Analysis of Vibrations and Noise in a Centrifugal Pump for Predictive Maintenance

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Abstract: *The article makes an analysis of the experimental results regarding the noises and vibrations that appear in the operation of a centrifugal pump, both on the pump and the electric drive motor, as well as on the elements of the installation. Noises and vibrations have both mechanical and hydraulic causes, in close connection with the flow rate of fluid or with the occurrence of the cavitation phenomenon. The maximum values of the noises and vibrations are tracking, their compliance with the limits of the specific standards is verified, and in case of exceeding the values, remedial solutions are proposed. Monitoring the operation of hydraulic machines in installations has the purpose of a correct operation, but also of a preventive maintenance.*

Keywords: *Vibrations, noises, centrifugal pump, cavitation, maintenance*

1. Introduction

The appearance of vibrations in hydraulic machines is due to mechanical causes (imperfections in bearings, bearings, eccentricities, friction, etc.) and hydraulic (detachment of the boundary layer on the blades, cavitation operation, imbalance of hydraulic forces, etc.). Vibrations and noises emitted into the atmosphere by machines and installations consume additional energy and have a detrimental influence on the service life of this equipment. Vibrations and noises also have an unfavorable effect on human health.
Vibration analysis is important for pump fault detection and predictive maintenance and was studied by D. Jung in [1], D. Siano in [2] and others. Vibration and cavitation in pumps are directly related and have been previously studied in [3-8].
Ahmed Ramadhan Al-Obaidi in [3] says that the hydraulic and mechanical sources of vibration in centrifugal pumps occur as a result from several problems: flow distribution, high velocity, interaction between the impeller and the volute through the rotation of the impeller in the pump particularly at volute tongue region.
Hydraulic sources of vibration in centrifugal pumps include blades passing forces, hydraulic imbalance, recirculation flow, cavitation, system instabilities, or water hammer in installation pipes [4]. The pumping installation includes the centrifugal pump, the electrical motor and its piping system with pipes, elbows, fittings, and valves. J. Tuzson in [5] says that "even through regular operation conditions, various kinds of physical processes create vibration such as hydraulic interaction with the piping system, improper installation or maintenance, application for the pump, and manufacturing designs and different types of faults".
"Typically, the mechanical vibration sources in the pump include several sources such as pressure fluctuations created in the fluid, imbalance, misalignment between shafts connections, and damaged bearings" [6].
In addition, other mechanical sources incorporate mechanical forces, improper usage of the pump as provided in the installation manual and the conditions emerging from the pumps' incorrect assembly and from wear [7, 8]. When cavitation occurs in the different types of machines, it leads to dropping in pressure at the impeller inlet below the water vapour pressure. This leads to increasing the level of noise and vibration due to unstable flow which, in turn, causes an increase in the pressure fluctuations within a pump [5].
For the purpose of correct operation, but also of preventive maintenance, this article makes an analysis of the experimental results regarding the noises and vibrations that appear in the

operation of a centrifugal pump, both on the pump and the electric drive motor, as well as on the installation elements.
The article is structured in 5 chapters: after the introduction, a theoretical approach to the phenomenon, with reference to amplitude, velocity vibration, accelerations, analysis with the RMS method (Root mean square) for pulsating and periodic phenomena. Chapter 3 presents the presentation of the experiment stand and the measuring devices, and in chapter 4 the author presents results and makes an analysis of them. The final chapter is dedicated to the conclusions and solutions to improve the operation of the pump in the installation. The work consists in the measurement and analysis of vibrations and noises emitted by a single-stage centrifugal pump type LCC of medium size, often used in pumping stations.
The operation of the pump is at variable speed, by frequency converter n = 2900-2500 rpm. Vibration measurements are made in 3 directions (horizontal x, vertical y and axial z).

2. Theoretical approach

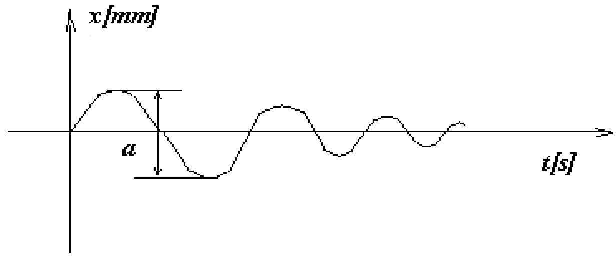
Vibrations are pulsating and periodic phenomena, with the following characteristic quantities:

X – displacement [*mm*];

a - amplitude; *t* – time [*s*]

$\dot{x}$ - velocity vibration [*mm/s*];

$\ddot{x}$ - acceleration $[mm/s^2]$



$$x = a \cdot \sin(\omega \cdot t + \varphi); \quad (1)$$

$$\dot{x} = a \cdot \cos(\omega \cdot t + \varphi); \quad (2)$$

$$\ddot{x} = -a \cdot \omega^2 \cdot \sin(\omega \cdot t + \varphi); \quad (3)$$

If the phenomena have a T-period, several measurements are made for the whole range of flows and their mean square deviation is calculated RMS (root mean square) [9]:

$$x_{MP} = \sqrt{\frac{1}{T} \cdot \int_0^T x^2(t)dt} \quad (4)$$

Methods used in theoretical analysis to understand the pattern of the vibration refer to FFT (Fast Fourier Transform) spectrum and are analysed with RMS (root mean square).
Also H. Ahmadi in [10] makes a theoretical but also experimental analysis on a centrifugal pump of comparable size with the pump used in the present experimental study, a useful study for comparing the results.

3. Experimental setup

The experimental stand consists in a centrifugal pump LCC 65-50-200, having suction pipe diameter 65 mm, discharge pipe diameter 50 mm and the diameter of the impeller 200 mm.
The experimental installation is shown in figure 1 and consists of a single-stage centrifugal pump for water *1*, driven by the asynchronous electric motor *2*, 5 kW at 2880 rpm equipped with frequency converter, an electromagnetic flow meter *3* on the discharge pipe, manometers *5* and pressure transducers *4*, for pumping head.

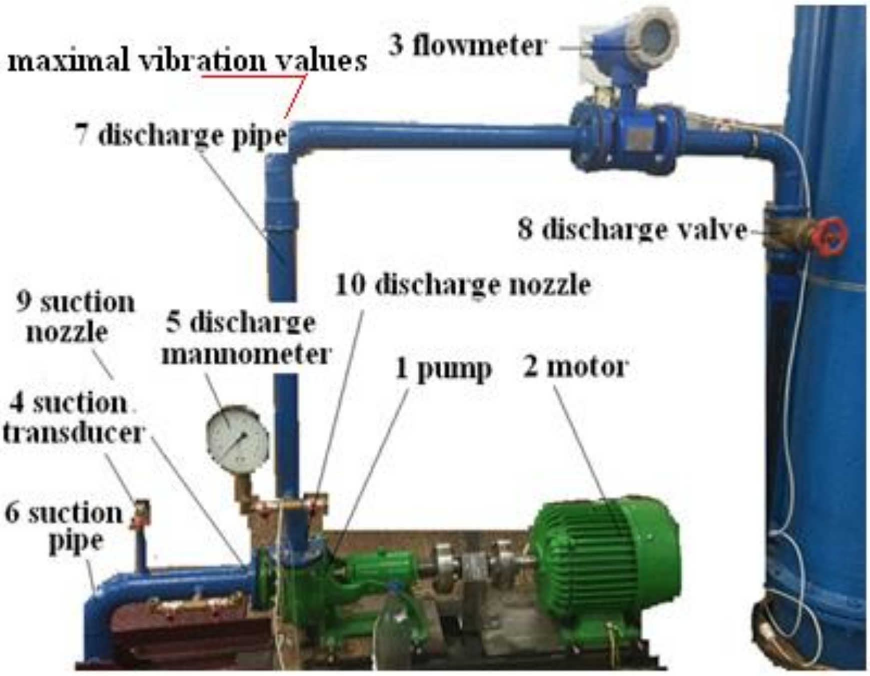


Fig. 1. Experimental stand

Vibration measuring transducers are built on the principle of accelerometers and are fixed with a magnet. Depending on the mode of transmission of the relative displacements, the transducers can be mechanical, electrical, or piezoelectric (figure 2), with a permanent magnet that is fixed on the machine housing.
Noises, with higher frequencies, are measured with a microphone built on various principles: mechanical, electro-dynamic or piezoelectric.
The location of the transducers is made in the most sensitive places for measurements, of maximum vibrations or of special interest.
The installation is equipped with a piezoelectric vibration transducer, figure 2, which takes over the movement and a Bruel and Kaer accelerometer, which indicates the speed of movement (mm / s), as well as with a microphone for recording noises. The accuracy of the measuring instruments is ±2%.
The vibration transducer is placed on the horizontal, vertical and axial direction of the pump, the electric motor, in different sensitive points or on elements in the installation, and the microphone for measuring the noise intensity is fixed consecutively at different azimuth angles, on a virtual circle of radius R = 1 m perpendicular to this plane.

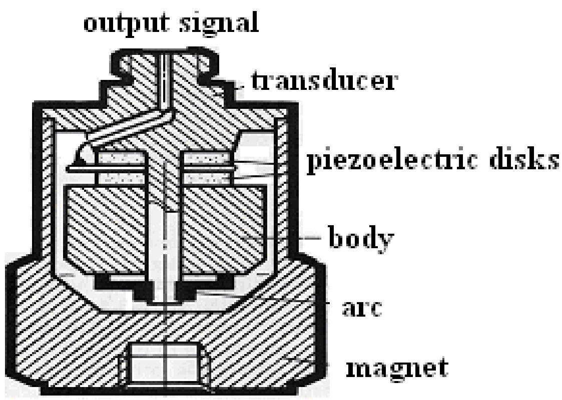


Fig. 2. The piezoelectric vibration transducer [9]

Operation procedure

One measures the velocity vibration in the horizontal x, vertical y and axial z directions and calculates the accelerations and displacements in the 3 directions. We are interested in the maximum values of vibrations, those for which the value of the sine is 1 [9].

$$\dot{x} = a\omega\,, \quad \ddot{x} = \dot{x}\omega \quad , \quad x = \frac{\dot{x}}{\omega} \tag{5}$$

The impeller of the centrifugal pump has *z* = 6 blades and variable rotation speed
n =2875-2552 rot/min.

The angular speed is

$$\omega = \frac{\pi \cdot n}{30} \tag{6}$$

And the oscillation frequency is:

$$f_v = \frac{z \cdot n}{60} \tag{7}$$

4. Results and discussion

The main tested characteristic sizes of the centrifugal pump - flow rate, head, rotational speed, angular speed and oscillation - are presented in Table 1.

Table 1: Centrifugal pump characteristics

Q (mc/h)	1.7	8.5	13.62	20.5	26.33	31.78
H (m)	32.5	30	27.2	21	14.3	3.8
n (rot/min)	2875	2820	2765	2656	2562	2552
ω (s-1)	300.92	295.16	289.40	277.99	268.16	267.11
f (Hz)	287.5	282	276.5	265.6	256.2	255.2

In the following we have exemplified for the suction flange of the pump, velocity vibration (mm / s) recorded with the measuring device in the 3 directions, the maximum amplitudes that are identical to the maximum displacements - Table 2 and a calculation example for the mean square deviation of the values of the velocity vibration, respectively the amplitudes / vibrations on the 3 directions – Table 3.

Table 2: Velocity vibration and amplitude / maximal displacement at suction nozzle

x˙	1.3	1.4	1.8	1.8	1.4	1.7
y˙	5.9	5.2	9.8	5.3	7.7	7.7
z˙	1.3	1	1	1.2	1.3	1.5
ax	0.0043	0.0047	0.0062	0.0065	0.0052	0.0064
ay	0.0196	0.0176	0.0339	0.0191	0.0287	0.0288
az	0.0043	0.0034	0.0035	0.0043	0.0048	0.0056

Table 3: Root mean square of vibration for suction nozzle

	RMS
x˙	0.198139
y˙	1.609635
z˙	0.134199
ax	0.000773
ay	0.005876
az	0.000563

The verification is done using the ISO 10816-3 vibration standard [11]. If the pump has an RMS vibration above the ISO 10816-3 vibration standard, it is necessary to do a more detailed analysis to determine the cause of the condition. Therefore, analysis of the vibration spectrum was performed to obtain the causes of vibrations that exceeded the standard values.
In figures 3-7 there are presented the results of the experimental determinations of vibrations in the form of velocity vibration (mm/s) for suction nozzle, discharge nozzle, discharge pipe, pump bearing house and electric motor casing, versus pump flow rate (m^3/h).

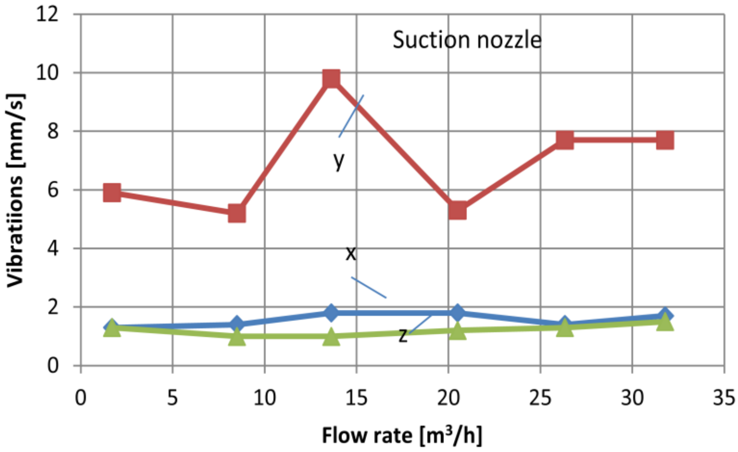


Fig. 3. Velocity vibration (mm/s) for suction nozzle

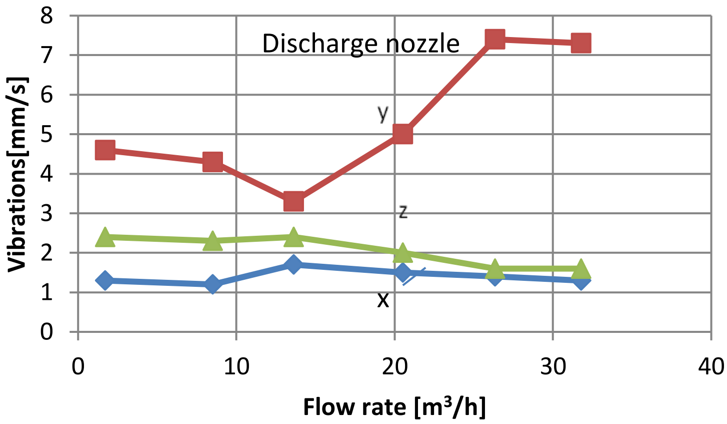


Fig. 4. Velocity vibration (mm/s) for discharge nozzle

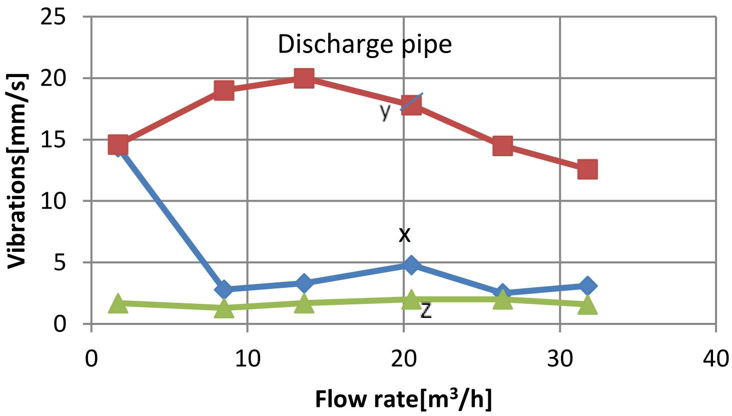


Fig. 5. Velocity vibration (mm/s) for discharge pipe

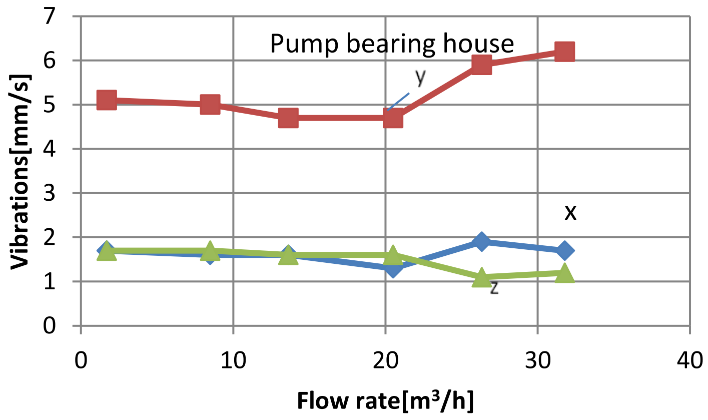


Fig. 6. Velocity vibration (mm/s) for pump bearing house

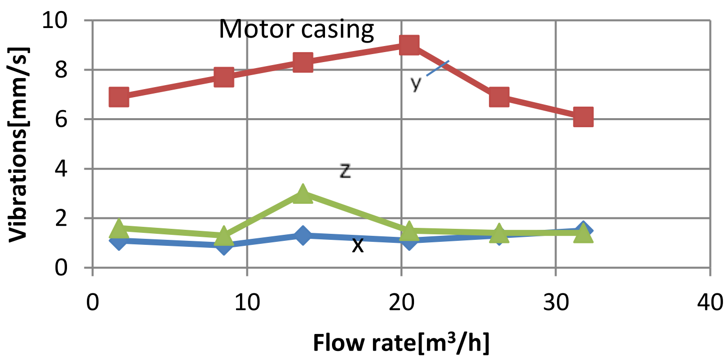


Fig. 7. Velocity vibration (mm/s) for electric motor casing

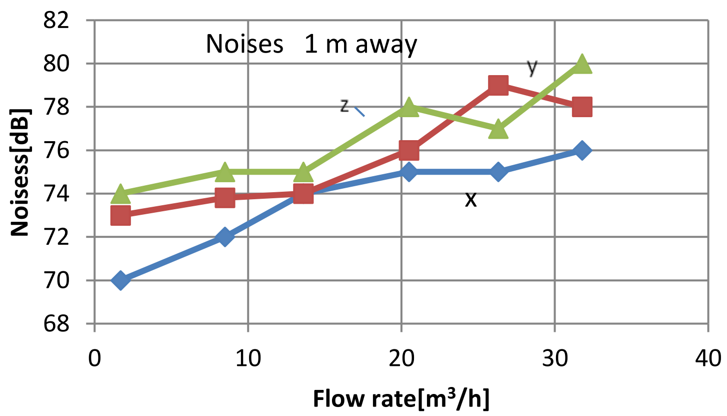


Fig. 8. Noises (dB)) at 1 m away from pump

Figure 8 shows the results of noise measurements at 1 m distance from the installation. Noise values at maximum flow rates are at the limit of the norms provided for hydraulic machines (75-80 dB) [12].

At the fully open valve (maximal flow rate) the noises are maximal and the vibrations on the discharge flange and the bearing body of the pump are also maximal.

The results show that the motor casing in the vertical and horizontal directions has the highest vibration value compared to other measurement directions. The highest velocity vibration value in the motor comes from the y direction which is 9 mm/s.
Regarding the pump bearing house, the highest velocity vibration value is 6.2 mm/s in vertical direction, 1.9 mm/s for horizontal and 1.7 mm/s for axial.
The highest velocity vibration values are at discharge pipe: 20 mm/s for vertical, 14.4 mm/s for horizontal and 2 mm/s for axial direction. Here the cause can be the water hammer phenomenon in the elbow of the installation, by the sudden change of the direction of movement. The results are comparable to those obtained on a pump of similar dimensions H Ahmadi in [10].
Based on the ISO 10816), in the studied pump installation, the average vibration value of the RMS velocity in few cases do not exceeded the standard limit. Only for discharge pipe the standard limit is exceeded. The solution for limiting the vibrations in the elbow consists in stiffening / fixing the installation elbow with clamps.
High vibration is a characteristic of damage to the pump. Analysis of the signal amplitude in the time and frequency domains carried out in the pump has been presented to predict and diagnose cavitation [13]. If left unchecked, this vibration will cause damage to the main components of the pump.
In the industry there are applications dedicated to monitoring and diagnosing pump faults based on vibration and noise analysis [14-15].

5. Conclusions

The following conclusions can be drawn from the analysis of vibrations on the installation of a centrifugal pump:

- In the vertical direction the vibrations are higher than in the horizontal and axial direction, the explanation being the sudden change of the flow direction in the radial rotor of the pump;
- On the suction flange the vibrations increase with the flow and as a result of the cavitation phenomenon that appears at the fully open valve;
- On the discharge pipe the vibrations are maximum, even 3 times higher than on the other parts of the pump and the installation, due to the ram blow phenomenon.
- On the motor housing the vibrations are higher than on the pump bearing, which leads us to the conclusion that the pump rotor is well balanced hydraulically;
- Noises are continuously increasing with flow, in all directions.

By monitoring the pump bearings in terms of vibration, but also the temperature, one can ensure a good operation of the pump, a correct maintenance when values appear outside the limit indicated by the standards and one can ensure a predictive maintenance.

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