

Investigation and analysis of the vibrational behavior of the rotating structure of a steam turbine

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Abstract:

Every machine has mechanical moving parts in recent generate internal stresses in its structure. These stresses manifest themselves through vibrations of the whole. Over time, imbalances in rotating machines appear. To conduct our research, we used a fan and measured the vibration speed with a sensor. Initially with unbalance and then with the presence of unbalance mass (m). The planning of the experiments was based on Taguchi's L9 orthogonal array. The statistical significance of the above -mentioned parameters on the results was explored using the analysis of variance (ANOVA). The relationship between responses' factors and the operating parameters is also established employing the multiple linear regression method. ANOVA results show clearly that the radius (r), mass (m), and rotational speed (N) are significant factors that influence the vibration speed.

1. Introduction

Turbines work in severe service environments, generally involving elevated temperature, pressure, and rotational speed, making them highly susceptible to vibration problems. These extreme operating conditions promote the occurrence of various dynamic defects, among these defects, rotor unbalance is the most significant [2] [3] [4]. Unbalance is detected when the center line of a rotor is out of phase with its shaft center line. the primary sources of unbalance are manufacturing imperfections in the component (blow holes in casting), unequal weights for rotor blades, corrosion wear, deposit built-up, high tolerances during fabrication and a missing part [5] [6]. Therefore, the influence of imbalance dynamic characteristics of the rotor has attracted the attention of researchers: Xiang et al. [7] analyzed the impact of residual unbalanced mass on vibration amplitudes of magnetically supported flywheel rotors by measuring dynamic displacements. Nayek and al. [8] developed an online unbalance identifying technique employing modeling and simulation to determine the eccentricity and

direction of the spindle, addressing dynamic imbalance issues caused by uneven mass distribution in rotors. Han et al. [9–10] demonstrated that the axial position of rotor unbalance has a significant impact on high-speed dynamic balancing and, using deep learning, they proposed a flexible rotor unbalance position identification method which was based on dynamic model simulations and experimental data. Thus, since unbalance is one of the main sources of vibrations in rotating machinery, vibration analysis emerges as an essential method for its early detection and diagnostic. The principle of vibration analysis is based on the idea that machine structures, excited by dynamic forces, emit vibration signals whose frequency is identical to that of the forces that caused them; and the overall measurement taken at a given point of the structure's vibration responses to the different exciting forces. It is therefore possible, using sensors placed at specific points, to record the vibrations transmitted by the machine structure and, through their analysis, to identify the source of the forces to which it is subjected. The technique of vibration analysis is now heavily used in industry

by finding its place in the predictive maintenance strategies. The origin of vibration of a structure resulting from the birth of various static and dynamic forces and are image defects that caused it [11]. Detecting a vibration of machine may be influenced by several factors:

- The impact of the vibration of adjacent machines.
- The size of the machine being guarded and the method of its mounting (rigid or flexible substrates).
- The choice of the direction and the measuring point.
- Equipment used (measurement chain) and integrated technology [11].

There are several reasons for unbalance phenomena. In our case, it is a mechanical imbalance (blade breakage, etc.). When a piece of the rotor, such as a blade, breaks and detaches, an instantaneous change in vibrations is generally observed. This change is better perceived if the amplitude and phase of the vibrations are simultaneously monitored in a vector representation. Blade losses also result in flow disturbances (presence of repeated pressure pulses). This study presents an experimental investigation into the effect of rotor unbalance on fan vibrations. By systematically modifying both the location and magnitude of the unbalance, the system's dynamic response is analyzed over a range of vibration speeds.

2. Methodology of work

2.1 Experimental device

The experimental study was conducted on a fan used as the reference test rig. To simulate different levels of unbalances additional masses were attached at specific positions on the blade spokes. This approach enabled the artificial reproduction of mechanical imbalance and the investigation of its influence on the vibrational behavior of the system. The resulting vibrations were measured using highly sensitive SKF vibrating pen plus (CMVP 50 (mm/s) RMS) figure1, providing the metrological accuracy required to capture the low amplitude displacements typical of rotating machinery.

2.2. The Experimental Test

Measurements were carried out the several strategic locations on the structure, considering both the

direction and orientation of detection to ensure a comprehensive recording of the vibration spectrum.

The experimental parameters considered include:



Figure .1. SKF vibrating pen plus (CMVP 50 5mm/s) RMS).

- The added unbalance masse (m),
- The radial distance from the axis of rotation (r),
- The rotor speed (N).

The functional diagram is presented in Figure 2.

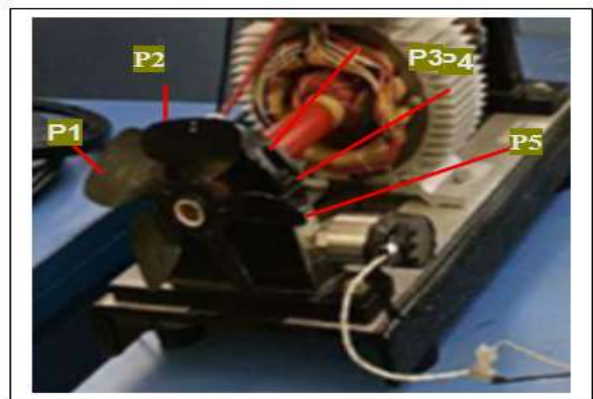


Figure. 2. Schematic diagram of vibration measurements

The vibration sensor was mounted directly on the fan bearing to avoid disturbances caused by airflow and to ensure greater reliability of the recorded signals. It represents a critical area where the dynamic forces generated by the rotor are transmitted. This choice allows for precise monitoring of the vibrational response of the system and a direct correlation between unbalance intensity and the measured amplitudes. Initial vibration measurements are carried out on the fan (without taking into account the imbalance due to the defect) at measurement points 1 to 5, distributed

uniformly over a total angle of 180°, i.e. a step equal to an angle ($\alpha = 45^\circ$).

3. Results and discussion

The experimental setup allows for precise adjustment for the rotational speed (N) within a controlled range of 300, 900 and 1200 rpm, ensuring accurate regulation of operation conditions. This capability provides a reliable basis for analyzing the dynamic response of the fun at different speeds. The measurements recorded in the absence of any any applied unbalance are presented in the table 1 below. It is seen that the influence of damping on the vibration level is considerably remarkable for the points P₁, P₂ et P₃ in the range [45°, 135°], absorption of vibration is well ensured and RMS vibration level (<15mm/s) is deemed eligible, but outside this zone the vibration level is important, it is considered unacceptable [12]The average values of vibration velocity (V) measurements as a function of rotational speed (N), mass (m) and radius (r) are shown in the table below (Table 3).

Design of experiments

Taguchi method was developed by Dr. Genichi Taguchi since 1960s in order to enhance the quality of manufactured products. Thereafter, this robust statistical method has attracted the attention of researchers' community. In fact, Taguchi method was intensively applied to a wide research activity such as: engineering, biotechnology, and marketing.Taguchi method is an experimental design technique that allows obtaining significant factors at low cost and a reduced number of experiments by using orthogonal arrays. On the other hand, the design factors could easily produce the best levels of measure.In this research, the data used for computation have been obtained by designing the experiments based on Taguchi L9 orthogonal array. Each input variable is varied according to three levels coded as1, 2, and 3. The levels of the input variables (i.e the mass (m), the radius (r), and the rotation speed (N)) are displayed in Table 4. On the other hand, following the Taguchi technique, the experiments' design consists of 9 runs as presented in Table 5 [13]. The unbalance force generating the vibration is expressed as:

$$F = m * r * \omega^2 \quad (1)$$

Where,

F= force (N)

m= mass (kg)

r= radius (m)

ω = speed (radian/sec)

The relationship (1) can be approximated by the following linear mathematical model:

$$yy = b_0 + \sum_{i=1}^k b_i . x_i \quad (2)$$

According to the experimental results presented in Table 5, regression equations were developed using the multiple regression method. This model is considered as linear function of the mass (m), the radius (r), and the rotation speed (N).the regression equations of the model adjusted for the vibration speed (V) expressed as follows:

$$V = -25,9 + 8,47m - 0,413r + 0,265N + 0,0108m*r - 0,0483m*N + 0,00524r*N \quad (3)$$

where V is the vibration speed (RMS), m is the mass (grs), r is the radius (mm), and N is the rotation speed (rpm). On the other hand, from Figures 8 and 9, which show the normal probabilities of the residuals of the vibration speed (V) model, it is clearly seen that the residuals fit almost perfectly to the straight line, which allows us to conclude that the errors have a normal distribution and therefore the terms of the deduced model are significant.A variance analysis (ANOVA) of the vibration speed was carried out. The main objective of this analysis is to study the effects of the input parameters, i.e., mass (m), radius (r), and rotation speed (N), on the responses studied. Due to conducting the experiments according to the Taguchi orthogonal array, results for various combinations of the input parameters were depicted in Table 5. It is worth noting that the analysis of the variance (ANOVA) is carried out for the level of significance of 5% (i.e., the level of confidence 95%). ANOVA results for V are displayed in Table 7. In fact, these tables show the degrees of freedom (DF), sum of squares (SS), mean square (MS), F-values (F-val.), and P-Value (Prob.). A low probability (Prob. < 0.05) indicates the statistical significance of the source factor for the corresponding response.The figure 10 shows the main factor effects on the vibration speed. It is clearly shown that the vibration speed is an increasing function of mass m, rotational speed N and radius r.

Table 1 ;Vibration speed measured by skf vibrometer without unbalance

Rotation speed (rpm)	P1 (0°)	P2 (45°)	P3 (90°)	P4 (135°)	P5 (180°)
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N ₁ (300)	12,5	8,9	7,8	10,1	25,2
N ₂ (900)	25,8	12,6	11,2	19,6	27,2
N ₃ (1200)	29,6	15,2	13,2	22,1	28,8

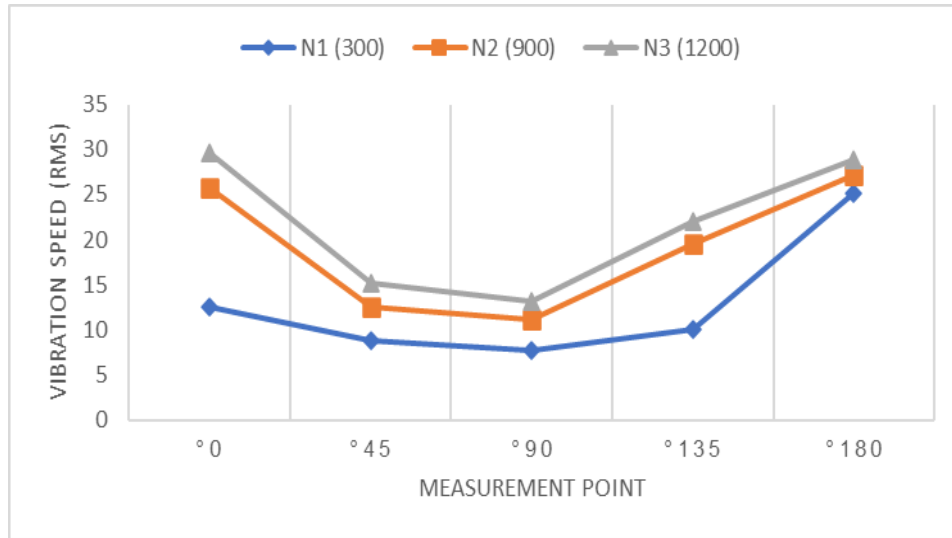


Figure .3. Variation of the fan's RMS) vibration speed V in the absence of unbalance

Table 2: Vibration speed measured by skf vibrometer with unbalance $m = 3$ grs.

Rotation speed (rpm)	P1 (0°)	P2 (45°)	P3 (90°)	P4 (135°)	P5 (180°)
N ₁ (300)	29,6	14,5	7,8	11,4	29,1
N ₂ (900)	30,1	16,3	10	15,5	31,9
N ₃ (1200)	37,4	17,9	11,3	16,5	33,3

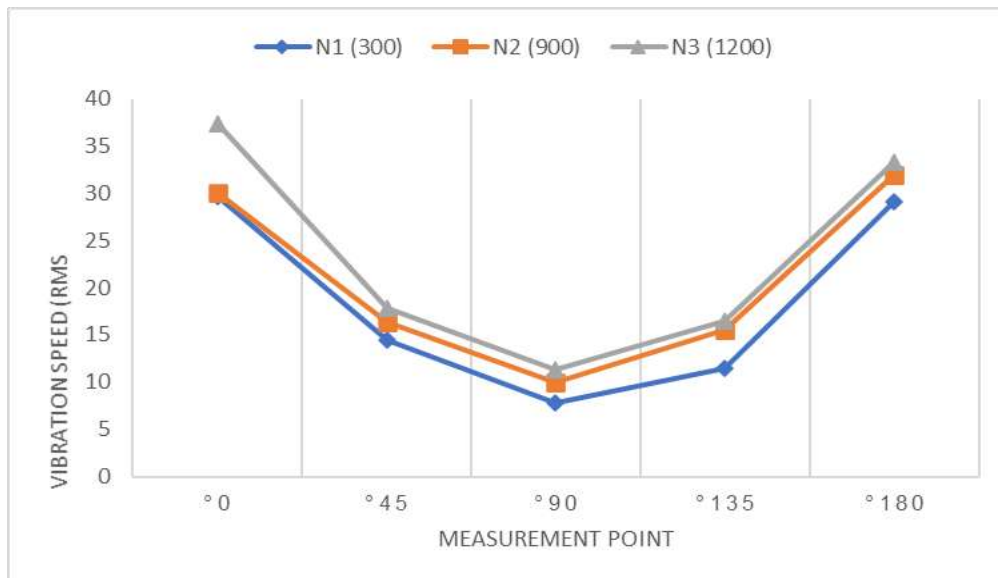


Figure. 4. Variation of the fan's RMS vibration speed V with unbalance $m = 3$ grs

Table 3 Vibration speed's value according to (N), (m) and (r).

	N ₁ = 300 rpm			N ₂ = 900 rpm			N ₃ = 1200 rpm		
Rayon (mm)	m ₁ =3 gr	m ₂ = 7 gr	m ₃ = 10 gr	m ₁ =3 gr	m ₂ = 7 gr	m ₃ = 10 gr	m ₁ =3 gr	m ₂ = 7 gr	m ₃ = 10 gr

25	11,4	29,22	38,4	11,4	31,43	46,2	16,5	29,85	38,6
35	21,2	30,11	44,5	26,4	35,51	49,3	30,5	39,12	44,5
40	25,3	36,5	46,1	27,3	37	51,4	35,6	42,5	49,8
70	31,6	34,66	49,3	35,2	52,14	56,7	50,7	59,1	60,4
80	35,02	37,67	50,2	48,3	56,66	58,9	50,83	55,14	60

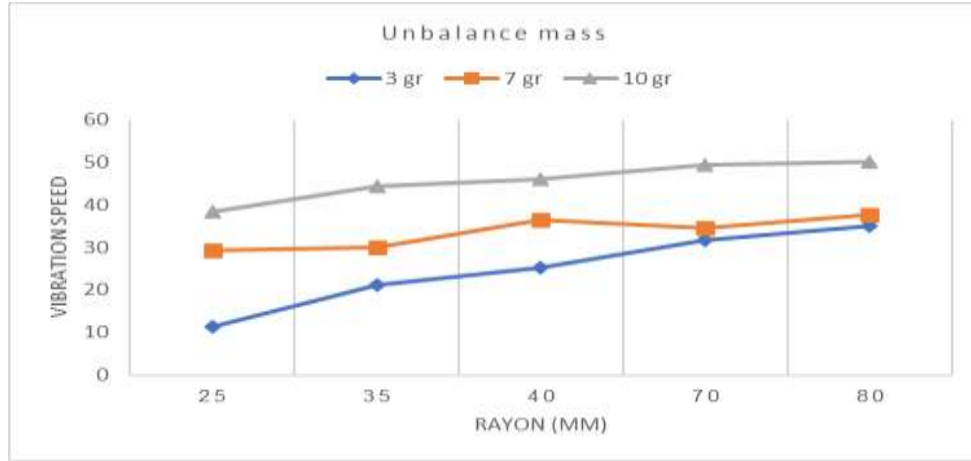


Figure .5. variation of vibration speed amplitude for $N_1 = 300$ rpm

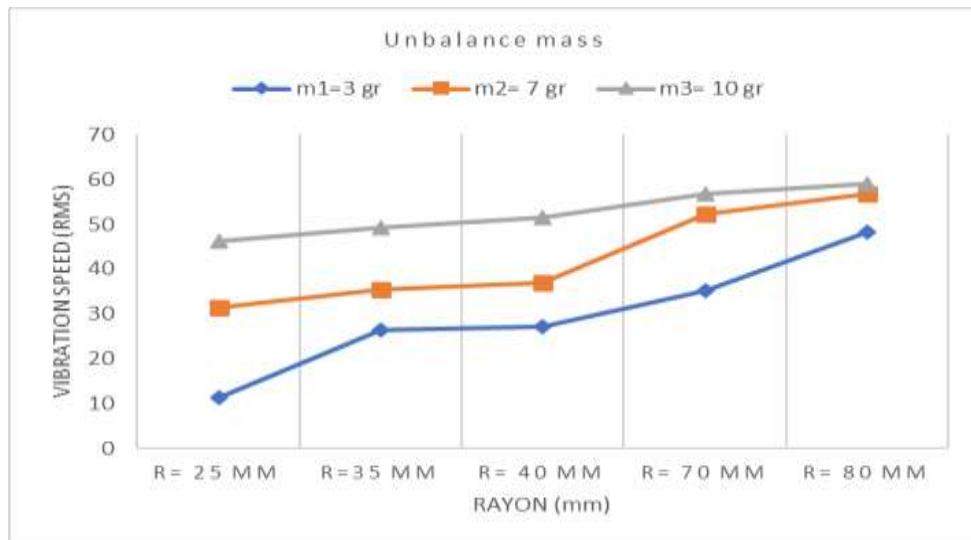


Figure .6. variation of vibration speed amplitude for $N_2 = 900$ rpm

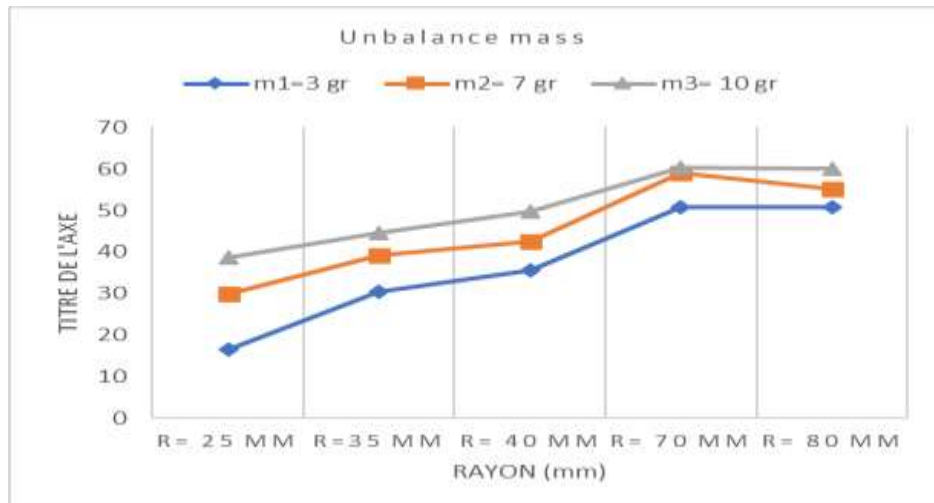


Figure .7. variation of vibration speed amplitude for $N_3 = 1200$ rpm

Table 4 Assignment of the factor levels.

Niveau	mass m (grs)	radius r (mm)	Rotationnel speed N (rpm)
1	3	25	300
2	7	40	900
3	10	70	1200

Table 5 Results of vibration speed for different combinations of operating parameters.

Essais	Coded Factors			Actual Factors			Responses' Factor
	X1	X2	X3	m (grs)	r (mm)	N (rpm)	V (RMS)
1	1	1	1	3	25	300	11,4
2	1	2	2	3	40	900	27,3
3	1	3	3	3	70	1200	50,7
4	2	1	2	7	25	900	31,43
5	2	2	1	7	40	1200	38,6
6	2	3	3	7	70	300	34,66
7	3	1	3	10	25	1200	38,6
8	3	2	1	10	40	300	46,1
9	3	3	2	10	70	900	56,7

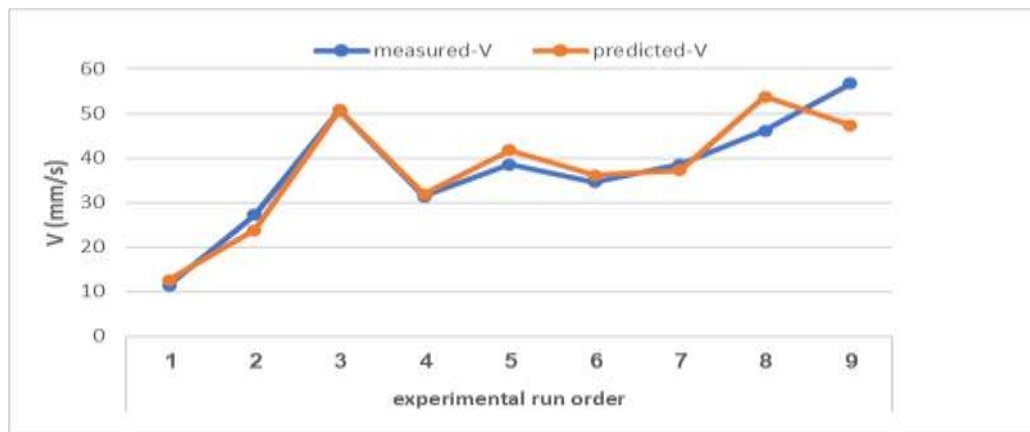


Figure 8: Comparison between the measured and predicted values for speed vibrations.

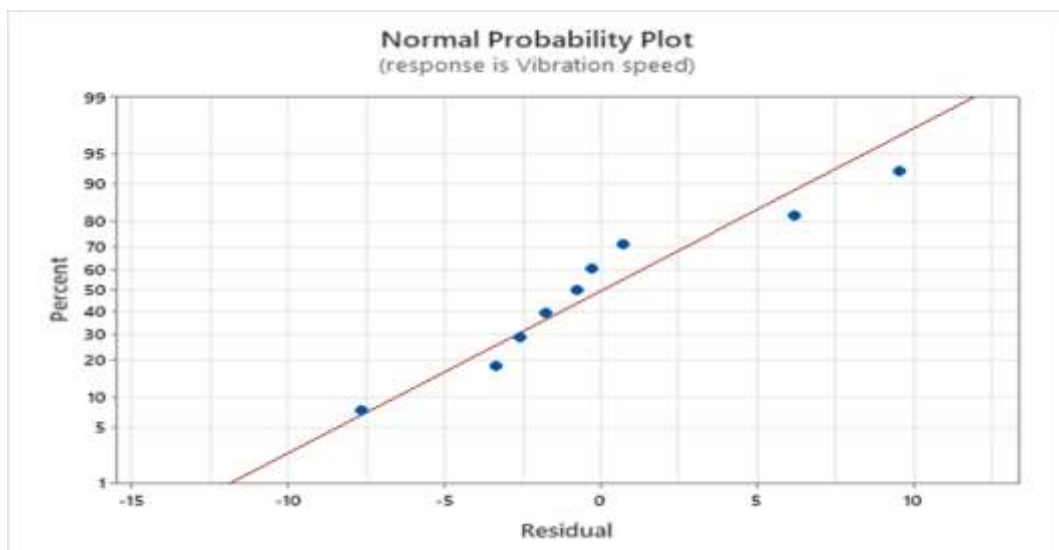


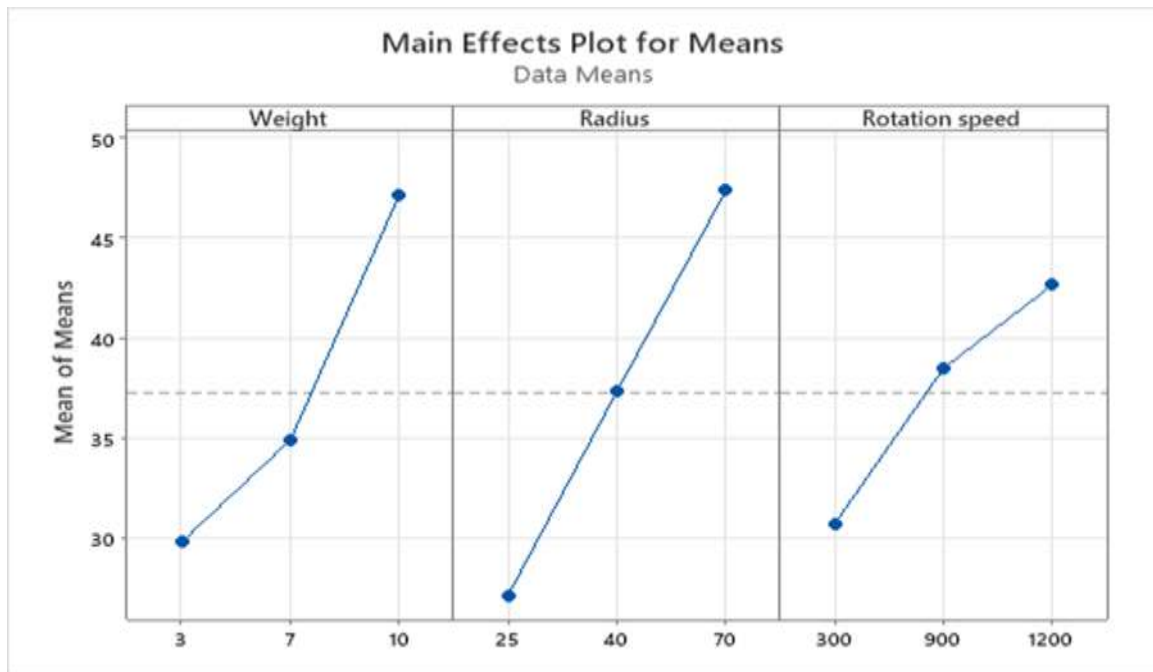
Figure .9. Normal probability curve for vibration velocity (V)

Table 6 Coefficient of determination.

Model	Coefficient of determination R^2
Vibration speed V (mm/s^2)	0.855

Table 7 ANOVA results for vibration speed (V).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	1239.2	413.07	9.85	0.015
Weight	1	430.2	430.23	10.26	0.024
Radius	1	589.7	589.68	14.06	0.013
Rotation speed	1	219.3	219.30	5.23	0.071
Error	5	209.8	41.95		
Total	8	1449.0			

**Figure.10.** Main factor plots: averages $\bar{f}$; A mass, B radius and C rotational speed

5. Conclusions

A vibration measured on a machine in operation is influenced by several factors, such as the machine environment, the method used to mount the sensor, his quality and technology and the size of the monitored system. Indeed, for the same engine load, an increase in the monitoring peak value at a given frequency can be diagnosed as an early deterioration of one of the machine's constituent parts.

On the other hand, the obtained mathematic model shows the effect of the operating parameters, i.e., mass (m), radius (r) and rotational speed (N), on the studied responses.

The principal results of this study are summarized as follows:

- Increasing the unbalanced mass fixed on the blade radius leads to a significant rise in vibration amplitude, thus confirming the rotor's sensitivity to variation in mass distribution.
- Rotational speed plays a critical role, as increasing speed results in an almost proportional growth in vibration amplitude, reaching peak values near the rotor's critical frequency. Such behavior is a typical characteristic of rotating systems subjected to mechanical unbalance.

This study uses an L9 orthogonal array for three design parameters: rotational speed, unbalance mass and their location on the radius. Nine experiments were performed, compared to 81 in total. The Taguchi method allows obtaining significant factors at low cost, with a short

experimental duration and a reduced number of experiments.

The comparison of both the experimental and predicted values show a good agreement between the results.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Use of AI Tools:** The author(s) declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

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