The Perception of Rhythmic Similarity:
A Test of a Modified Version of Johnson-Laird's Theory

Jasba Simpson, David Huron
Conrad Grebel College
University of Waterloo
Waterloo, Ontario
N2L 3G6

Introduction

Although many aspects of musical experience appear to be dominated by impressions of *resemblance*, music theory has provided little guidance concerning how to characterize or measure the degree of similarity between various musical passages. How is it that a listener is able to say that passage 'A' is more similar to passage 'B' than it is to passage 'C'?

Recently, Johnson-Laird (1991) has proposed a theory of rhythmic prototypes that has repercussion for the perception of rhythmic similarity. Specifically, Johnson-Laird claims that all rhythms generated from a given prototype are perceived as rhythmically similar. Further, Johnson-Laird suggests that certain prototypes are particular to specific genres of music.

Johnson-Laird assumes that (Western) rhythms are perceived within a metrical framework of duple, triple, or quadruple beats. Johnson-Laird distinguishes three basic ways in which a beat may be experienced. These basic beat experiences are referred to as "note" (a note onset coincides with the beat), "syncopation" (a note within the beat is followed by a note whose onset is after a metrical unit of greater importance than the metrical unit corresponding to the onset of the first note), and "other" (a beat that conforms to neither of the two previous types). A prototype of each measure is constructed by assigning each beat as one of three beat types. An example of a prototype for a triple meter measure with note onsets on each beat is "note-note-note". Johnson-Laird proposes that all one-measure rhythms derived from a single prototype should be judged as more similar to one another than to those based on a different prototype. Using the previous example rendered in 3/4 time, a measure of 3 quarter notes and a measure of 6 eighth notes are more similar to each other than a measure of one eighth note rest followed by 5 eighth notes (corresponding to the measure prototype "other-note-note").

Johnson-Laird's syncopated beat type relies on the events in the following beat because it is a theory of rhythm production. To create a syncopated note, there must be no note coinciding with the following beat of greater metrical unit. However, from a perceptual point of view, a listener is unable to distinguish the syncopated beat type from the "note" or "other" beat types until the next beat occurs. Using a theory of rhythmic production to model perception fails as it implies that listeners are retrospectively perceiving beat types. We suggest rather that listeners perceive a syncopation at the moment when a beat of greater metrical unit than the onset of the current note is traversed. We therefore assign the syncopated beat type to a beat which has been traversed by a note whose onset coincided with a beat of lesser metrical unit. Using two-beat prototypes, "sync-other" now becomes either "other-sync" or "note-sync".

In this paper, three tests of a perceptually modified version of Johnson-Laird's theory are reported. In the first instance, a perceptual experiment is described whose goal was to determine whether listeners perceive rhythms sharing the same prototype as more similar than rhythms of different prototypes. In the second instance, a sample of notated music was examined in order to determine the degree to which actual musical practice conforms to one of several predictions made by Johnson-Laird. In the third instance, a further perceptual experiment is described where listener's perceptions of real music is correlated with prototype analyses. The results provide broad empirical support for Johnson-Laird's theory of rhythmic similarity.

Experiment I

Four musician subjects were recruited from an undergraduate population. Stimuli were presented in a two-alternative forced-choice paradigm. For each trial, four different rhythms were presented in two pairs. One pair was composed of two rhythms that shared the same prototype while the other pair had two rhythms from different prototypes. Subjects were asked to judge which of the two pairs contained rhythms that sounded most similar to each other.

Each trial maintained a constant metric framework. Each pair of rhythms was preceded by two measures of metronome clicks in order to establish the meter and tempo. The first beat of each measure in the metric context was accented. A two measure rest separated the first and second pair of rhythms. After the second pair of rhythms, a four measure response period elapsed before the onset of the next trial.

Trials were organized in two blocks of 10 trials. All trials in each block employed stimuli whose measures had the same number of beats. Hence, each subject heard a triple-meter block and a quadruple-meter block.

The results of experiment I are summarized in Table 1.

Subject	Agreement with Theory
1	16/20
2	14/20
3	15/20
4	19/20

TABLE 1. Results of Experiment I

These results are significant at the $p < 0.001$ confidence level. Experiment I showed that rhythms conforming to the same rhythmic prototype are more likely to be judged similar.

Experiment II

Johnson-Laird suggests that musical genres can be distinguished by the use of stereotypic measure prototypes. As testing this hypothesis suggests an exhaustive notated music analysis, a different hypothesis is proposed. The redundancy in the use of measure prototypes is expected to be high for early music and to progressively decrease as musical styles adopt more and more complicated rhythms.

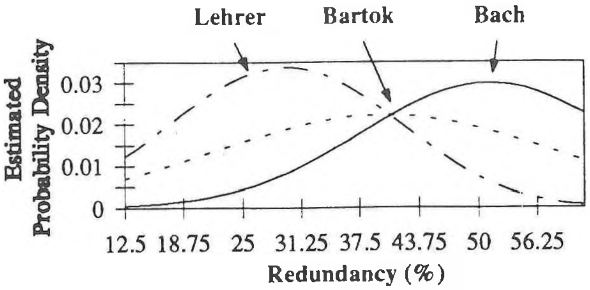

Figure 1. Results of Experiment II

To test this hypothesis, the redundancies in the use of one-measure rhythmic prototypes in 54 individual works by Bach, Bartók , and Lehrer were calculated using an information measure. Probability density functions were then estimated using Parzen windows (Duda & Hart, 1973) and are presented in figure 1. As a histogram, Parzen windows approximates the underlying probability function that is responsible for producing a set of data. However, unlike a histogram, Parzen windows requires no assumption about the size of the bins which may greatly affect the shape of a histogram.

There is a significant difference in the means of the distributions. Works by Lehrer have a quarter the redundancy in the use of rhythmic prototypes as compared to Bach. Bartók sits in the middle of the two, both in redundancy and in history.

Experiment III

Three subjects were recruited from an undergraduate population. Subjects were all musicians. An ecological test was administered to collect subjective measures of similarity within an audited musical work. Recordings of the 15 Inventions by J.S. Bach were made available to each subject. Subjects were instructed to listen to the inventions as often as wished and in any desired order. They were asked to rate each invention according to the perceived rhythmic complexity within each piece.

As a first estimate of perceived rhythmic similarity within a musical piece, the redundancy in the use of one-measure prototypes was calculated for each invention. The results of experiment III are summarized in Table 2. Kendall's Q measures the concordance between two variables. The coefficient ranges between 0 and 1, with 0 signifying no agreement and 1 signifying complete agreement.

Subject	Kendall's Q	Significance
1	0.5802	0.2985
2	0.4781	0.4964
3	0.5379	0.3741
All	0.5320	0.0554

TABLE 2. Results of Experiment III

Although the results are not significant taken individually, the concordance is skewed in the predicted direction. As a group, the subjects showed marginal significance.

Discussion

The first perceptual experiment provided significant empirical evidence supporting the modified Johnson-Laird theory of rhythmic prototypes as a useful predictor of human perception of rhythmic similarity. However only musicians were tested, amongst whom the best results were obtained from those most involved with musical activity. It may be that rhythmic prototype recognition is an acquired means of organizing perceived rhythms. Further tests with non-musicians could provide empirical support for this hypothesis.

The ecological test produced marginally significant results (p = 0.0554).

Johnson-Laird's theory of rhythmic prototypes applies only to a single stream of notes and so examining 2-part music raises some problems. For the two-part inventions, each part was analyzed separately and their redundancies averaged. The listener however was perceiving both lines simultaneously. This divided attention across two auditory streams and its effect on rhythmic perception is beyond the scope of this proposed theory of rhythmic similarity.

Johnson-Laird's original theory remains untested. As there was no experimental evidence to support the original theory, a modification was undertaken and the resulting theory directly tested. Generally speaking, Johnson-Laird's original theory makes less distinctions between beats than the modified theory. Therefore using the original prototype definition to rate the results of the perceptual experiments would not be expected to produce greater significance.

Conclusion

The modified version of Johnson-Laird's theory of rhythmic prototypes presented in this paper helps in characterizing the human perception of rhythmic similarity. The three tests carried out provided for broad empirical support of the proposed theory.

The first of the two perceptual tests produced significant results, whereas the second more ecologically valid showed a marginally significant positive correlation with the proposed theory. The theory examined in light of a sample of notated music supports the hypothesis that musical genres can be distinguished by the redundancy in the use of prototypes. The empirical support presented in this paper invites further study of rhythmic prototypes along the lines suggested by Johnson-Laird.

References

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DETECTION OF BEARING FAILURE IN MACHINES

H.R. Martin
Department of Mechanical Engineering
University of Waterloo
Waterloo, Ontario N2L 3G1

Introduction

One of the potential problems common to all types of bearings is that at failure, the resultant machine repair can be costly, both financially and in production loss.

The vibrational energy emitted from rolling contact bearings can be monitored in a number of ways:

1. Overall amplitude of vibration level, based on time domain data.
2. Frequency spectrum of the time signal, usually up to 25 kHz.
3. Examination of the shock waves generated through the bearing housing when the rolling elements move over a damaged area.
4. Statistical parameter measurements applied to the time signal.

It is the latter approach that will be highlighted in this presentation.

Machined or ground surfaces are not perfectly smooth but consists of a pattern of asperities. In fact, only about 0.1% of the nominal contact area actually touches under normal loading conditions. When these surfaces are moving, as is the case of rolling element bearings, the asperity tips are alternatively welding and breaking off. Even so, most bearing surfaces exhibit randomness in asperity distribution in the direction of the machine process.

It has been well established in the metrology literature that the distribution of asperity weights for an undamaged surface to be normal, that is Gaussian in nature. It is this feature that allows the statistical parameter approach to work.

Background to the Statistical Parameter Method

The asperity distribution can be detected with an accelerometer, attached as near as possible to the bearing housing. This will, of course, also collect data relating to ball passing frequencies and other structural resonances. It is necessary therefore to separate the random data from deterministic data, by filtering. Fortunately, this usually works out quite well, and removing signal content below 2.5 kHz is usually satisfactory. The remaining data, from most bearings at normal running speed, should be mainly random. As the surface deteriorates due to damage, the "bell" shaped probability density function starts to lose its classic characteristics. Statistical moments can then be used to sense these changes.

In general, odd moments are related to information about the position of the peak of the PDF in relation to the mean value, while even moments indicate the characteristics of the spread of the distribution. It can be shown theoretically that the fourth moment, normalized by dividing with the square of the second moment, results in a coefficient called 'Kurtosis.' This has a value of 3.0, if the data exhibits a normal PDF. Values greater than 3.0 indicate damage developing, and less than 3.0 usually indicate deterministic signal contamination.

$$M_2 = \frac{1}{N}\sum_{i=1}^{N}\left[x_i^2 - \overline{x^2}\right] \tag{1}$$

$$M_4 = \frac{1}{N}\sum_{i=1}^{N} x_i^4 - \frac{4}{N}\,\bar{x}\sum_{i=1}^{N} x_i^3 + \frac{6}{N}\,\overline{x^2}\sum_{i=1}^{N} x_i^2 - 3\overline{x^4} \tag{2}$$

and

$$Kurtosis = \frac{M_4}{\left(M_2\right)^2} \tag{3}$$

One significant advantage that statistical methods have over the spectral approach is that the results from the former are essentially insensitive to load and speed changes, Fig. 1. Table 1 shows the moments as calculated from theory for different signal types. Notice the difference between random and Gaussian random.

Typical Results

Raw data can be collected in a number of ways. Under laboratory conditions, accelerometers positioned on the casing surrounding bearings under investigation can input analog signals directly into an A/D board in a microcomputer. Conditioning, filtering, and analysis can then be carried out using a variety of software packages. In-house software can be written in 'C' or Pascal for example, or such general commercial packages such as MATLAB, can be used very effectively. How the data processing is handled depends on the funds available, and the flexibility required for the mathematical processing.

In field work, for example on top of a 54 storey building in an elevator shaft, recording data from the accelerometers directly into a good quality tape recorder is often a much easier route to take. The processing can then be carried out in the relative comfort of the computer at home base.

Table 1

	Moment		Normalized Moment using $(M_2)^n$				
Data type	M_1	M_2	N_3	N_4	N_5	N_6	N_7
Sine	0.00	0.50	0.00	1.48	0.00	2.44	0.00
Square	0.00	1.00	0.00	0.98	0.00	0.98	0.00
Triangle	0.00	0.34	0.00	1.75	0.00	3.71	0.00
Random	0.48	0.07	0.13	1.94	82.90	4.74	2.81
Random Gauss	0.01	0.94	0.20	3.01	2.44	14.30	20.70

Fig. 2, shows the time domain results for similar bearings under different damage conditions, as summarized in Table 2.

Table 2		
Bearing Number	Condition	Kurtosis Value
1	good	2.9
2	Hair line mark outer raceway	3.8
3	Severe scratches outer raceway	4.4

Plotting Kurtosis values against acceleration magnitudes is often termed a damage map, so for example in Fig. 3, a good bearing is first run lubricated, and then cleaned out and run dry. The numbers indicate Kurtosis measurements taken in the following frequency bands,

1. 2.5 to 5.0 kHz
2. 5.0 to 10.0 kHz
3. 10.0 to 20.0 kHz
4. 20.0 to 40.0 kHz
5. 40.0 to 80.0 kHz

Laboratory tests have shown that the damage map can be used to identify the type of damage process in progress. This summary is shown in Fig. 4.

Conclusions

The wide range of methods of detecting bearing damage that are available, have their individual strengths and weaknesses and are therefore dependant on the application. An understanding of the methodology involved in digital data processing is important in order to ensure valid interpretation of the results.

Statistical methods of various types are now being investigated, Kurtosis being the most tested approach so far and seems to offer a lot of potential for the future. Currently investigations are being carried out using other distributions such as the Beta and Weibull functions, applied to gearing as well as bearings. However, confidence still has to be built up with extensive field testing of these techniques.

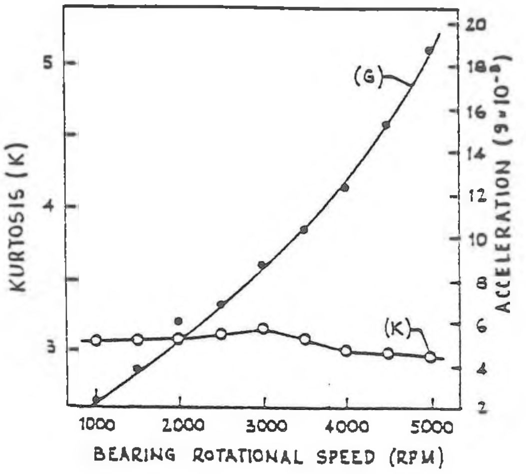


Fig 1 . Kurtosis and "g" level as Functions of Bearing Rotational Speed.

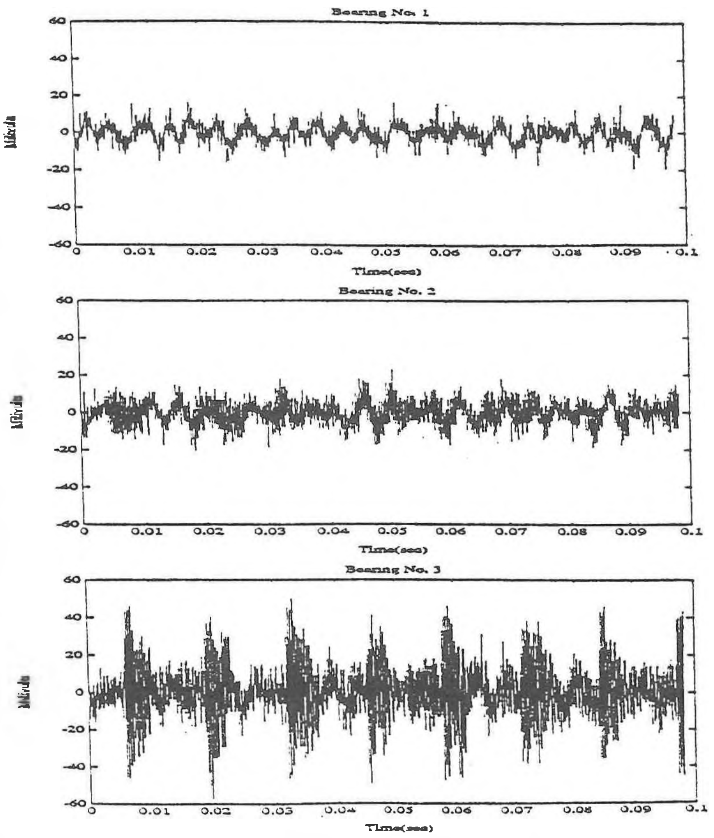


Fig 2. Vibrational Data for Different Stages of Damage.

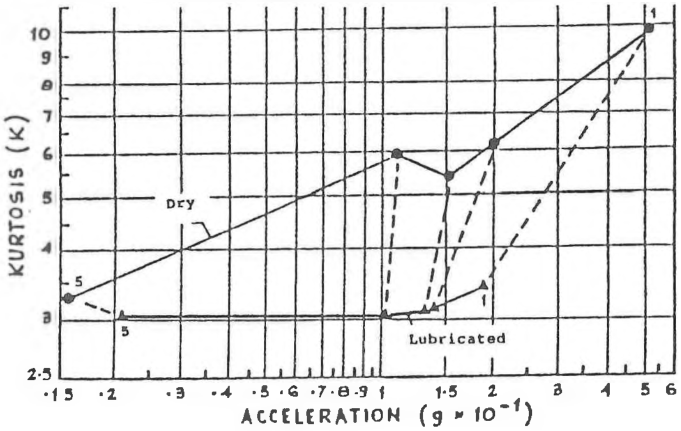
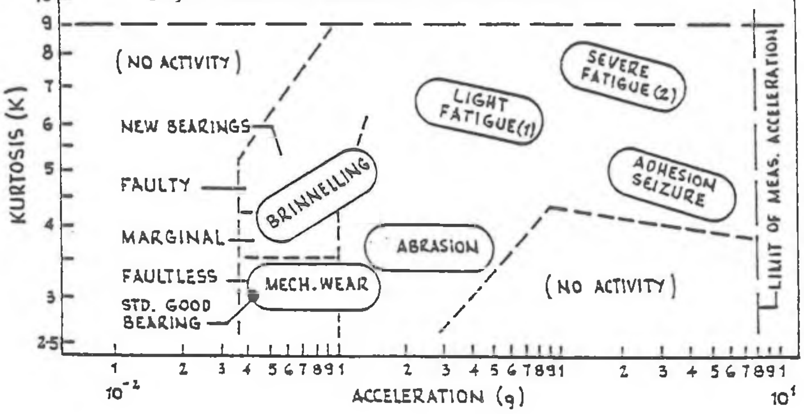


Fig 3. Difference between a Dry and Lubricated Bearing.

Fig 4. Tentative Centres of Diverse Damage Activities.



The Development of a Cost Effective Engine Dynamic Signal Monitoring and Diagnostic System

Jimi S.Y. Tjong
Doug K. Chang
Dave Mathias

Sirk A. Zena
Ford Motor Company
Windsor, Ontario

John R. Runge
Checksum Inc.
London, Ontario

Zygmunt Reif
University of Windsor
Windsor, Ontario

ABSTRACT

This paper describes the development of a cost effective engine dynamic signal monitoring and diagnostic system for use in a high volume engine manufacturing plant as well as in a research environment for development of new engine components.

Modal analysis was performed to determine the optimum locations of vibration transducers. The techniques of decomposition of raw signals obtained from an engine are described.

The engine dynamic signal monitoring and diagnostic system has been successfully implemented in on-line assembly of engine. In all cases, the system is capable of detecting and isolating manufacturing and assembly defects.

INTRODUCTION

Today, one of the key goals of an engine manufacturer is to achieve higher quality and productivity at competitive cost. This coupled with higher standard of customer satisfaction, requires not only innovative concepts in engine design, manufacturing and assembly processes, but also the integration of on-line engine monitoring and diagnostics system which is capable of detecting manufacturing and assembly defects.

This paper describes the development of a viable and cost effective engine dynamic signal monitoring and diagnostic system for detecting and locating manufacturing and assembly defects by means of time domain noise and vibration signature analysis.

TIME DOMAIN AVERAGING

The time domain signal processing techniques are extremely useful for engine diagnosis because of their abilities to correlate the amplitude of the signals at corresponding angular positions of the crankshaft.

Time domain averaging (TDA) is a powerful technique for extracting periodic components from a complex dynamic engine signal. It is accomplished by simply averaging several time traces, data point by data point, producing an average time trace. It is useful for detection of faults which occur consistently at a certain locations in a cycle.

VARIANCE ANALYSIS

In the last section time domain averaging was described, which allows the extraction of periodic components which are always present in the signal. The other components which are not always present but occur at specific location in a cycle are termed as semi-periodic can be extracted by variance analysis of the signals.

The mathematical descriptions of the TDA, including its properties as a filter in eliminating non-cycle linked signals, and variance are provided in reference (1).

MEASUREMENT SYSTEMS

Two systems, time locked and position locked, are used to accomplish time domain averaging and variance analysis. The time locked system is consisted of a digital storage oscilloscope interfaced and controlled by computer that is triggered by TTL (Transistor-Transistor Logic) signals which are generated by an inductive voltage at #1 spark plug firing.

In the position locked system, exact measure of angular position can be achieved by sampling the data at a rate dictated by a 512 pulse per revolution encoder, installed in-line with the drive train. This encoder generates external sampling clock. Thus, a sampling resolution of up to 0.6 degrees of crank rotation can be achieved. The custom designed engine signal monitoring and diagnostic system was used coupled with specially build encoder system. This system uses the PIP (Profile Ignition Pickup) and CID (Cylinder Identification) signals from the engine electronic control for triggering the start of the event and hence enable to reference the zero crank angle to piston # 1 on the firing stroke.

Figures 1 and 2 show the waterfall plots of vibration variance of a defective engine at varying speed with time lock and position lock data acquisition system, respectively. With position lock system the angular location of the peaks indicating defect are consistenly at 390 degree. While the time lock system the locations of the peaks were scattered.

EXPERIMENTAL RESULTS

The experimental results are divided into two sections: (a) Dynamometer test and (b) cold test.

DYNAMOMETER TEST

Warranty field return engine with noise complaint was analyzed to determine the root cause. Vibration measurements were made with accelerometers mounted on the cylinder block wall. Figure 2 illustrates the waterfall plot of vibration variance with respect to crank angle. The plot indicates that the distinct amplitudes are occuring at about 390 degrees crank angle which coincide with the peak pressure of cylinder #5. Upon engine teardown and measurements, it was revealed that the concentricity of the piston ringland with respect to skirt was excessive in the thrust direction. When piston number 5 was replaced with concentric ringland with respect to skirt piston, the vibration was drastically reduced as clearly illustrated in Figure 3.

COLD TEST

With the successes of using the custom designed engine dynamic signal monitoring and diagnostics system for evaluating piston design as well as diagnosing warranty field return engines, the next step is to apply the same system in cold test for on-line detection of manufacturing and assembly defects.

Modal analysis was performed in a partially assembled engine (as shown in Figure 4) and the results were reviewed for all modes of vibration up to 3200 Hertz. The optimum locations of accelerometers were selected for two reasons: (a) exhibiting the maximum response and (b) accessible for accelerometers carried by hydraulic actuated arm to reach.

Figure 5 illustrates the waterfall plot of vibration variance which is generated by partially assembled engine with connecting rod bearing missing. Distinct amplitudes appear coresponding to the side force reversals in the piston.

The experiments were repeated and the results indicate the feasibility of using the system for consistent on-line detection of missing rod bearing, missing cap bearing and loose connecting rod nuts.

CONCLUSIONS

The signal processing techniques used in this paper are useful in relating the vibration signal to the rotational angle of the crankshaft of the engine and hence to its components such as the piston regardless of fluctuation of engine speed.

As the result of experimentation in the cold test stand, a custom designed engine dynamic signal monitoring and diagnostics system is implemented for the rapid and precise detection of manufacturing and assembly defects. This has resulted in increased productivity and quality and reduced manufacturing cost.

The dynamometer test results indicate that the system has been successfully used for the root cause determination of warranty field return engines as well as for evaluating engine component design changes.

REFERENCE

1. Braun, S. and Seth, B., " Analysis of Repetitive Mechanism Signatures", J. of Sound and Vibration, 1980.

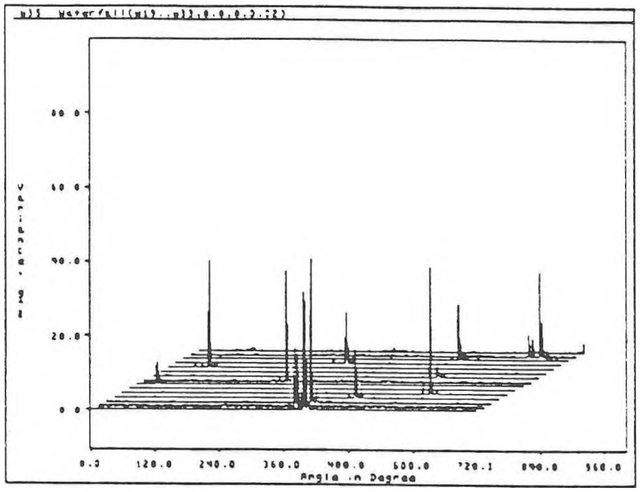


Figure 1: Vibration variance of defective engine at varying speed using time locked measurement system.

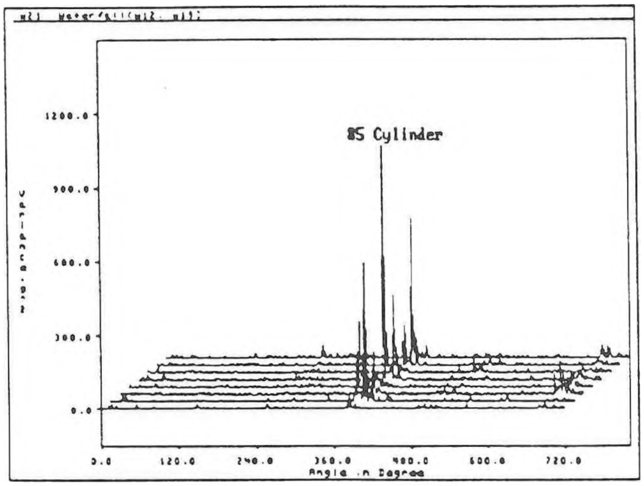


Figure 2: Waterfall plot of vibration variance with respect to crank angle for warranty field return engine - position locked measurement system.

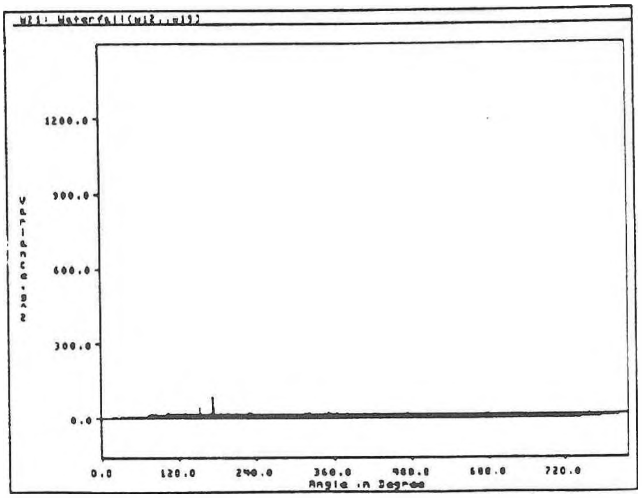


Figure 3: Waterfall plot of vibration variance with respect to crank angle for warranty field return engine after replacing with concentricity of piston ringland with respect to piston skirt.

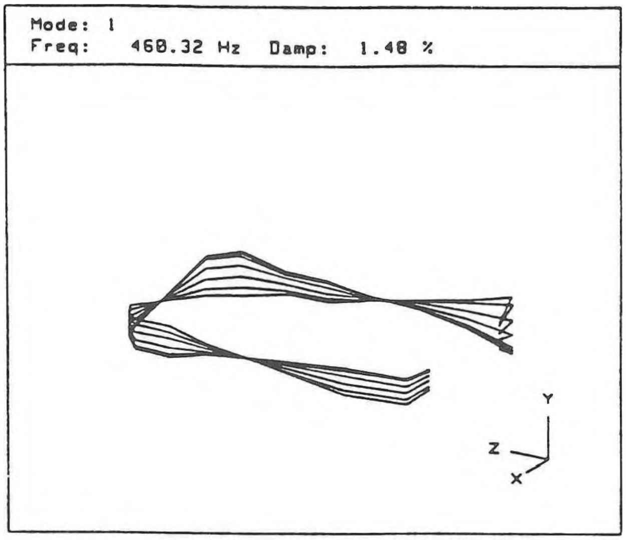


Figure 4: The first mode shape of the oil pan rail.

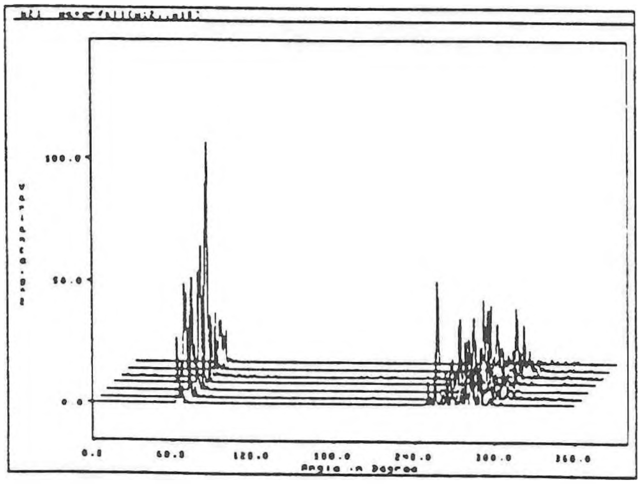


Figure 5: Waterfall plot of vibration variance of partially assembled engine with missing connecting rod bearing.