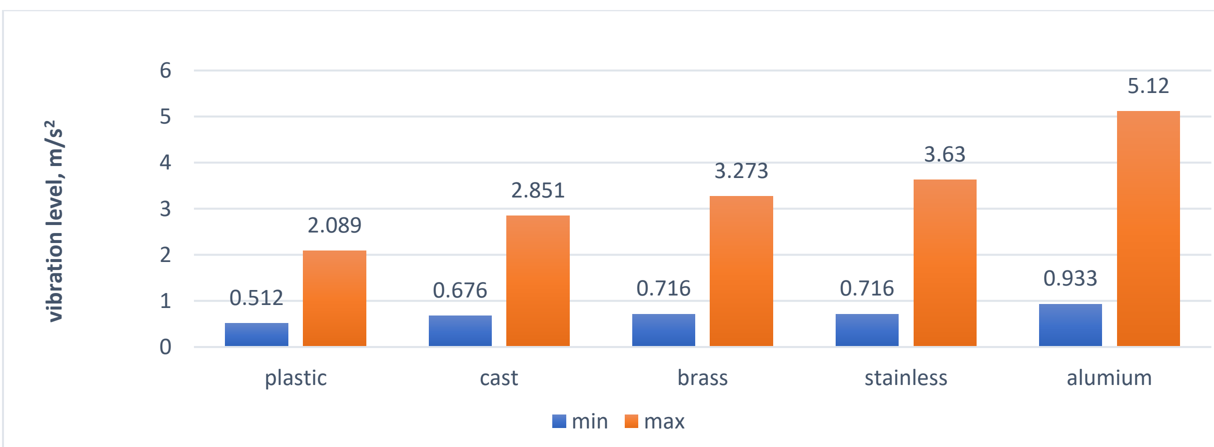
(b)

Fig. 5 Vibration level at 0. 82 bar absolute suction pressure, (a) Variation with discharge, (b) Minimum and maximum values for different impeller materials.

However, at the other two suction pressures of 0.62 and 0.38 bar absolute, a big variation of the vibration level with the impeller material in the no-cavitation operation range, see Figure 6-a& 7-a. In the cavitation operation zone, the difference between the maximum and the minimum vibration levels increases as can be seen from both Figures 6-b& 7-b. As cavitation developed at 0.62 and 0.38 bar absolute, the differences in vibration levels between materials became more pronounced, with aluminum producing the highest vibration while the plastic material impeller still gives the lowest vibration level, as shown in these figures.

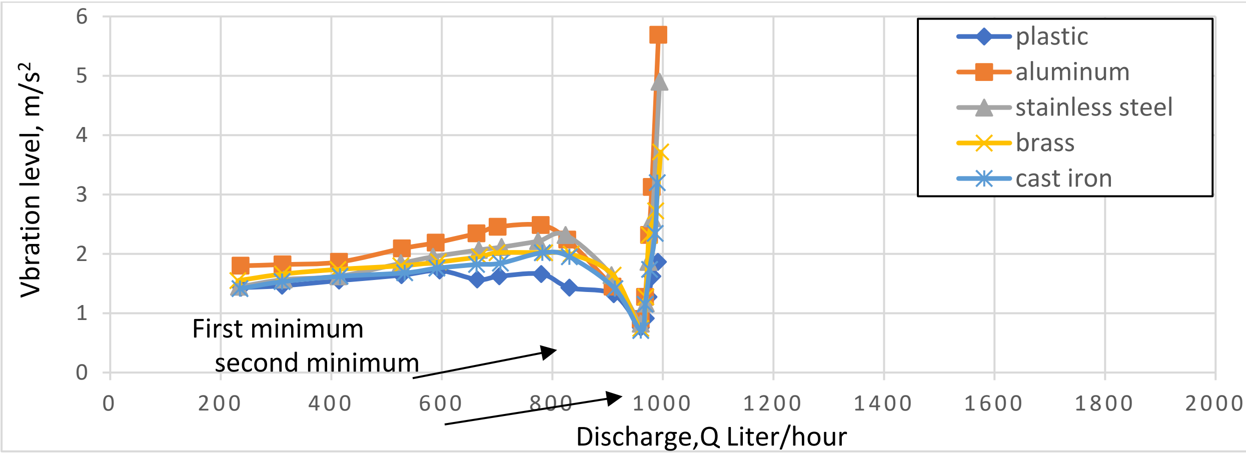


(a)

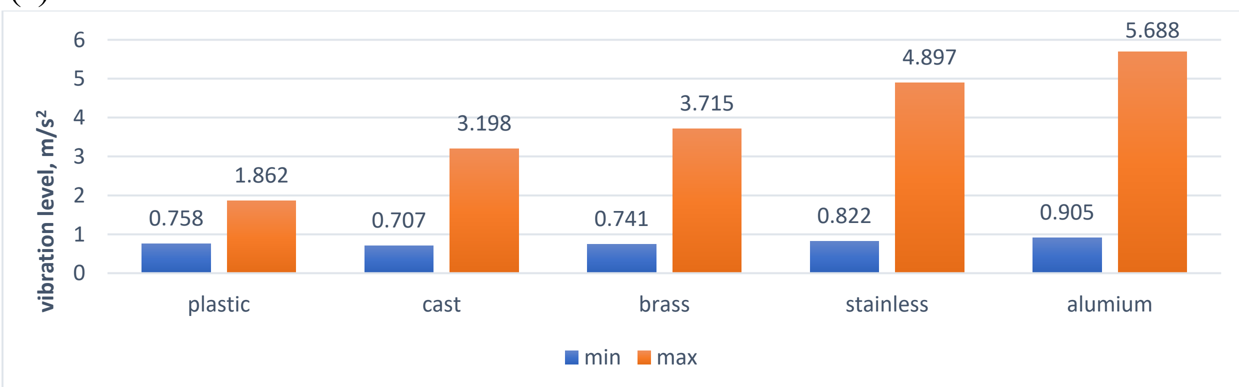


(b)

Fig. 6 Vibration level at 0.62 bar absolute suction pressure, (a) variation with discharge, (b) minimum and maximum values for the five different impeller materials.



(a)

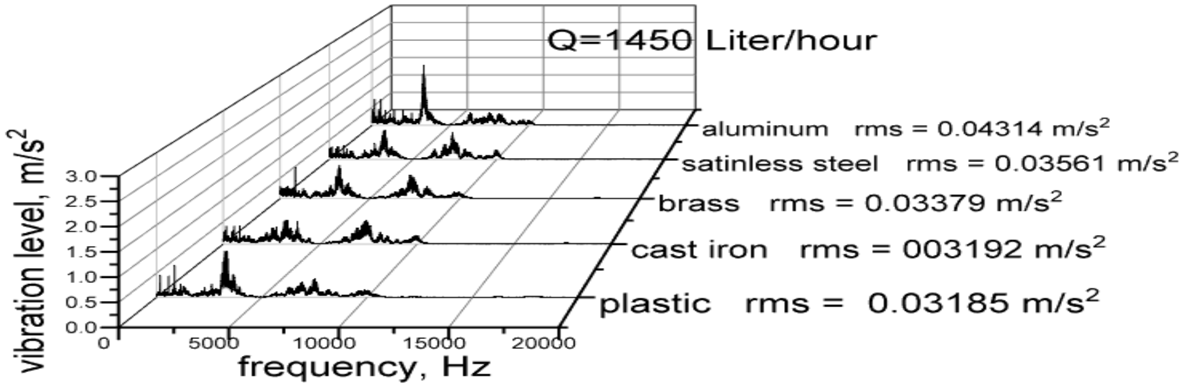


(b)

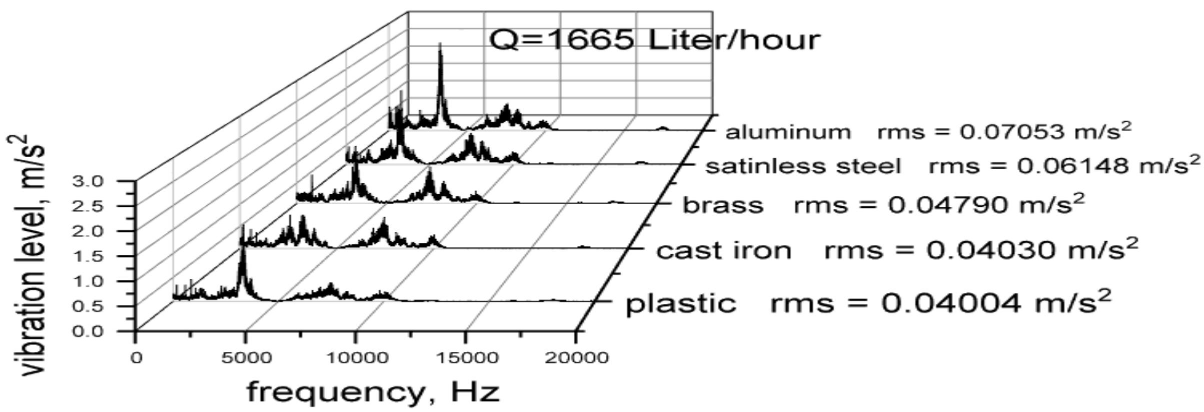
Fig.7 Vibration level at 0.38 bar absolute suction pressure, (a) variation with discharge, (b) minimum and maximum values for the five different impeller materials.

4.3. Fast Fourier transform (FFT) analysis

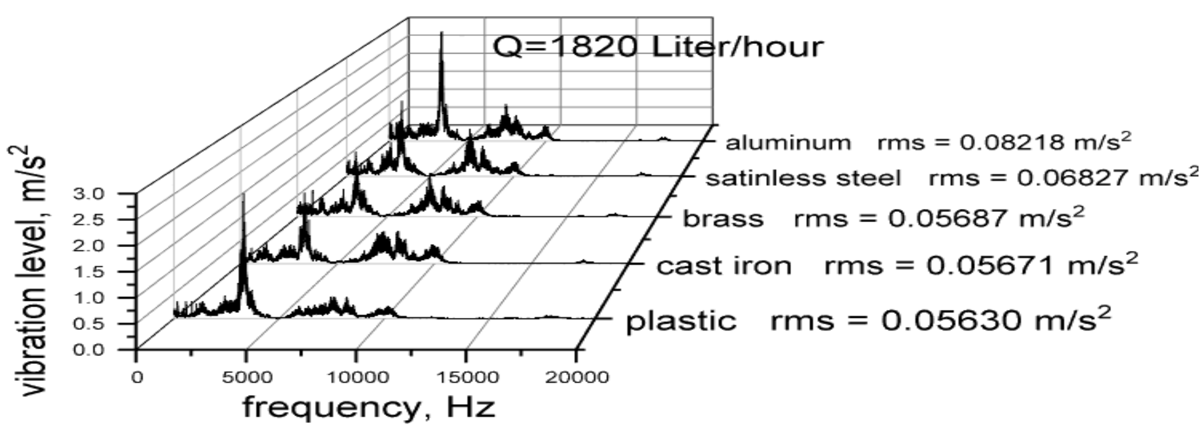
The Fast Fourier Transform (FFT) analysis of the generated vibration spectrum from the pump in the frequency range 20 - 20000 Hz is clearly presented in (Figures 8–10) for the five different impeller materials at suction pressures of 0.82, 0.62 and 0.38 bar-absolute. For each suction pressure, three operating cases are shown to represent (a) no-cavitation case, (b) starts of cavitation case and (c) cavitation case. FFT analysis (Figures 8–10) revealed a peak vibration amplitude around 3700 Hz, which increased as the pump operation changes from normal operation to cavitation case specially at low suction pressures. For the Aluminum impeller, for instance, at suction pressure 0.62 bar-absolute, the root mean square (rms) of vibration increases from 0.05508 to 0.07805 to 0.08490 m/s^2 corresponding to normal operation, start-of-cavitation, and cavitation case respectively. This peak vibration amplitude could be a good indication of cavitation diagnosis. Plastic impellers consistently showed lower peak amplitudes, confirming their vibration-reduction potential.



(a) no-cavitation (Q = 1450 Liter/hour)

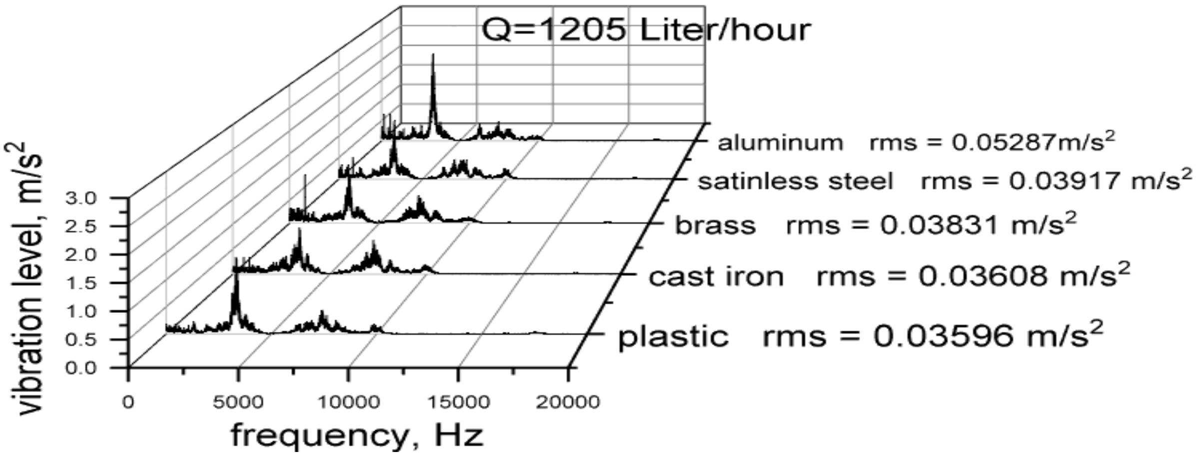


(b) start of cavitation (Q = 1665 Liter/hour)

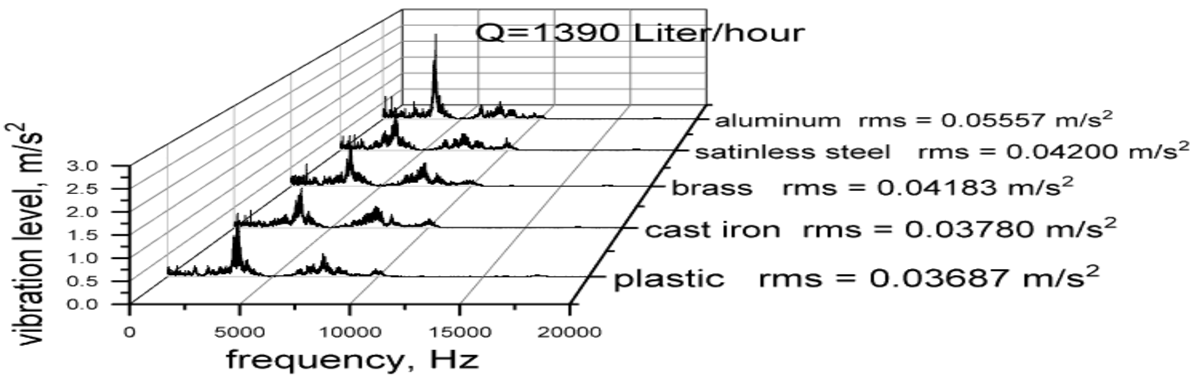


(c) cavitation (Q = 1820 Liter/hour)

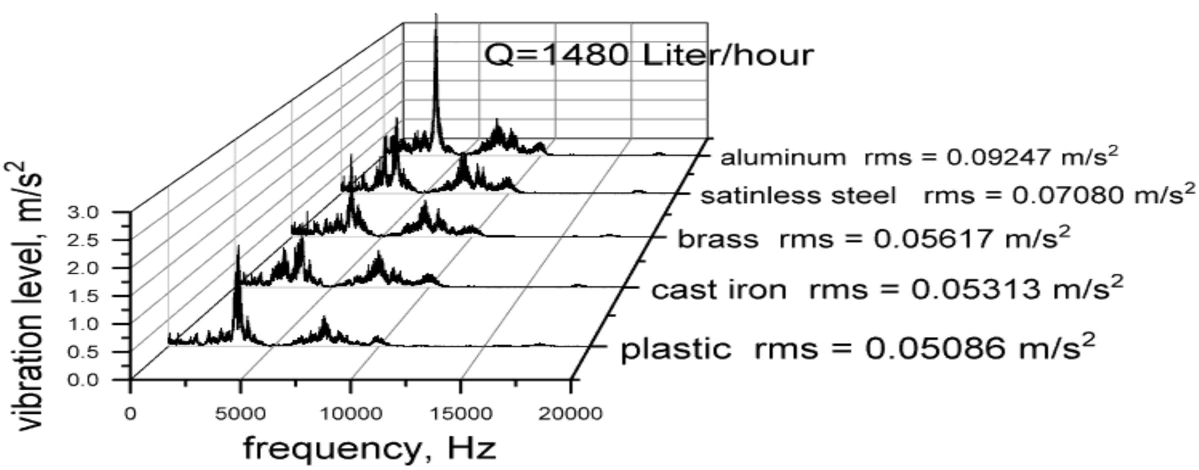
Fig. 8 Vibration level spectrums for three operating cases: (a), (b) and (c) at the suction pressure of 0.82 bar absolute for the five different impeller materials.



(a) no-cavitation (Q = 1205 Liter/hour)

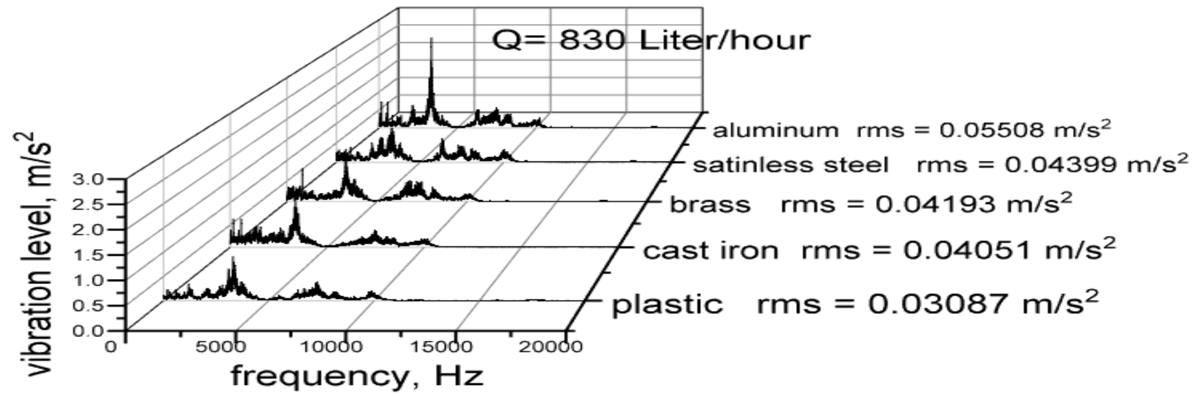


(b) start of cavitation (Q = 1390 Liter/hour)

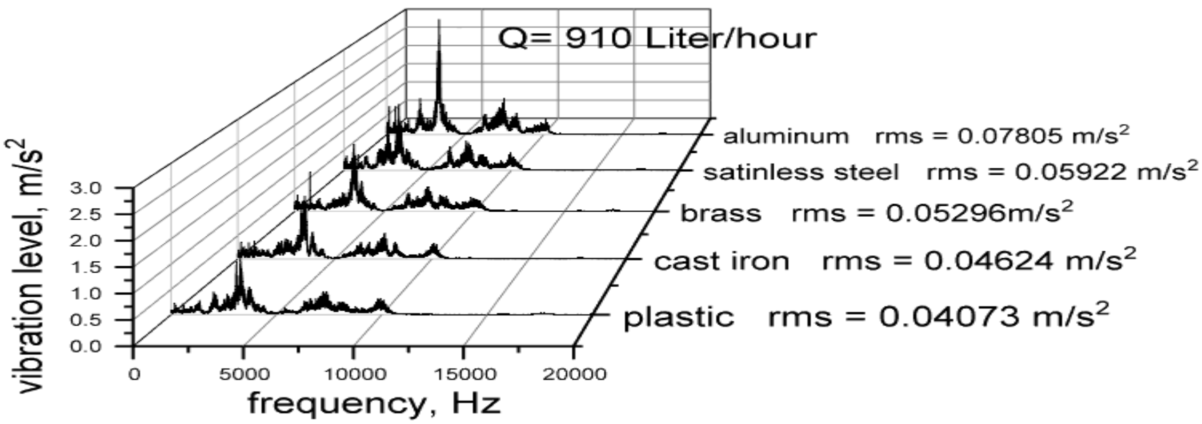


(c) cavitation (Q = 1480 Liter/hour)

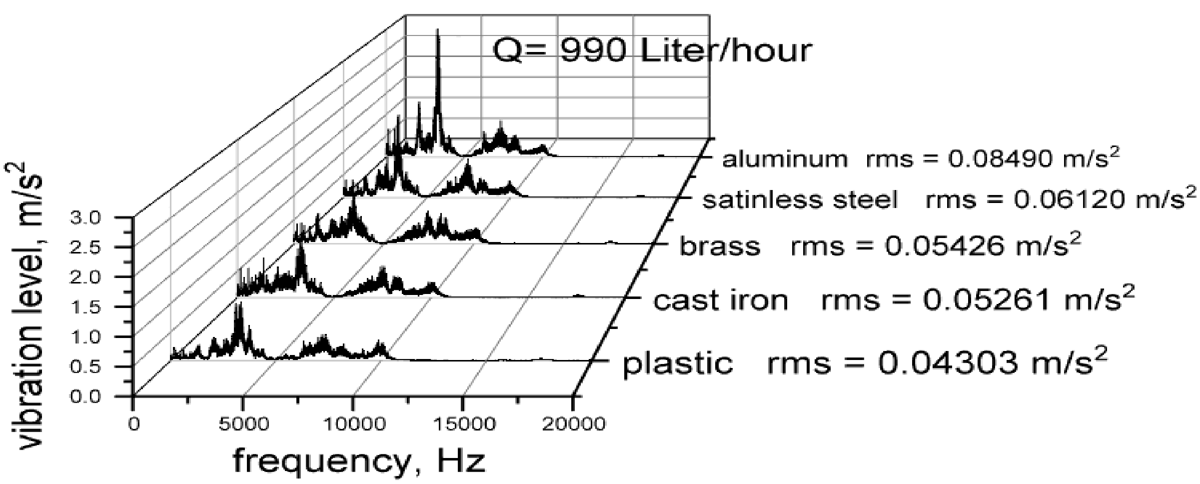
Fig. 9 Vibration level spectrums for three cases: (a), (b) and (c) at the suction pressure of 0.62 bar absolute for the five different impeller materials.



(a) no-cavitation (Q = 830 Liter/hour)



(b) start of cavitation (Q = 910 Liter/hour)



(c) cavitation (Q = 990 Liter/hour)

Fig.10 Vibration level spectrums for three cases: (a), (b) and (c) at the suction pressure of 0.38 bar absolute for the five different impeller materials.

4.4. Root mean square (rms) of vibration amplitude level

The vibration amplitude calculated used root mean square (rms) where its value is used to compare the generated vibration from each impeller. A comparison of the root mean square (rms) of vibration between the five impeller materials during the three modes of operation (no-cavitation, start of cavitation and cavitation) for 0.82, 0.62 and 0.38 bar-absolute suction pressures are shown in Figures 11-13. It is clearly noticed that the plastic impeller has the lowest rms of vibration level among the other brass, cast-iron, stainless-steel, and aluminum impellers. Moreover, the highest rms of vibration level is produced by the aluminum impeller material.

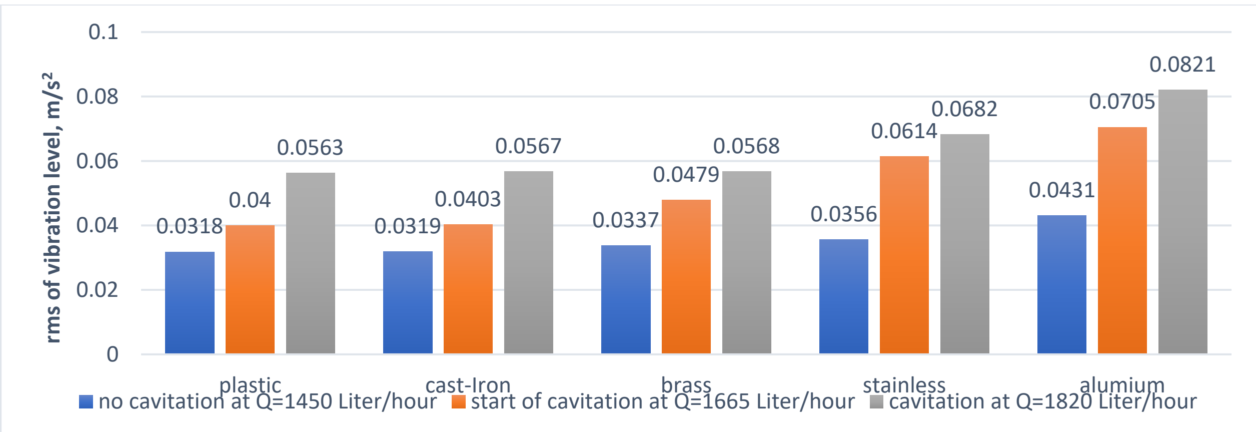


Fig. 11 The average vibration level at 0.82 bar absolute suction pressure for three cases: (a) no-cavitation (Q = 1450 Liter/hour), (b) start of cavitation (Q = 1665 Liter/hour) and (c) cavitation (Q = 1820 Liter/hour)

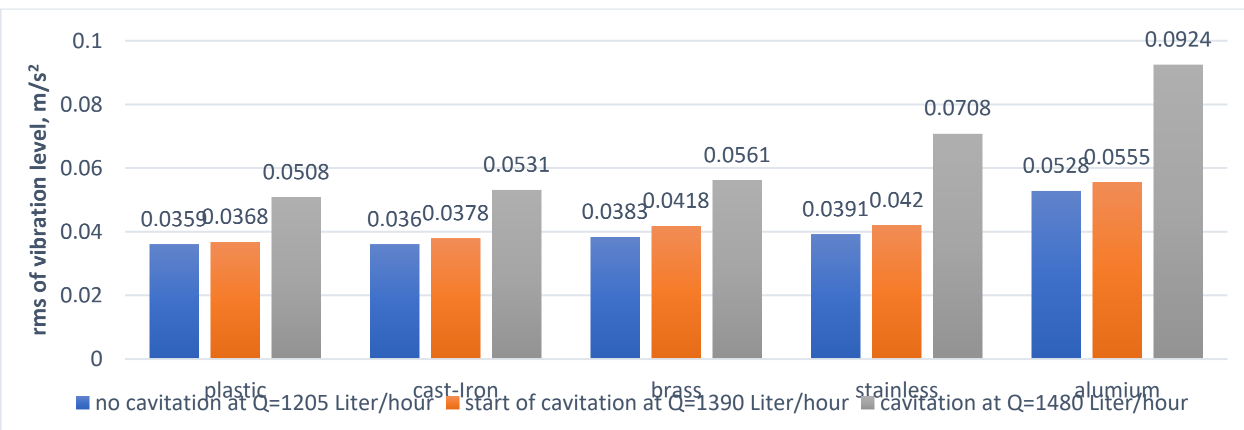


Fig. 12 The average vibration level at 0.62 bar absolute suction pressure for three cases: (a) no-cavitation (Q = 1205 Liter/hour), (b) start of cavitation (Q = 1390 Liter/hour) and (c) cavitation (Q = 1480 Liter/hour)

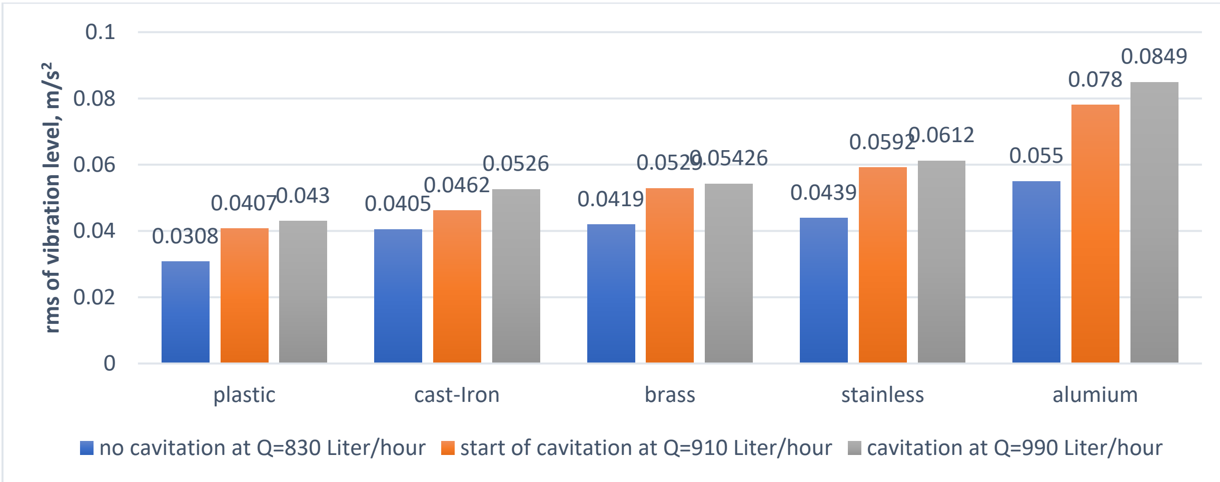


Fig.13 The average vibration level at 0.38 bar absolute suction pressure for three cases: (a) no-cavitation (Q = 830 Liter/hour), (b) start of cavitation (Q = 910 Liter/hour) and (c) cavitation (Q = 990 Liter/hour)

5. Conclusions and Future Recommendations

The current study analyzed the vibration behavior of five impeller materials — plastic, cast iron, brass, stainless steel, and aluminum— of a centrifugal pump under normal and cavitation conditions. Both the start and progression of cavitation were discussed for these impeller materials at fixed rotational speed of 2850 rpm and variable absolute suction pressures (0.08 to 0.92 bar-absolute). From the experimental analysis of the vibration emissions and vibration level, the following conclusions were drawn:

1. Plastic impeller generated the lowest vibration level making it ideal for applications as compared to the cast-iron, brass, stainless-steel and aluminum impellers.
2. Aluminum impeller produced the highest vibration level as compared to plastic, cast-iron, brass, and stainless-steel impellers.
3. Cavitation increased vibration levels across all impeller materials, with peak frequencies around 3700 Hz serving as reliable indicators of cavitation onset.
4. The average vibration level, computed from Fast Fourier Transform (FFT) analysis, increases due to cavitation for all impeller materials.

Future work will involve using computational fluid dynamics (CFD) models along with the vibration model based on different impeller material to further explore and understand the relationship between flow dynamics and vibration behavior.

Investigating the effects of varying pump rotational speeds and additional materials will also enhance the understanding of vibration mitigation strategies in centrifugal pumps.

References

[1] Al-Obaidi, A., Pradhan, S., Asim, T., Mishra, R., Zala, K.: Numerical studies of the velocity distribution within the volute of a centrifugal pump. 27th Condition monitoring and diagnostic engineering management international congress 2014 (COMADEM 2014), 2014.

[2] Houlin, L., Yong, W., Shouqi, Y., Minggao, T., Kai, W.: Effects of blade number on characteristics of centrifugal pumps. Chinese Journal of Mechanical Engineering (23), 1-5 (Jan 2010).

[3] Zhu, H., Iu, N., Wang, C., Si, Q., Wu, J., Deng, F., Liu, X.: Prediction of cavitation evolution and cavitation erosion on centrifugal pump blades by the DCM-RNG Method. Journal of Mechanical Sciences (2021), 1–12 (November 2021).

[4] Askew, J.: Centrifugal pumps: avoiding cavitation. World Pumps (2011), 34-39 (2011).

[5] Tan, T., Zhu, B., Cao, S., Chuan, W., Wang, B.: Numerical simulation of unsteady cavitation flow in a centrifugal pump at off-design conditions. Journal of Mechanical Engineering Science (228), 1994-2006 (2013).

[6] Chakraborty, S., Pandey, K., Roy, B.: Numerical analysis on effects of blade number variations on performance of centrifugal pumps with various rotational speeds. International Journal of Current Engineering and Technology (2), 143-152 (2012).

[7] Ngh, V., Zinzuvadia, M., Saurin, S.: Parametric study and design optimization of centrifugal pump impeller. International Journal of Engineering Research and Applications (4), 45-49 (2014).

[8] Hosien, M., Selim, S.: experimental study of cavitation criterion in centrifugal pumps. Journal of Visualization (17), 87 (2014).

[9] Cudina, M.: Detection of cavitation phenomenon in a centrifugal pump using audible sound. Mechanical Systems and Signal Processing (17), 1335-1347 (2003).

[10] Cernetic, J.: The use of noise and vibration signals for detecting cavitation in kinetic pumps. Journal of Mechanical Engineering Science (223), 1645-1655 (2009).

[11] Bull, V., Civale, J., Rivens, I., Ter, G.: Cavitation detection using a fiber optic hydrophone: a pilot study. AIP Conference Proceedings (85), 1359 (2011).

[12] Espinel, E., Prada, G., Rojas, J.: Cavitation study in centrifugal pumps through acoustic signal analysis. International Journal on Engineering Applications (9), 258-267 (2021).

[13] Cudina, M., Prezelj, J.: Detection of cavitation in operation of kinetic pumps use of discrete frequency tone in audible spectra. Applied Acoustics (70), 540-546 (2009).

[14] Cudina, M., Prezelj, J.: Detection of cavitation in situ operation of kinetic pumps: effect of cavitation on the characteristic discrete frequency component. Applied Acoustics (70), 1175-1182 (2009).

[15] Albraik, A., Althobiani, F., Gu, F., Ball, A.: Diagnosis of Centrifugal Pump Faults Using Vibration Methods. Journal of Physics (364), 18-20 (2012).

[16] Suhane, A.: Experimental Study on Centrifugal Pump to Determine the Effect of Radial Clearance on Pressure Pulsations Vibrations and Noise. International Journal of Engineering Research and Applications (2), 1823- 1829 (2012).

[17] Ramadevi, R.: Classification of Vibration Signal to Detect Pump Cavitation Using Discrete Wavelet Transform. International Journal of Computer Applications (93), 36-39 (2014).

[18] Mousmoulis, G., Karlsen-Davies, N., Aggidis, G., Anagnostopoulos, L., Papantonis, D.: Experimental analysis of cavitation in a centrifugal pump using acoustic emission vibration measurements and flow visualization. European Journal of Mechanics (75), 300-311 (2019).

[19] Abdulaziz, A., Kotb, A.: Detection of pump cavitation by vibration signature. Australian Journal of Mechanical Engineering (15), 103-110 (2015).

[20] BS 5316-2:1977, ISO 3555:1977, BS EN ISO 9906:2000, Specification for acceptance tests for centrifugal, mixed flow and axial pumps, Class B Tests, MCE/6. BSI, March 1977.