Optimization of Energy Consumption through Industrial Maintenance

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Abstract. Within rotating machines, tiny imperfections can cause significant vibration amplifications, representing a risk to their proper functioning while leading to a deterioration in the quality and quantity of production. This study examines the impact of unbalance defects on the energy consumption of an industrial system, through the application of two complementary methods: vibration analysis and infrared thermography.
Keywords. Defects, energy consumption, infrared thermography, industrial maintenance and vibration analysis.

1 Introduction

Industrial Rotating machines are found in many different sectors of industry [1,2]. Basic rotating machines can be found in a variety of products and systems ranging from electric motors of vacuum pumps, steam turbines of all sizes, pumps and compressors of automotive powertrains hence the interest of this study,...

The rapid increase in the operating speeds of rotating machines over the past few decades has presented new problems for designers [3]. Rotating shafts are subject to increasing vibration as the speed increases. These vibrations can be dangerous if they are not well estimated (especially if they are underestimated), leading to a bad dimensioning of the parts whose consequences can be catastrophic both on the machine and on its users [4]. In this work, we aim at knowing the influence of an unbalance on a rotor, including vibrations on energy consumption, using the techniques of vibration analysis and infrared thermography [5, 6].

Rotating machines have certain phenomena of their own that are directly related to its rotary motion [7, 8]. They usually consist of three main components, including the rotor, bearings and their support structure, with the aim of performing a specific task: transforming energy, transmitting motion ... etc [6]. Rotating machines produce vibrations, the image of dynamic forces generated by moving parts. Vibration plays a central role among the factors to be taken into account for accurate defect detection and diagnosis. Indeed, variations in a machine's vibration are often the first physical sign of an anomaly, potentially leading to degradation or even breakdown [6].

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Mechanical vibrations are related to the existence of dynamic forces, particularly internal to the mechanism. In the case of internal forces [8], they are related to a malfunction linked to a rotor imbalance, a shaft misalignment, mechanical wear, an electrical fault, cavitation, etc.

It is assumed that all rotating machines have an unbalance [9]. The unbalance is any eccentric mass m_b of a rotor. It is located at a distance d from the geometric center of the shaft figure1. This excitation force is generated at a frequency directly proportional to the rotation speed, and its amplitude is proportional to the square of the rotation speed. The unbalances have different origins we often talk about inhomogeneities of the material, but there are other causes a literature review [10].

Its appearance may be related:

• A non-symmetrical distribution of the rotor mass around its axis of revolution. This creates an offset between the geometric center and the center of mass [8];

• Shaft deformation under the effect of the rotor's, own weight encourages divergence between the machine's geometric center and center of rotation.;

• The unbalance distribution of a rotor depends on the position of the center of mass of each section in relation to the axis of rotation, which is different from the geometric axis that passes through the centers of the bearings. In the case of one-piece rotors consisting of machined wheels, a change in the position of the centers of mass due to machining deviations is also observed [10 ,11].

• The machining deviation (eccentricity and parallelism) can also cause the unbalance

• For turbine blades the natural distribution gives an unbalance that depends on their relative positions of assembly of the parts. It is also possible that the bearings are not aligned with the geometric axis of the rotor [12, 13].

We can also talk about stress relaxation, non-axisymmetric wear due to fatigue from vibrations, working conditions in the presence of dust, chemicals etc.. Susceptible to bring unbalance that can evolve with time.

The critical speed when a natural frequency of the rotor, at a given speed of rotation, coincides with the excitation frequency due to the unbalance, we speak of critical speed. As its name indicates, these particular speeds correspond to an operating regime for which the machine enters into resonance, which can represent a risk of failure directly linked to the amplification of lateral vibrations. This risk is all the more important when a low damping is present in the structure.

In the absence of damping, rotating machines are carefully designed to operate at speeds significantly below their first critical speed. This is quite often the case for small rotating machines with low mass and supported by bearings with high stiffnesses. It is generally the large rotating machines such as centrifugal compressors, gas or steam turbines or large power generators that pose more risks due to their mode of operation, since they often operate at speeds exceeding at least the first critical speed.

• The parts assembled on a rotating shaft naturally move their centers of mass. This is the case for turbines, electric motors [15], ...

As a synthesis, the excitation force generated by the presence of the unbalance is a centrifugal force that acts on the vibratory behavior of the rotor. As the centrifugal forces increase with the square of the rotation speed, they become very important at very high speeds. Hence the importance of balancing rotating machines, especially those operating at very high speeds, in order to limit the effect of the excitation generated by the unbalance on the lateral vibrations.

2 Theoretical Study

Unbalance is the major cause of vibration problems, as shown in “Fig.1”, which illustrates a simple case of unbalance in a rotor. In reality, the center of gravity axis is more like a snake wrapped around the axis of rotation.

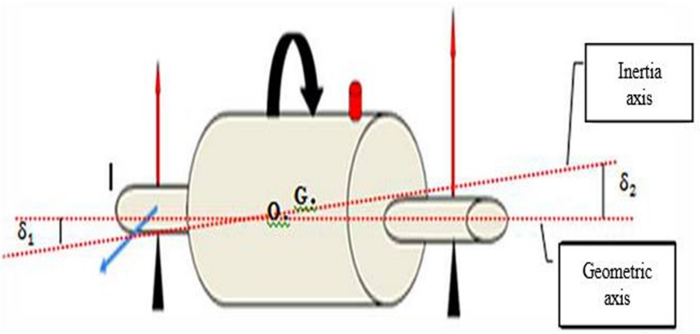


Fig. 1. Position of the rotor axis of inertia.

If we could measure the position of the axis of inertia, the disturbance would not exist. The imbalance can be simplified modeled as follows:

$$p_1 = \delta_1\Omega^2 \sin(\Omega + \varphi_1)$$
$$p_2 = \delta_2\Omega^2 \sin(\Omega + \varphi_2) \quad (1)$$

The unbalance, defined by its kinetic energy, occurs when a mass m_b is located at a point B of the disk plane, at a specific distance from its geometric center C, as shown in “Fig. 2” [14].

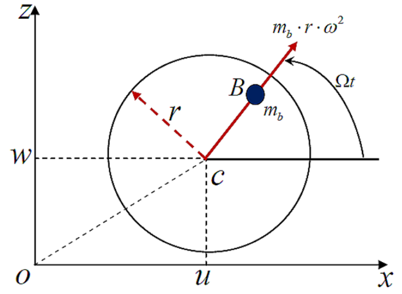


Fig. 2. Centrifugal force due to unbalance.

Where Ω: angular speed of rotation, m: mass, r: radius of shaft (or wheel) and f: centrifugal force.

Centrifugal force is one of the main driving forces in rotating machines. In reality, no matter how precisely machines are constructed, it is impossible to achieve perfect coincidence of the center of gravity with the axis of rotation. The causes of this phenomenon, commonly referred to as unbalance, come from:

•The design (some parts may not be perfectly symmetrical);

•The technology (non-homogeneous material);

•Manufacturing (everything is produced within certain tolerances; rotating parts have a runout);

•Assembly (i.e. with mounted rotors).

That is, the representation as a function of time. However, in reality, the vibrations are much more complex and occur at different frequencies equal to the multiple elements of the machine in functioning [16-20]. The unbalance coordinates in the stationary reference frame OXYZ are as follows:

$$\overrightarrow{OB} = \begin{Bmatrix} u + d\cos\Omega t \\ cte \\ w + d\sin\Omega t \end{Bmatrix} \tag{2}$$

Hence the speed:

$$\vec{v} = \frac{d\overrightarrow{OB}}{dt} = \begin{Bmatrix} \dot{u} - d\Omega\sin\Omega t \\ 0 \\ \dot{w} + d\Omega\cos\Omega t \end{Bmatrix} \tag{3}$$

And the kinetic energy of the unbalance transforms into:

$$T_b = \frac{1}{2} m_b (\dot{u}^2 + \dot{w}^2 + \Omega^2 d^2 + 2\Omega d\dot{u}\sin\Omega t - 2\Omega d\dot{w}\cos\Omega t) \tag{4}$$

The term ω^2 $d^2/2$ is constant and will not be involved in the equations. Since the mass of the unbalance is negligible compared to the rotor mass, the expression for the kinetic energy can be approximated by:

$$T_b \approx m_b d\Omega(\dot{u}\sin\Omega t - \dot{w}\cos\Omega t) \tag{5}$$

Three types of unbalance can be distinguished based on the mass distribution on the rotor and its effect on the position of the principal axis of inertia relative to the axis of rotation: static, torque, and dynamic unbalance. [21].

3 Experimental Monitoring Protocol

3.1 Description of the Experimental Monitoring Protocol ISP

The experimental device or monitoring platform is presented in “Fig.3”. It is composed of a three-phase motor group of 3000rpm of power 1.1 KW equipped with a variable speed drive. This test bench is connected by a vibration sensor on the bearing P2 “Fig.1” and a thermal camera for temperature measurement. The two measured parameters transmit the data in real time to a computer where the processing is done using software.

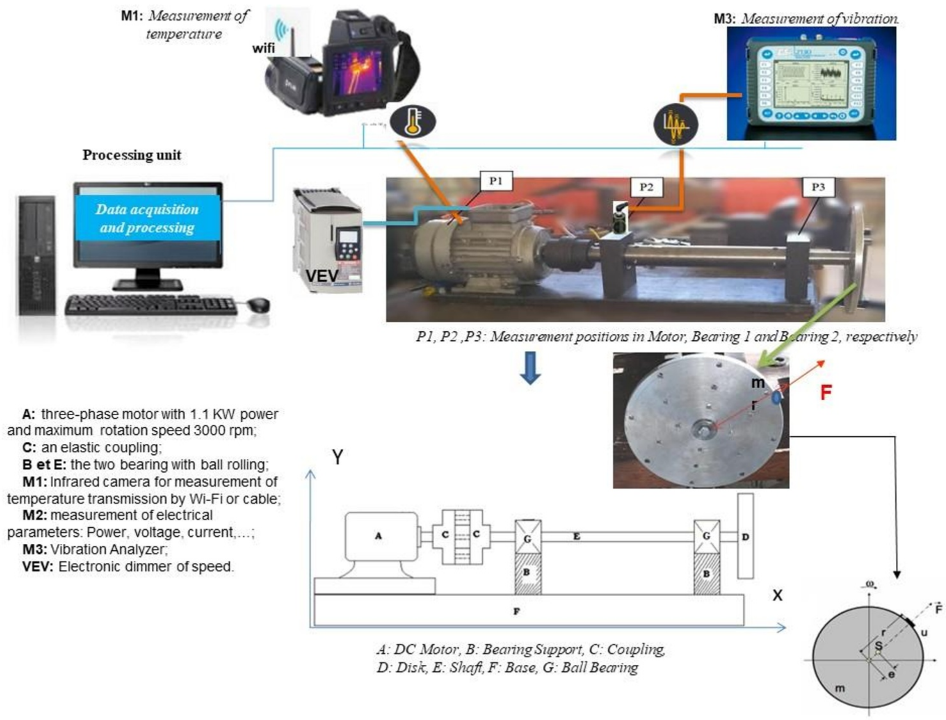


Fig. 3. Monitoring platform.

3.2 Choice of monitoring tools

To find out the origin and the severity of the defect, Table 1 shows comparisons between the two different methods of preventive maintenance used in our research work. In fact, each method has its preferred field of application.

Table 1. Comparison between the different methods of preventive maintenance.

	Main advantages	Main limitations	Preferred field of application
Vibration analysis	-Detection of defects at an early stage - Possibility to perform a thorough diagnosis - Allows continuous monitoring - Allows for remote monitoring the equipment remotely. (remote maintenance)	- Spectres, sometimes difficult to interpret. - In the case of continuous monitoring, relatively expensive installations. expensive.	- Detection of defects of all the organs kinematics of the machine (unbalance, alignment defects, set, etc.) and of its structure.
Thermographic analysis	- Allows you to perform a quick check of the of the installation. - Interpretation of results is often immediate interpretation of the results.	- Detection of defects at a less early stage than vibration analysis - Control limited to what that the camera "sees (surface heating). - Does not allow to to carry out an in-depth diagnosis.	- Detection of all defects that cause overheating (lack of lubrication)

4 Results and discussion

4.1 Analysis of unbalance defect results

In “Fig.4” we present the modulus of the vibration spectrum measured at the level of bearing P2. We can notice the first important PIC which appears at the frequency fr=50Hz which is the frequency of motor [12]. This result obtained highlights the unbalance defect.

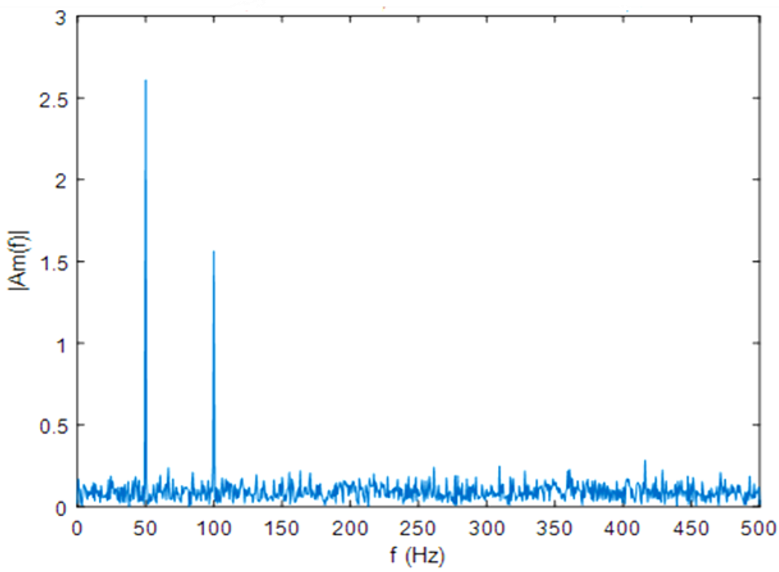


Fig. 4. Modulus of the vibration spectrum measured at the bearing.

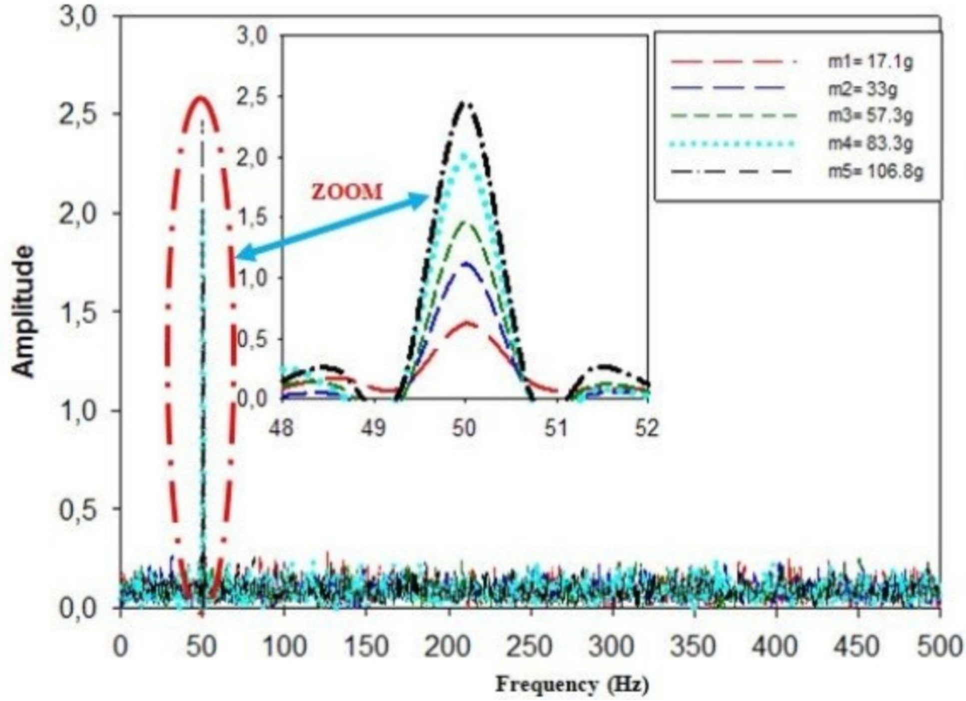


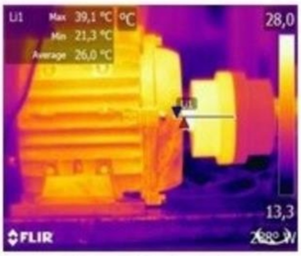
Fig. 5. Mass variation spectra.

Secondly, for different speeds of rotation we varied the masses. From "Fig.5" we can see that, by increasing the unbalance with the help of the masses, the amplitude of vibration increases considerably with the increase in speed. This increase in mass increases the torque that the motor has to develop, which implies that the energy consumption becomes important [9].

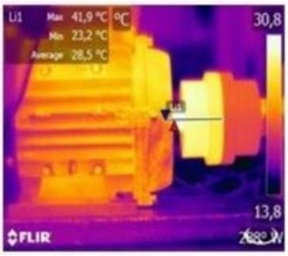
4.2 Temperature measurement by infrared camera on the engine according to the masses

Thermography is a predictive maintenance method that can be used to monitor the condition of industrial machines, structures and plant systems, and not just electrical equipment. It is based on the use of instruments specially designed to monitor infrared energy emission, i.e. surface temperature, in order to determine operating conditions. By detecting thermal anomalies (i.e., areas that are hotter or cooler than they should be).

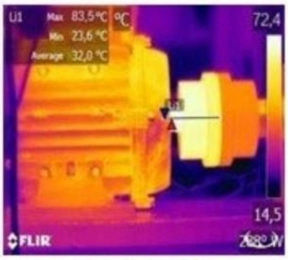
As an example, the images below show the results obtained by the infrared camera of the electric motor and the coupling, for a rotation speed of the shaft at 3000 rpm and for three different masses.



Mass = 0 unloaded



Mass 1 = 17.1 g



Mass 2 = 106.8 g

Fig. 6. Thermal image of the electric motor with different masses.

It can be seen that the temperature of the motor and coupling rises with increasing mass at constant velocity [10]. It becomes increasingly significant at speeds exceeding 3000 rpm.

4.3 Energy consumption for each unbalance

In fig.7 we present the results of the energy consumption according to the masses at constant speed of 3000rpm. We notice that the more the unbalance becomes important the more the consumed power is important and in trail the rise of the temperature of the electric motor.

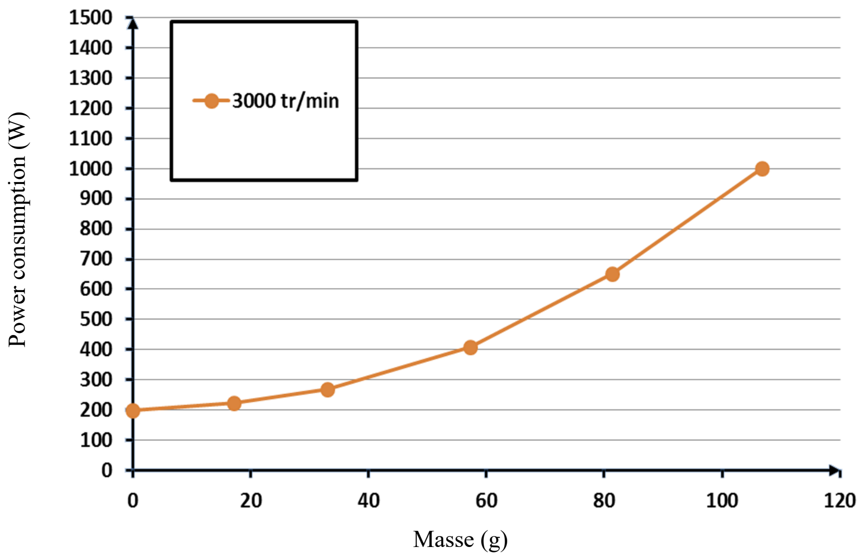


Fig. 7. Energy consumed according to the unbalance.

5 Conclusion

The contribution of our work is of crucial importance, as it investigates the impact of unbalance on the energy consumption due to vibration and heating temperature of electric motors. We set up a monitoring platform equipped with high-precision measuring instruments and sophisticated data processing software. Our results are as follows:

• Increased energy consumption: We have shown that electric motor energy consumption increases significantly with increasing unbalance and rotational speed. Notably, this increase is more pronounced for the last three speeds, highlighting a critical dimension.

• Rising engine temperature: Our research has also confirmed a rise in engine temperature in direct relation to increasing rotational speed and unbalance. This is a crucial indicator of motor health, since excessive temperatures can lead to failures and unexpected stoppages.

• Prediction of component service life: We have developed a predictive model to estimate the lifetime of each component, based on predefined thresholds.

• Intelligent monitoring of industrial equipment: By introducing real-time monitoring of vibration, energy and temperature parameters, our work is generating a major breakthrough for the industrial sector. It helps anticipate breakdowns, improve equipment reliability, and reduce energy consumption by eliminating unbalance-related failures.

Our research offers a valuable approach to anticipating production lines, boosting equipment reliability, and achieving substantial energy savings by reducing incidents, particularly those linked to unbalance, which are the focus of our study. The elimination of unbalance results in a significant reduction in energy consumption, along with a marked improvement in the reliability of the industrial system.

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