

THE MODELING OF THE EFFECT OF LUBRICANT VISCOSITY ON THE VIBRATION OF A GEAR SYSTEM

Wafa Krika¹ – Azzedine Bouzaouit^{2*}

¹Department of Mechanical Engineering, Faculty of Technology, The 20th August 1955 University of Skikda, 21000, Algeria

²LRPCSI Laboratory of Research, Faculty of Technology, The 20th August 1955 University of Skikda, 21000, Algeria

ARTICLE INFO

Article history:

Received: 15.01.2017.

Received in revised form: 12.09.2017.

Accepted: 10.10.2017.

Keywords:

Rotating machine

Gear system

Lubricant viscosity

Vibration

DOI: <https://doi.org/10.30765/er.38.3.1>

Abstract:

As a part of conditional maintenance, rotating machines are monitored and diagnosed in real time to increase their service life and ensure their availability in the industry. Our work aims to follow the evolution of the vibration for rotating machines through the integration of inverse problems such as degradation of the lubricant quality. Experimental tests were made in order to characterize the influence of quality lubricant (viscosity) on the vibration of a component of a rotating machine. Realized experimental bench is composed of gear device lubricated with lubricants of different viscosity grades and rotated at a variable rotational speed. In each case we measure the value of vibration. Following this experience, a vibration model has been developed depending on the change of state of lubricants, based on the results of planned experience. Further, a correlation analysis on the model obtained was realized and the results show an agreement between theory and experiment.

1 Introduction

Monitoring and diagnosing play an essential role in safe operation and performance of rotating machinery, fortunately, there are powerful monitoring tools such as vibration analysis, lubricant analysis, thermography and acoustic analysis, and others enter as part of the conditional preventive maintenance [1].

Vibration analysis, through its effectiveness, is taking a very important place in the context of setting up a conditional maintenance. It can follow the state of the rotating machine during the functioning to avoid unwanted stops. In regards to this, several detection indicators have been proposed and used as global measure of vibration level such as: the peak value, energy, RMS, average value, and others [2, 3].

Though often used in industry, vibration analysis is not the best solution to secure and optimize the operation of lubricated rotating machinery; therefore, we seek other methods of surveillance. On the other hand, vibration analysis is also widely used to complement other methods, when they are not sufficient to make a diagnosis and this is particularly the case of the oil analysis that detects early stage of degradation of a lubricant, for example [4,5,6].

Lubrication in the mechanical systems is the first maintenance operation essential to reduce friction, energy losses, and wear of the members in contact. 50-80% of total defects found in components for rotating machines are linked to deficient lubrication, resulting from the use of inadequate lubricant (lack or excess, aging, solid or liquid contamination). Over the course of the service, lubricants tend to

degrade, to lose their lubricating properties due to chemical decomposition and to become contaminated by the particles caused by wearing of the parts in contact; lubricant analysis is an effective mean of monitoring [7].

From quality point of view, inadequate lubrication greatly reduces the life of the moving parts in a lubricated machine. The choice of the lubricant quality must be particularly studied [8].

In this context, our study is to monitor the RMS vibration values of a mechanical member (the case considered is a gear system) lubricated with lubricants of different viscosity grades in order to characterize the vibration behavior which can be generated by the degradation of the viscosity.

Secondly, we present a mathematical modeling by the linear regression method based on results of planned experience in order to develop a model characterizing the vibration, depending on the lubricant state change.

2 Experimental work

2.1 Gear system

Fig.1 shows the gear device used in the experimental tests of our work. It is compound essentially of a pinion, a wheel charged by a constant load of 10 kg, and an oil bath formed to the lower part of the toothed wheels to ensure their lubrication by splash.

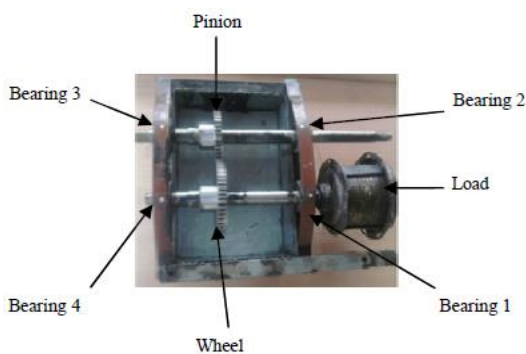


Figure 1. Gear system.

The geometrical characteristics of the gears are as follows:

The pitch diameter for pinion and wheel is respectively 76.84 mm, 135.10 mm and the number of teeth is 32 and 55, with a module 2,4 mm.

The device is driven by an electric motor in order to vary the rotational speed of the system. We have

taken four measurement points which were selected on the four bearings of our gear system (P1, P2, P3 and P4), two for the driving pinion and the other two for the receiving wheel, see Fig. 2.

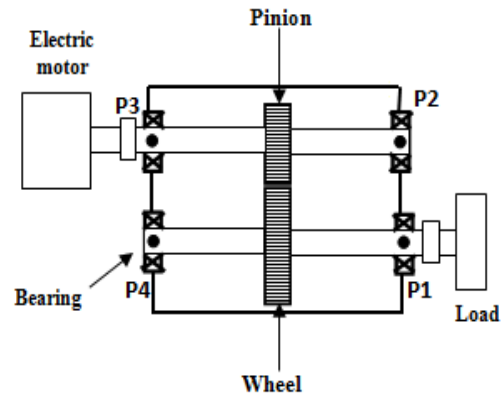


Figure 2. Experimental device gear.

2.2 Lubricants tested

For the lubrication of the gear system we have used six lubricants that their viscosities (V1, V2, V3, V4, V5, and V6) are given by the Table 1.

Table 1. Characteristics of lubricants

Lubricant codes	Type of lubricant	Kinematic viscosity at 40 °C in Cst
V1	Oil ISO 32	28.8 to 32.2
V2	Oil ISO 68	61.2 to 74.8
V3	Oil SAE 15W40	105
V4	EP2 grease	150
V5	Oil SAE 20W50	158
V6	Oil SAE 90	215

2.3 Vibrometer “Penplus-SKF”

For the vibration measuring we used a Vibrometer (PenPlus-SKF) shown in the Fig.3, that is a highly reliable portable instrument capable of measuring vibration caused by rotational problems. It gives the overall level RMS of the vibration velocity.



Figure 3. Photography of vibrometer Penplus SKF.

3 Experimental results

For each lubricant at the different rotational speeds (N1 = 31.5, N2 = 45, N3 = 63, N4 = 90, N5 = 125 and N6 = 180) RPM, we measured the (RMS) values of the vibration velocity on the four points using the vibrometer. The experiments with every lubrication condition were repeated several times to check repeatability.

3.1 Influence of rotational speed on the vibration velocity

Fig. 4 shows the evolution of average vibration velocity measured at points P1, P2, P3, and P4 according to the rotational speed for different viscosities tested (V1, V2, V3, V4, V5 and V6) of Table 1.

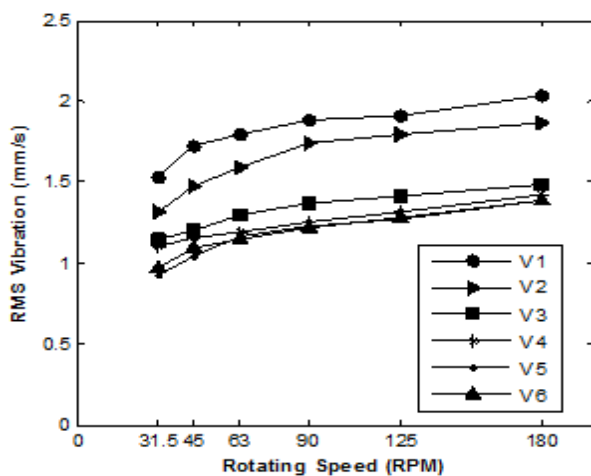


Figure 4. Evolution of the vibration velocity as a function of the rotational speed.

The vibration velocity is affected by the speed of rotation, a gradual increase in RMS values can be observed during the increase in the speed of rotation. This behavior is repeated for each lubricant.

Also, it can be observed in the case of using both lubricants (SAE 15W40 oil and EP2 grease) which have the viscosities, (V3 and V4) a slight stabilization of the vibration level of the tested system used for different speeds (the two curves have low slopes), that is to say that these viscosities are considered ideal for the lubrication of this system.

3.2 Influence of lubricant viscosity on the vibration amplitude

This part of our study was devoted to research and determining relationship between viscosity of a lubricant and vibration that can be produced during normal operation of the gear system.

Fig. 5 shows the variation in the average vibration velocity at different viscosities of the lubricants for each rotation speed from (N1 to N6).

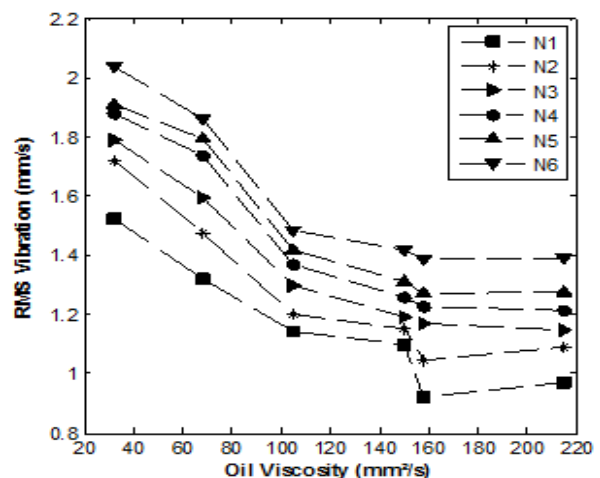


Figure 5. Variation of the vibration velocity as a function of the lubricants viscosity.

It is clear that the vibration varies inversely to the viscosity of the lubricant that is to say if the quality of the lubricant deteriorates (decrease in viscosity), the vibration level of our gear system increases accordingly.

This influence reflects the damping effect of the oil film between the surfaces in contact with its reduction increases the level of vibration.

4 Modelling the influence of the lubricant quality on the vibration for the gear system

4.1 The method of regression analysis and correlation

A regression analysis seeks to determine a relationship expressing the link between so-called dependent variable and one or more so-called independent variables. The correlation is defined as a linear relationship between the two variables and the correlation coefficient measures the greater or less dependence between these two variables [9].

4.2 The method of least squares

In the analysis of regression and correlation, the most used method is the method of "least squares" proposed by Gauss. The principle of this method is to use (\hat{y}) or "y valued", as opposed to (y) which represents the "y observed" [10]. We are looking for the parameters a and b . The difference of ordinates between a point (x_i, y_i) and the right point having the same abscissa is:

$$y_i - \hat{y}_i = y_i - ax_i - b \tag{1}$$

y_i : Observed value.

\hat{y} : Value calculated according to the model.

The linear correlation coefficient is calculated by the formula:

$$R = \sqrt{1 - \frac{\sum_{i=1}^n (\bar{y}_i - \hat{y}_i)^2}{\sum_{i=1}^n (\bar{y}_i - \bar{y})^2}} \tag{2}$$

The adjustment is valid for $(0.70 < |R| < 1)$.

4.3 The multifactorial method

In the general case of an optimization parameter (y) of a technological process, simultaneously influencing several factors $X_j (j \in \{1 \div m\})$

$$y = f(x_1, x_2, \dots, x_m) \tag{3}$$

This process is described by the following model:

$$y = C \cdot x_1^{b1} \cdot x_2^{b2} \cdot \dots \cdot x_j^{bj} \cdot \dots \cdot x_m^{bm} \tag{4}$$

The determination of C and b_j is done either by the succession of unifactorial tests either by planning experiments method.

4.4 Presentation of the model (Planning experiments)

Linearizing equation (4) gives:

$$\ln y = \ln C + b_1 \ln x_1 + b_2 \ln x_2 + \dots + b_j \ln x_j + b_m \ln x_m \tag{5}$$

$$\dot{y} = b_0 + b_1 x'_1 + b_2 x'_2 + \dots + b_j x'_j + b_m x'_m \tag{6}$$

Equation (6) represents the multiple linear regression models, the regression coefficients are noted by b_j . The number of experiments to be performed is determined according to the formula:

$$n = p^m \tag{7}$$

Where:

p : Number of level factors.

m : Number of factors.

n : Number of tests

For signs we give (-) and (+) for high and low levels of each factor respectively.

The range of variation of each factor is presented by the Fig. 6.

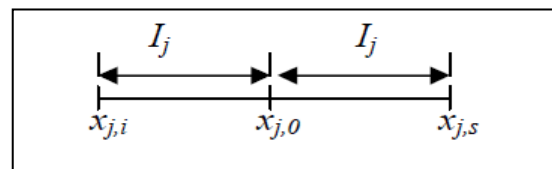


Figure 6. Basic level and the range of variation of each factor.

The codification of the factors is given by:

$$K_j = \frac{x_j - x_{j,0}}{I_j} \tag{8}$$

For model:

$$K_j = \frac{2(\ln x_j - \ln x_{j,S})}{(\ln x_{j,S} - \ln x_{j,i})} + 1 \quad (9)$$

It is possible to gather all the elements of the experiment in a table, which is called matrix experiments [11].

For the calculation of the regression coefficients b_j where ($j=0: m$) the MMC is used which gives:

$$b_0 = \frac{1}{n} \sum_{i=1}^n Z_0 y_i' \quad (10)$$

$$b_j = \frac{1}{n} \sum_{i=1}^n Z_{j,i} y_i' \quad (11)$$

With: $j \in (1, m)$

The Z_0 quantity is a coded indication of an imaginary variable that takes only the value (+1) and is used for determining the free member b_0 of the equation.

Equation (5) can also be written:

$$\ddot{y} = b_0 + b_1 k_1 + b_2 k_2 \dots + b_j k_j + b_m k_m \quad (12)$$

We can put the last equation in the following form:

$$\hat{y} = e^{\ddot{y}} \quad (11)$$

4.5 Model validation

Either the input parameters (factors) the following:

- The viscosity takes values ($x_{1\min} = 32$ and $x_{1\max} = 215$) mm²/s.
- The rotational speed takes values ($x_{2\min} = 31.5$ and $x_{2\max} = 180$) RPM.
- y_i are the output parameters (measured vibrations).

For two input parameters, we have a model of the following form:

$$y = C x_1^{b_1} \cdot C x_2^{b_2} \quad (14)$$

We can write:

$$\ddot{y} = b_0 + b_1 k_1 + b_2 k_2 \quad (15)$$

In the Table 2, the main parameters are grouped which establish the vibration model with \bar{y}_i as the average vibration.

Table 2. Experimental results of vibration measurements

Test number	Codification of factors			Measured vibration \bar{y}_i	$\hat{y}_i = \ln \bar{y}_i$	Factor values	
	Z_0	Z_1	Z_2			X_1	X_2
1	+1	-1	-1	1.525	0.421	32	31.5
2	+1	+1	-1	0.970	-0.030	215	31.5
3	+1	-1	+1	2.037	0.711	32	180
4	+1	+1	+1	1.391	0.330	215	180

The calculation of the regression coefficients gives the values: $b_0 = 0.358$, $b_1 = -0.208$, $b_2 = 0.1625$; and for the codifications k_1, k_2 , are given by:

$$k_1 = 1.049 \ln x_1 - 4.637 \quad (16)$$

$$k_2 = 1.147 \ln x_2 - 4.957 \quad (17)$$

By replacing the values of regression coefficients and codifications in equation (15), we obtain:

$$\ddot{y} = 0.5169 - 0.218 \ln x_1 + 0.186 \ln x_2 \quad (18)$$

So the equation of vibration model will be:

$$\hat{y} = e^{0.5169} \cdot x_1^{-0.218} \cdot x_2^{0.186} \quad (19)$$

If it is assigned to the vibration velocity V , and x_1 and x_2 are replaced by their respective magnitudes, we have the equation for the vibration model:

$$V = e^{0.5169} \cdot v^{-0.218} \cdot N^{0.186} \quad (20)$$

Where V : Vibration velocity, mm/s, N : Rotation speed, RPM and ν : Kinematic viscosity, mm^2s^{-1} . According to the model equation obtained, it is found that the vibration varies inversely with the viscosity; on the other hand, it is proportional with the speed of rotation.

The adjustment of this model with obtained experimental measurements is done in the following way: Consider V_m the vibration measured and V_c the vibration calculated by the resulting model. As well the correlation coefficient R is calculated by the least square method using equation (2). The comparison between the vibration values obtained by the model and those measured for each rotation speed is presented by the Fig.7.

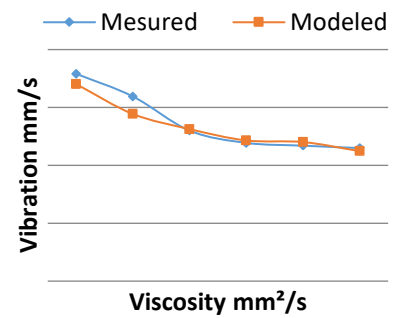


Figure 7c. Comparison between the models developed and measures for speed $N3=63$ RPM.

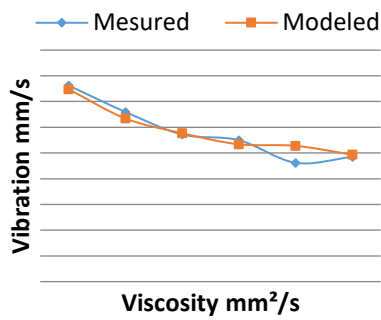


Figure 7a. Comparison between the models developed and measures for speed $N1=31.5$ RPM.

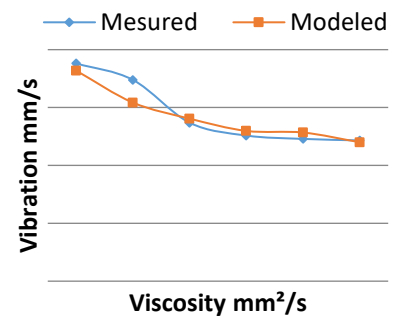


Figure 7d. Comparison between the models developed and measures for speed $N4=90$ RPM.

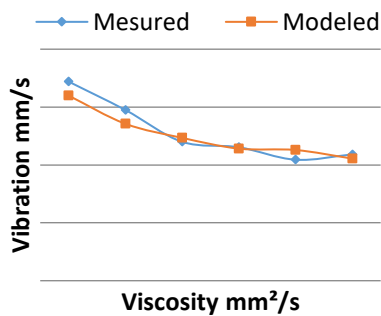


Figure 7b. Comparison between the models developed and measures for speed $N2=45$ RPM.

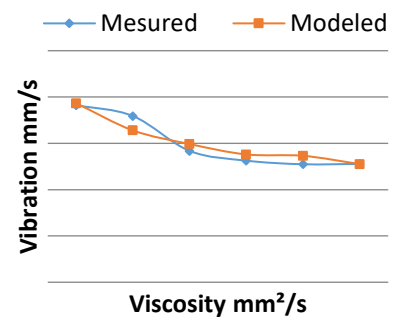


Figure 7e. Comparison between the models developed and measures for speed $N5=125$ RPM.

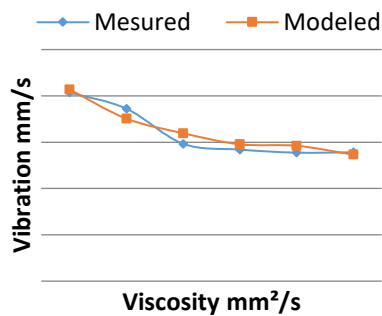


Figure 7f. Comparison between the models developed and measures for speed N6=180 RPM.

In the Table 3 correlation coefficient R was evaluated for each case obtained.

The correlation coefficient R is closer to 1, which gives a good approximation of the variation of the vibration depending on the viscosity and the speed of rotation. We observe a good correlation between modeled and measured vibrations.

Table 3. The calculated coefficients of correlation

Rotation speed (RPM)	31.5	45	63	90	125	180
Correlation coefficient R	0.9663	0.9745	0.9789	0.9608	0.9523	0.9605

References

- [1] Héng, J.: *Practice of preventive maintenance*, Edition Dunod, Paris, France, 2002.
- [2] Bigret, R., Féron, J.: *Diagnostics Maintenance availability for rotating machines: models - measures - analysis of vibrations*, Edition Masson Paris, 1995.
- [3] Patil, S., Gaikwad, A.: *Vibration Analysis of Electrical Rotating Machines using FFT*. IEEE-31661, 4th ICCCNT, Tiruchengode, India, 2013.
- [4] Maznan, I., Izzuddin, Z., Mohd, I.: *Condition Monitoring of Variable Speed Worm Gearbox Lubricated With Different Viscosity Oils*. Applied Mechanics and Materials Vols. 773-774, Switzerland 2015.
- [5] Lakihal, A., Hadjadj-aoul, E.: *A new diagnostic strategy by conditional preventive maintenance*, 4th International Conference on Computer Integrated Manufacturing CIM'2007, Algeria, 03-04 November 2007.
- [6] Jingwei, G., Peilin, Z., Baoyuan, L., Zhengjun, X.: *An Integrated Fault Diagnosis Method of Gearboxes Using Oil Analysis and Vibration Analysis*, 1-4244-1135-1/07/2007 IEEE, the Eighth International Conference on Electronic Measurement and Instruments ICEMI, 2007.
- [7] Qunfeng Z., Guangneng, D., Yanling, Y., Tonghai, W.: *Performance Deterioration Analysis of the Used Gear Oil*, Advances in Chemical Engineering and Science, 2016, 6, 67-75.
- [8] Serrato, R., Maru, M., Padovese, L.: *Effect of lubricant viscosity grade on mechanical vibration of roller bearings*, Tribology International, 40 (2007), 1270–1275.
- [9] Dodge, Y.: *First steps in statistics*, Edition Springer Verlag, France, 2006.
- [10] Chareille, P., Pinault, Y.: *Descriptive statistics*, Editons Dunod, Paris, 1997.

5 Conclusion

The main objective of the present work is to underline the importance of lubricants in the functioning of the parts for rotating machines and the choice of their quality. Based on the results obtained, it can be drawn that the vibration increases in proportion to the speed of rotation, varying inversely to the viscosity of lubricant, that is to say, the degradation of the lubricant quality (reduction in viscosity) causes the increase in the vibration level of our gear system. Therefore, the lubrication of the lightly loaded gears at average speeds, which are lubricated with relatively viscous oil, causes the separation of the teeth. This is done by a sufficiently thick film removing any metal to metal contact. Therefore, vibration in this case will be insignificant. According to the results obtained from the regression model proposed of the vibration depending on the lubricant viscosity, it can be concluded that there is a strong linear correlation (correlation coefficient values $R \geq 0.95$). We see that good agreement between theory and experiment is clearly expressed.

- [11] Kamoun, A., Chaabouni, M., Ayedi, H.: *Design of experiments and surface treatments*, Engineering Technique (M 1428), 2001.