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Nondestructive Testing of Welded Test Setup Construction By Vibrational Behaviour

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Abstract: In this study, the factors influencing the root causes of failure initiations are examined by conducting the original experimental implementation and condition monitoring techniques on a welded test setup construction. In target of root cause failure detection, vibration data are acquired through radial and axial directions for the analysis. A test setup system has been designed by gathering inspiration from an existing system in industrial environment and the test setup constructed by welding method in joinings of main steel parts. Unbalance and mechanical looseness failures are practised at one rotation frequency on the test setup. Vibrational data are collected in three axis simultaneously through four-channel data acquisition card (DAQ) integrated with the computer system. According to the study results, vibration analysis in detection of tested failures has been judged to be successful. In the study, it is mentioned that prognosis and diagnosis may go in incorrect evaluation respect to the concurrent symptoms of failure data consisting main orders of the base frequency and natural frequencies that lead to resonance.

Keywords: Vibration; fourier; signal; welded.

Titreşim Davranışı ile Kaynaklı Test Düzeneği Konstrüksiyonunun Tahribatsız Test Edilmesi

Özet: Bu çalışmada, arizi kusur kök nedenlerine etki eden faktörler, kaynaklı bir test düzeneği ve özgün deneysel uygulama ile durum izleme teknikleri kullanılarak incelenmiştir. Kök neden arıza tespiti hedefine ulaşabilmek için ise, titreşim verileri radyal ve eksenel yönlerde toplanmıştır. Bu test düzeneği kurulumu endüstriyel ortamda varolan bir sistemden esinlenerek dizayn edilmiş ve test düzeneğinde ana düzenek, sehpa parçaları kaynaklı yöntemle birleştirilme yoluna gidilmiştir. Dengesizlik ve mekanik gevşeklik kusurları test düzeneğinde belirlenmiş dönme frekansı etkisinde oluşturulmuştur. Titreşim verileri bilgisayar sistemi ile entegre dört kanallı veri toplama kartı (DAQ) aracılığıyla aynı anda üç eksende toplanmıştır. Çalışma sonuçlarına göre, test edilen kusurların tespiti titreşim analizi ile başarılı olduğu sonucuna varılmıştır. Çalışmada, prognoz ve diyagnoza dayalı teşhis ve tanı işlemlerinde, temel frekans ve rezonansa neden olan doğal frekansların çakışmalarından dolayı eş zamanlı belirtilerin yanlış değerlendirmelere neden olabileceği ortaya konulmaktadır.

Anahtar kelimeler: Titreşim; fourier; sinyal; kaynaklı.

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1. Introduction

In order to reduce the unit production cost; various optimization methods, logistics, spare parts, work-study applications, six sigma and many other methods are implemented within the scope of lean manufacturing techniques and operations research. By spreading in our country, innovative maintenance techniques of predictive maintenance based on condition monitoring will consequence in nominal or extended machine life; and other consequences will be increase in quality product output, reducing in spare parts inventory, falling in product unit cost and probable positive developments in occupational health. Not only large enterprises benefits from innovative condition monitoring techniques, but also widespreading in small and medium-sized enterprises will maintain benefits mentioned above and also will have gainings in prevention of electrical losses and less unscheduled interruptions due to mechanical failures such as misalignment, unbalance, mechanical looseness, bearing damage. These gainings will make a significant contribution in sustainability of the quality production.

In dynamic systems, there are two main reasons controlling the amplitude and frequency of vibration as external forces and system dynamic characteristics. Alternating any of these reasons will change the vibration response occurred in the system. [1]. Because the machine is sensitive to the slightest structural or procedural changes in the vibration response, vibration analysis in business is one of the most popular and accepted methodology [2]. Case basis of the monitoring techniques, degradation processes to identify some of the features indicative of equipment with appropriate reading of sensor measurements and these features are based on an understanding of health care equipment and monitoring techniques [3]. Heart of the condition-based maintenance is the continuous monitoring process enables the display state of signals by using certain types of sensors and indicators [4]. The machine has usually suffered specific damages that can be traced throughout the operational life cycle of the machine type. Machine condition monitoring technology is the science of examining and evaluating, mostly based on vibration measurement including collection of symptoms and analysing symptomatic status [5]. In the machine that has rotating elements; defect phenomenons are inevitable while symptoms such as heat accumulating, wear, looseness etc. can not be detected at the initiation period which are caused by failures in manufacturing, installation and tolerance. In order to detect initiation of defects over rotor, model or signal based methods are used in general [6]. Maintenance plans are prepared based on condition monitoring techniques in order to detect failures in the early state and to prevent unplanned stoppages in induction machines. [7].

2. Material-Methods

Test apparatus; AC induction motor, double inlet centrifugal fan, consists of five feet of flexible coupling and frequency changer. The test apparatus is placed on the steel sheet and a stable tripod. The system as a whole, data acquisition card and the motor is integrated in monitoring system associated with a computer system. In order to join steel parts, welding has been implemented for construction of the test setup. Testing apparatus in Figure 1 presents the view.

Theoretically the frequencies used in the test (T) and applied (A) are shown in Tab. 1, the approximate values. Theoretical frequencies shows the value set on the digital frequency changer; according to data obtained during the application of the numerical frequency value set, actual frequency ranging suffered some losses. Harmonic 1x expressed as a frequency value that is recognized as the fundamental frequency; 2x, 3x and the values in the upper orders and are called harmonics of the fundamental frequency. In the table, the frequency is set with the f symbol for frequency converters and represents the harmonic order with h symbol.

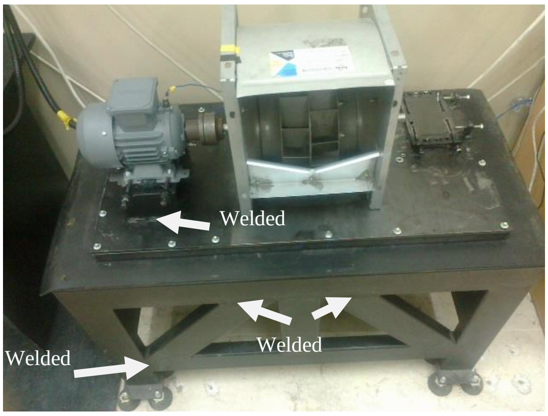


Figure 1. Welded Construction Test Setup

Table 1. Harmonics in theoretical and application - f(Hz), h(x)

(h) / (f)	1x		2x		3x		4x		5x	
	T	**A**	**T**	**A**	**T**	**A**	**T**	**A**	**T**	**A**
50	50	47,61	100	95,22	150	142,83	200	190,44	250	238,05

Measurements were made during the tests at electrical frequency of 50 Hz and rotational period was measured as 2800 min^{-1}. Possible failure frequencies and harmonics is taken into account when calculating the bearing and fan-induced vibrations of the test apparatus.

Over the basic failure frequency measurements made by calculating bearing related equations are presented in Tab. 2.

Table 2. Main failure frequencies

f (Hz)	ω_s (Hz)	ω_{bpf} (Hz)	ω_c (Hz)	ω_{bpfo} (Hz)	ω_{bpfi} (Hz)	ω_{bsf} (Hz)
50	47,61	476,1	19	152	248	98,16

Frequency calculations relevant with bearing :

$$\omega_{bpfo} = \omega_s\left(\frac{n}{2}\right)\left[1-\left(\frac{r}{d}\right)\cos\phi\right] \qquad (1)$$

$$\omega_{bpfi} = \omega_s\left(\frac{n}{2}\right)\left[1+\left(\frac{r}{d}\right)\cos\phi\right] \qquad (2)$$

$$\omega_{bsf} = \omega_s\left(\frac{d}{2r}\right)\left[1-\left(\frac{r}{d}\cos\phi\right)^2\right] \qquad (3)$$

$$\omega_c = \frac{\omega_s}{2}\left[1-\left(\frac{r}{d}\right)\cos\phi\right] \qquad (4)$$

$$\omega_{bpf} = \omega_s n_b \qquad (5)$$

ω_{bpfo}: Outer ring passing frequency (Hz), ω_{bpfi}: Inner ring passing frequency (Hz), ω_{bsf}: Ball spin frequency (Hz), ω_c: Cage frequency (Hz), ω_s: Shaft frequency (Hz), ω_{bpf}: Fan blade passing frequency (Hz), n: Number of balls, r: Diameter of ball, ϕ: Angle of contact, d: Diameter of division circle, n_b: Number of fan blades = 10

Unbalance mass in the test was performed by loading 23 g of weight, as shown in Figure 2.

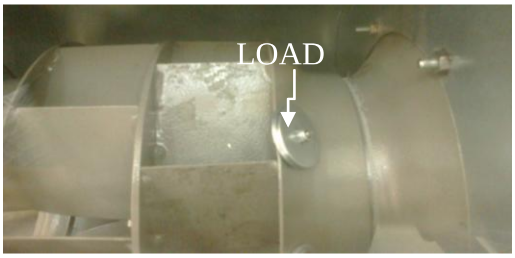


Figure 2. Unbalance phenomena on fan wings

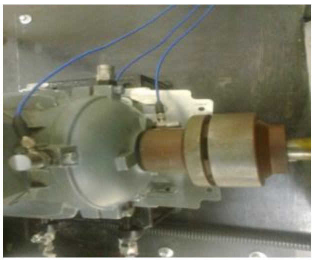


Figure 3. Mechanical looseness at footings by shim

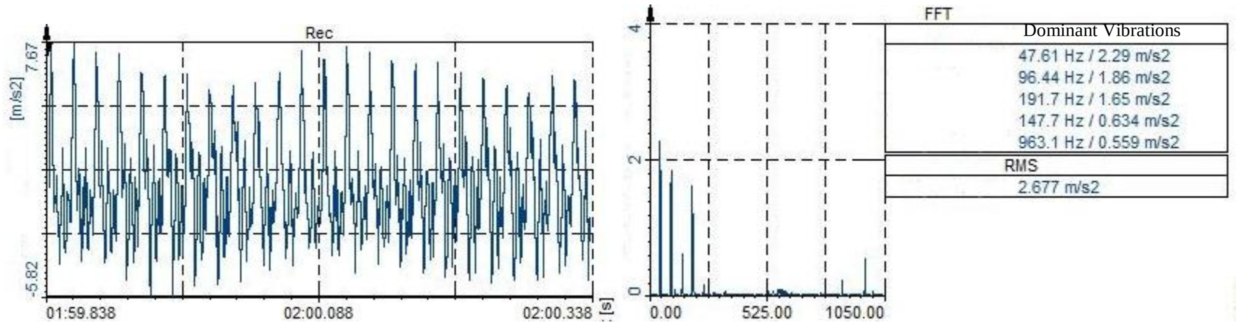
At 0.1 mm and 0.5 mm level in vertical direction, all consequences brought occur at two different levels as looseness in the front two legs of the electric motor in Figure 3 is examined.

3. Experimental

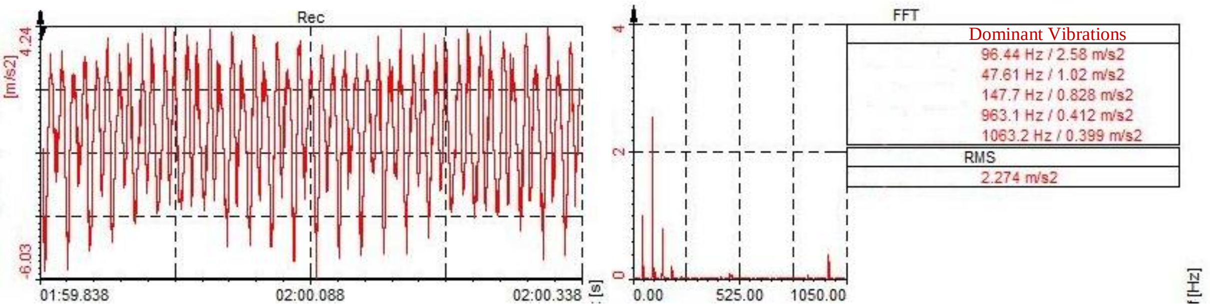
Vibration measurements are done in radial (vertical, horizontal) and axial measurements during the tests. In this study, the data collected through the vertical direction is presented in the name of radial direction. In order to detect natural frequencies for comparison, damping tests are implemented on welded test setup when the system is not dynamic.

3.1. Failure of unbalance at 23g level

In the radial direction according to Figure 4, maintaining 23 g load caused unbalance symptom as dominant harmonic 1x and it is observed as the highest amplitude vibration signal of 2.29 m/s^2, and 1x in the axial direction as the second harmonic is observed through dominant signals. Unbalance effect has been detected significantly in the radial, axial direction and irregularities are found in values of the peak-to-peak waveform chart.



(a) Radial way waveform graph (b) Radial way spectrum graph



(c) Axial way waveform graph (d) Axial way spectrum graph

Figure 4. Vibrational data of unbalance failure at rotating speed 2880 min^{-1}

In both directions regarding bearing defect frequencies zone, cage frequency harmonic 51xω_c excited natural frequency signal at 963.1 Hz and it has emerged among the top five in the frequency of the dominant signals. In the axial direction regarding bearing defect frequencies zone, it is observed that natural frequency at 1063.2 Hz has been excited by cage frequency harmonic 56xω_c. Unbalance effect in the radial direction spectral data is detected as clearly, misalignment symptom appeared on the axial direction in spectral data.

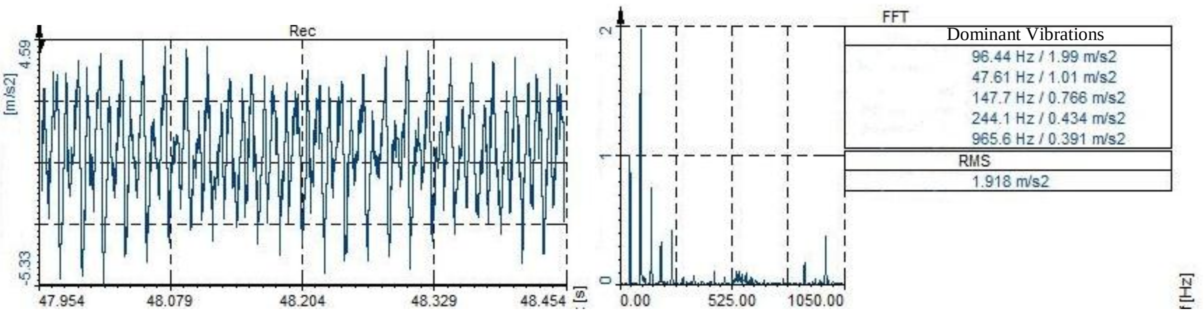
The unbalance forces in the radial direction of the dominant fundamental frequency 1x (47.61 Hz) harmonic at 2.29 m/s^2 is determined by the amplitude value. The unbalance harmonic 1x in the axial direction at frequency 47.61 Hz as 1.02 m/s^2 has been observed with the amplitude value. 1x harmonic of the fundamental frequency is observed only as a sign of unbalance compared to the radial direction the dominant signal measurements. RMS (Root Mean Square) values increased in the radial direction and the axial direction in comparison with reference levels. 963,1 Hz and 1063,2 Hz natural frequencies are observed only in unbalance test. The highest five amplitude formed in 2880 min^{-1} rotation period caused by unbalance flaw occurred on the same frequencies in the five dominant signals of reference data.

Table 3. Vibration signals of unbalance failure at 2880 min^{-1} – (S=Signal)

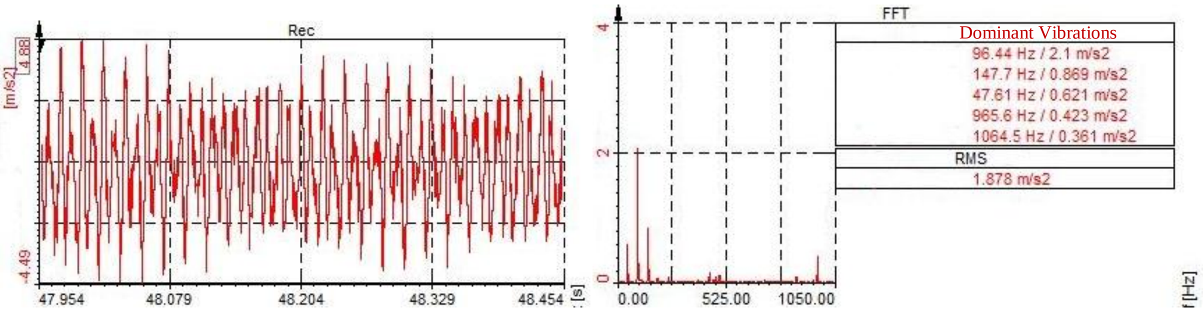
MEASUREMENT	**1.S**	**2.S**	**3.S**	**4.S**	**5.S**	**RMS (m/s^2)**
U / 2880 min^{-1} / 23 g / (R)	1x	f_n (2x)	f_n (4x)	f_n (3x)	f_n (51xω_c)	2.677
U / 2880 min^{-1} / 23 g / (A)	f_n (2x)	1x	f_n (3x)	f_n (51xω_c)	f_n (56xω_c)	2.274

3.2. Failure of mechanical looseness at 0.1 mm level

In radial and axial direction, signal at 95.21 Hz (2x) excited a signal at the natural frequency at 96.44 Hz and consequently superharmonic resonance has been observed with the highest signal amplitude. Unbalance harmonic 1x is appeared as second dominant harmonic in radial direction, and appeared as the third dominant signal in the axial direction. In both directions, cage frequency at 964.8 Hz (51xω_c) excited natural frequency at 965.6 Hz and cage frequency at 1061.28 Hz (56xω_c) excited natural frequency at 1064.5 Hz in the axial direction and superharmonic resonance frequency is detected. Other signals are observed due to induced mechanical looseness and bearing signals. Fluctuations in the waveform chart is observed. Data graphs are given in Figure 5.



(a) Radial way waveform graph (b) Radial way spectrum graph



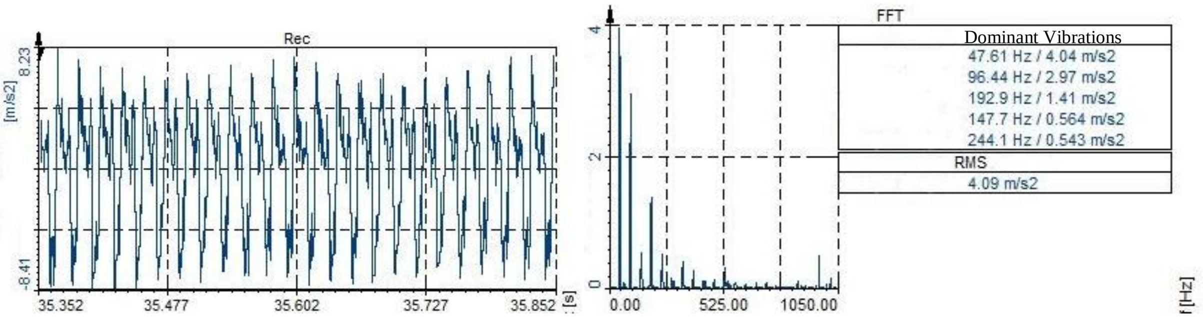
(c) Axial way waveform graph (d) Axial way spectrum graph

Figure 5. Vibrational data in 0.1 mm mechanical looseness at 2880 min^{-1}

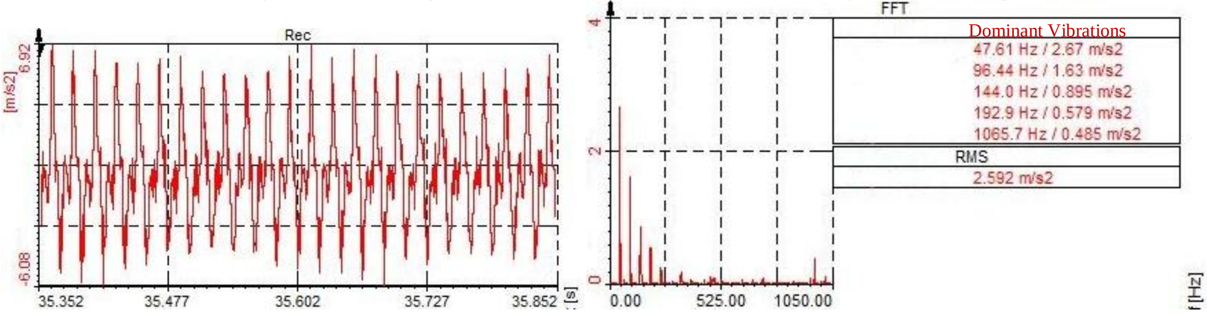
In the radial direction vibration signals detected in the highest five amplititudes are; natural frequency at 96.44 Hz, 47.61 Hz (1x) base frequency, natural frequency at 147.7 Hz, natural frequency at 244.1 Hz, natural frequency at 965.6 Hz; in the axial direction, signals are observed as the natural frequency at 96.44 Hz, the natural frequency at 147.7 Hz, 47.61 Hz (1x) base frequency, natural frequency at 965.6 Hz, natural frequency at 1064.5 Hz. Mechanical looseness in the radial direction spectrum of symptoms are observed more pronounced**.**

3.3. Failure of mechanical looseness at 0.5 mm level

The dominant signal of natural frequency at 96.44 Hz belonging mechanical looseness testing at 0.1 mm level in radial and axial direction is replaced with unbalance harmonic 1x in the level of 0.5 mm; the 96.44 Hz signal has replaced as sub-dominant. Respect to the Figure 6, in both directions unbalance harmonic 1x is observed in the first dominant harmonic signal. In the bearing defect frequencies zone, signal at 1065.7 Hz frequency has been detected and it isobserved only in the axial direction through five dominant signals. Other signals are observed in mechanical looseness and bearing effects. Unbalance effects are evident in the waveform chart and fluctuations in peak-to-peak value is determined.



(a) Radial way waveform graph (b) Radial way spectrum graph



(c) Axial way waveform graph (d) Axial way spectrum graph

Figure 6. 0.5 mm mechanical looseness vibrational data at 2880 min^{-1}

In radial direction, 47.61 Hz (1x), 96.44 Hz (f_n), 192.9 Hz (f_n), 147.7 Hz (f_n), 244.1 Hz (f_n) signals in frequency; and in the axial direction, 47.61 Hz (1x), 96.44 Hz (f_n), 144 Hz (f_n), 192.9 Hz (f_n), 1065.7 Hz (f_n) signals in frequency are detected. At 2880 min^{-1} rotating period in tests harmonic 1x is observed as the dominant signal at 0.5 mm level; this suggests that the effects become more dominant for unbalance failure respect to the high vibrations occur due to lack of uniformly distributed forces caused by the high oscillations besides effect of mechanical looseness.

According to Tab. 4, in both directions natural frequency signal that is excited by 2x misalignment harmonic occurred at 0.1 mm level and unbalance harmonic 1x is observed at 0.5 mm level and these two harmonic signals has emerged as the dominant signals. Regarding signals at increasing frequencies beside the signal at 2x; harmonic 2x has led to the definition of inclusion in mechanical looseness. Signals at bearing defect frequencies zone and increase in the amount has been detected; this situation indicates that the bearing's response is increased relevant with tests.

Table 4. Mechanical looseness signals at rotation speed of 2880 min^{-1}

MEASUREMENT	1.S	2.S	3.S	4.S	5.S	RMS (m/s^2)
ML/2880 min^{-1} /0.1 mm/(R)	f_n (2x)	1x	f_n (3x)	f_n (5x)	f_n (51xω_c)	1.918
ML/2880 min^{-1} /0.1 mm/(A)	f_n (2x)	f_n (3x)	1x	f_n (51xω_c)	f_n (56xω_c)	1.878
ML/2880 min^{-1} /0.5 mm/(R)	1x	f_n (2x)	f_n (4x)	f_n (3x)	f_n (5x)	4.09
ML/2880 min^{-1} /0.5 mm/(A)	1x	f_n (2x)	f_n (3x)	f_n (5x)	f_n (56xω_c)	2.592

Natural frequencies excited by harmonic 2x are detected as the most dominant signals at 0.1 mm level in radial and axial directions; and harmonic 1x is detected as the most dominant signal respect to the 0.5 mm level,.

At 2880 min^{-1} rotation period, change in the amount of mechanical looseness spectrums is shown in Figure 6. mechanical looseness symptoms have been observed better in the data through radial direction.

According to spectrum data in 0.5 mm mechanical looseness level, 1x signal amplitude seems to have become the most dominant harmonic signal that is the symptom of unbalance. Also, in the bearing defect frequencies zone, bearing mediated signals became more evident in both directions at 0.5 mm level. RMS values rise in parallel to increase of level in mechanical looseness.

4. Results and Discussion

Respect to the findings relevant with unbalance test; 23 g load effect has been detected in the viration measurement in the radial direction. Time domain has been studied and the main symptom of unbalance failure as 1x harmonic has been appeared and determined successfully. Natural frequencies appeared respect to the lower orders of the 1x and cage frequencies of the bearing element.

Even though, natural frequencies that excited by the 2x harmonic has been obtained in the first order on both the radial and axial direction at 0.1 mm level of mechanical looseness, 1x harmonic is appeared in the first order at 0.5 mm level of mechanical looseness. At 0.1 mm level, 2x harmonic is typical symptom of mechanical looseness and has been detected successfully. On the other hand at 0.5 mm level, 2x harmonic appeared in the second order which excites the natural frequencies that can be interpreted as mechanical effect can be detected too. Reversely at the 0.5 mm level; as consequence of the increasing oscillations, unbalance failure appeared with the symptom of main characteristic 1x harmoning in the first order.

In comparison with unbalance and mechanical loosenes failure tests; unbalance test with 23 g load and mechanical looseness presented traditional consequence; on the other hand, unbalance failure occured additionally on mechanical looseness at 0.5 mm mechanical looseness in 2880 min^{-1} rotation period.

5. Conclusions

Respect to the experimental test and results; test setup constructed by metal body joined with welding method may have some natural frequencies which might be excited by orders of main frequency and bearing frequencies. High amplititude vibrations those caused by resonance phenomena due to natural frequencies should be detected before or during the construction of metallic structures and should be avoided as much as possible in order to prevent demolition of mechanical elements.

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