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(54) Title: COMPONENT FAILURE DETECTION SYSTEM

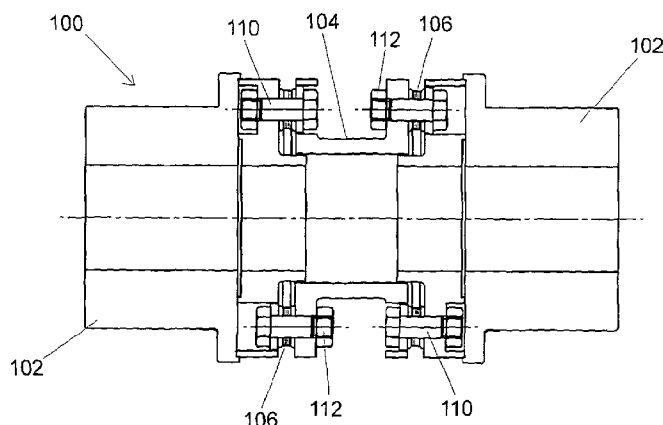


Fig 1.

(57) Abstract: An apparatus for detecting fatigue induced failure of an assembly having a single flexible element or a series of flexible elements stacked in juxtaposed engagement, for transmitting power from one component to another, the assembly having a cyclic operating speed frequency includes at least one sensor mounted in proximity to said assembly, the sensor providing an analogue signal corresponding to an airborne acoustic signal emitted by the assembly, means for amplifying the analogue signal, filter means to reduce background noise from the analogue signal, an analogue to digital converter for converting the analogue signals to a digital signal, means for sampling the digital signals in respect of the operating speed frequency of the assembly and means for analysing the digital signals and providing an output upon the occurrence of one or more digital signal spikes in an operating cycle.



Component Failure Detection System

The present invention relates to an apparatus for detecting coupling defects of power transmission couplings during dynamic operation of rotating equipment or machinery. In particular the invention relates to the detecting of defects in power transmission couplings including a flexible assembly comprising one or more flexible elements.

For rotating and reciprocating equipment, non-intrusive monitoring systems are commonly used in applications where real time monitoring of the rotating and reciprocating equipment on process plants is impeded by long distances or difficulty of access. Efficient operation and maintenance of rotating and reciprocating equipment is essential to maximise production and minimise downtime. Non-intrusive monitoring systems are used to detect or predict equipment defects before catastrophic failure of the equipment occurs, which would result in loss of production capacity and possible injury of personnel.

It is desirable to detect and locate equipment defects while the equipment is in-situ so as not to interfere with the production. Removing equipment from the production for routine inspection is undesirable, as production is lost during shutdown.

Acoustic emission transducers and apparatuses to monitor specific applications and determine failure of components related to rotating equipment and machinery have been developed in the past. US patent 4,493,042 et al presents the application of acoustic monitoring to detect and judge failures of roller bearings. Other inventions were made in developing specific signal processing algorithm to determine component failure based on acoustic emission data EP2031386 A1.

Generally the acoustic emission technology used hitherto for detecting failure of components related to rotating equipment and machinery use acoustic emission sensors that are place on a component or component surrounding structure to detect sound-waves that transmitted through the structure (structural acoustic emission sensors),

Power transmission couplings are components that transmit torque at a speed ratio of 1:1 between the shaft ends of a driving and driven machine. They are incorporated in the drive train to compensate small misalignments between the shaft ends due to mounting tolerances and operational displacements of the shafts and minimize the bearing loads associated with the misalignment. One of the most common industrial applications of couplings is the use in refineries to connect driver and pump or driver and compressor.

In a typical power transmission coupling as illustrated in cross section in figure 1 a hub 102 or adapter is provided on the end of a shaft on both driven and driver equipment and a transmission unit 104 connects the hubs 102 together to transmit drive and torque from the driver equipment to the driven equipment. A flexible assembly 106 is provided as interface between each hub 102 and transmission unit 104 to absorb angular, radial and axial misalignment between the driven and driver equipment. An example of a flexible assembly 106 is the flexible membranes found in John Crane ® T Series™ and M Series™ couplings, in which the flexible assembly 106 comprises a series of flexible elements 108 as illustrated in figure 2. The flexible elements 108 are stacked together on juxtaposed engagement, the flexible assembly 106 being secured alternately to a hub 102 and the transmission unit 104 by an even number of bolts 110, 112, which pass through holes 114 spaced angularly about the flexible elements 108.

During each shaft revolution the flexible assembly (106) and individual flexible elements (108) are exposed to torsional stresses due to the drive torque and bending stresses due to shaft misalignment.

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When operating a coupling within the specified design limits, the flexible elements achieve a theoretical infinite service life of more than 10^6 load cycles. However, if conditions exceed the specified limit, operation beyond the misalignment limit and/ or torque transmission beyond the design limit, the coupling will eventually fail due to fatigue stress cracks in the flexible elements 108 of the flexible assembly 106.

10

Such failure, in most cases developing over several days (weeks) from the onset of the first crack, could have costly consequences due to secondary damage to the machine or drive, production interruption and in some cases posing a severe health and safety risk.

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Because each flexible assembly 106 comprises a series of individual flexible elements 108, it is difficult to detect failure of an individual flexible element 108 of flexible assembly 106. Each flexible element 108 during operation emits a different acoustic trace or signal.

20

Most importantly, initiation of the failure of the flexible assembly 106 starts with fretting i.e. rubbing between individual flexible elements 108 followed by failure of a first flexible element 108 followed by failure of a second flexible element 108 and so forth. Therefore, the coupling is able to function for some time before catastrophic failure of the flexible assembly 106.

25

Detecting acoustic emissions emitted by a defect in the flexible element 108 of a coupling 100 using structural acoustic emission is unlikely to be

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successful and would not be possible with any of the existing detection technologies because a structural acoustic emission sensor can not be placed close to the couplings membrane unit but needs to be placed at some distance away on the machinery casing, where the sound

5 consequently has to pass several component interfaces that eliminate the chance of detecting the signal within the noise of the surrounding machinery (bearing noise, process noise etc). For example with the coupling shown in figure 1, with structural acoustic emission sensors as used with detection apparatuses described in US patent 4,493,042 et al,

10 the sound would need to be transmitted from the flexible element 108 to the bolts 110, 112, from the bolts 110, 112 to the hub 102, from the hub to the machine shaft, from the shaft to a connecting bearing and from the bearing, which is a strong source of acoustic emission too, to the casing where the structural sensor is placed.

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In accordance with the present invention, it has however been found that using an acoustic emission sensor to directly detect high frequency airborne sound waves in a range between 25 kHz to 90 KHz and placing one or more of these sensors in the proximity of the coupling between 1

20 cm and 200 cm, sound-waves of the flexible element defects can be detected.

However, using a much lower frequency than typically used with structural acoustic emission sensors, an advanced and specific signal conditioning

25 and detection algorithm had to be developed to differentiate a signal from the coupling membrane and other sources of sound as well as developing an algorithm that detects whether the signal constitutes a defect of one or more flexible elements 108 right up to detecting a complete failure of the flexible assembly 106.

30

Furthermore, many rotating and reciprocating assemblies are used on large scale process plants, and each process plant may comprise a multitude of power transmission couplings, mechanical seals, gas seals
5 and bearings emitting different acoustic trace or resonance. Therefore, a specific fault detecting algorithm is required.

An object of the present invention is to provide a non-intrusive component failure detection system using an acoustic method that is able to detect
10 failure of a flexible assembly 106 of a power transmission coupling.

According to one aspect of the present invention an apparatus for detecting fatigue induced failure of an assembly having a single flexible element or a series of flexible elements stacked in juxtaposed
15 engagement, for transmitting power from one component to another, the assembly having a cyclic operating speed frequency, said apparatus comprises;

at least one sensor mounted in proximity to said assembly, the sensor providing an analogue signal corresponding to an airborne acoustic
20 signal emitted by the assembly;

means for amplifying the analogue signal;

filter means to reduce background noise from the analogue signal;

an analogue to digital converter for converting the analogue signals to a digital signal;

25 means for sampling the digital signals in respect of the operating speed frequency of the assembly; and

means for analysing the digital signals and providing an output upon the occurrence of one or more digital signal spikes in an operating cycle.

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According to another aspect of the present invention a method of detecting fatigue induced failure of an assembly having a single flexible element or a series of flexible elements arranged in juxtaposed engagement, for transmitting power from one component to another, the assembly having a

5 cyclic operating speed frequency, said method comprises;

providing at least one sensor for monitoring an airborne acoustic emissions of said assembly,

said sensor or sensors converting airborne acoustic signals emitted by the assembly into analogue signals;

10 amplifying the analogue signals;

filtering the analogue signal to reduce background noise;

converting the analogue signals to digital signals;

sampling the digital signals in respect of the operating speed frequency of the assembly; and

15 analysing the digital signals to determine the occurrence of one or more specific signal patterns in an operating cycle, said occurrence of one or more specific signal patterns indicating a failure of one or more of the flexible elements of the assembly.

Preferably the or each acoustic sensor is placed from 1 to 200 cm from the
20 assembly, with an unobstructed path to the assembly.

According to a preferred embodiment of the invention the analogue signal is filtered using an envelope demodulator which averages the peak
25 analogue signals over a time frame and replaces them with mean value analogue signals.

According to a further embodiment of the present invention, the sensor for airborne acoustic emission may be connected to means for processing the acoustic signal via a node and gateway, the node being connected to the
30 gateway wirelessly. Each node preferably comprises at least one sensor operable to measure the acoustic emission of the flexible assembly, a

signal processor for processing data from said at least one sensor and a combined wireless transmitter and receiver interface; each gateway comprises a signal processor for processing data from each node and a combined wireless transmitter and receiver interface; and a computer
5 connected to the gateway, characterised in that data from each node is transmitted to the gateway via radio frequency and said command station sends a configuration message from the gateway to each node to specify one or more analysis function to perform.

10 The invention is now described by way of example only and with reference to the accompanying drawings, in which:-

Figure 1 illustrates a cross section of a typical membrane coupling;

15 Figure 2 illustrates a typical flexible element of the membrane coupling;

Figure 3 illustrates an acoustic emissions detection system for determining fatigue induced failure of an assembly according to the present invention;

20 Figure 4 illustrates enveloping of acoustic signals according to the present invention;

Figure 5 illustrates absolute digitised acoustic signals of an intact coupling according to the present invention;

25

Figure 6 illustrates Fast Fourier Transformation Spectrum of an intact coupling according to the present invention;

Figure 7 illustrates acoustic signals of a coupling with one fractured
30 flexible element according to the present invention;

Figure 8 illustrates Fast Fourier Transformation Spectrum of a coupling with one fractured flexible element according to the present invention;

5 Figure 9 illustrates acoustic signals of a coupling with two fractured flexible elements according to the present invention;

Figure 10 illustrates Fast Fourier Transformation Spectrum of a coupling with two fractured flexible elements according to the present invention;

10 Figure 11 illustrates acoustic signals of a coupling with three fractured flexible elements according to the present invention;

Figure 12 illustrates Fast Fourier Transformation Spectrum of a coupling with three fractured flexible elements according to the present invention;

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Figure 13 illustrates the digital acoustic signals derived from a high order statistical sampling process;

Figure 14 illustrates the digital acoustic signals derived from combining the Fast Fourier Transformation Spectrum and the high order statistical sampling process; and

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Figure 15 illustrates RMS values of the digital acoustic signals.

25 Referring to Figure 3, a schematic of an acoustic emissions detection system 200 for determining fatigue induced failure of the flexible assemblies 106 of a power transmission coupling 100 according the present invention is shown. The acoustic emissions detection system 200 comprises an acoustic emission transducer 202 for detecting variations in

30 acoustic signals or stress waves emitted from a stack of flexible elements 108 forming the flexible assemblies 106 of the power transmission

coupling 100 shown in figures 1 and 2. Such acoustic signals or stress waves are commonly generated as a result of flexing, bending, stretching and frictional stress caused by the flexible elements 108 under operation. More importantly, characteristic signals are emitted by the flexible elements 108 when a crack initiates and propagates.

The frequency bandwidth of the acoustic emission transducer 202 is selected to reduce picking up background whilst being sensitive to be able to pick up acoustic signals generated by the flexible assembly 106, by detecting the airborne acoustic signals

The acoustic emission transducer 202 is a piezo-electric transducer designed to convert acoustic signals into an analogue signals. For detecting airborne acoustic signals, the acoustic emission transducer 202 operates in a frequency range between 25 to 90 kHz.

The analogue signals are then sent to a control module 204. The control module 204 comprises an amplifier 206 for amplifying the analogue signal and an envelope modulator 208 where the peak analogue signals are averaged over a time frame and replaced by mean values. The advantages of using the envelope modulator 208 are that:

- unnecessary noise is removed
- minimise the required sampling rate for digitisation.
- minimise the computational effort for signal processing

Figure 4 illustrates the peak signals being averaged over a time frame and replaced by mean values for filtering the background noise.

The analogue signals are converted into digital signal by an analogue to digital converter, where the digital signals are then sent to a data acquisition module 210. The data acquisition module 210 samples the

signal in discrete data sets, whereby the sampling time covers a minimum of 2 shaft revolutions. Afterwards each data set is split, whereby one set of digital signals is sent to a signal processor 212. The signal processor 212 uses a Fast Fourier Transform to calculate the frequency components of the signal –frequency domain-. The remaining signal set is left as acquired in the time domain.

Both, time domain and frequency domain of the signal are then sent to a diagnostic module 214 to determine the occurrence and frequency of signal characteristics with respect to the rotational speed of the coupling 100.

Figures 5 to 12 illustrate typical signals processed by the diagnostic module 214. Figures 5, 7, 9 and 11 illustrate the absolute digital acoustic signals acquired from the data acquisition module 210, whereby specific signal patterns are used to determine failure of each flexible element 108 as the coupling 100 rotates. Figures 6, 8, 10 and 12 illustrate the digital signals derived from using the Fast Fourier Transformation sampling process, whereby signals are analysed in a spectrum with respect to the frequency of the coupling shaft.

Figures 5 and 6 illustrate a fully functional coupling without defect, wherein figure 5 only displays background noise. Frequency related to the coupling shaft is absent from figure 6.

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Figures 7 and 8 illustrate a fracture of one flexible element 108 of the coupling 100. Figure 7 displays the time domain of the sampled signal set with one dominant signal spike A and figure 8 displays the frequency domain of the sampled signal set that shows an increase in amplitude of the principle and harmonic frequencies related to the coupling speed.

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Figures 9 and 10 illustrate two flexible elements 108 being fractured on the coupling 100. Figure 9 displays two signal spikes A and B, and figure 10 displays a further increase in the amplitude of the coupling 100 shaft frequency and a further increase in amplitude of harmonic frequencies in the frequency domain of the sampled signal set.

Figures 11 and 12 illustrate three flexible elements 108 being fractured on the coupling 100. Figure 11 displays three signal spikes A, B and C, and figure 12 displays a further increase in the amplitude of the coupling 100 shaft frequency and a further increase in amplitude of harmonic frequencies in the frequency domain of the sampled signal set.

In a second embodiment, the signal processor 212 calculates high order statistical values namely Skewness and Kurtosis from the sampled signal set acquired by the data acquisition module 210 and sends the values to the diagnostic module 214 to identify coupling and non-coupling related signals and specific faults related to the flexible element 108 in a given time frame.

Figure 13 illustrates the signals produced by the diagnostic module 214 using the high order statistical sampling process, whereby the results from the Skewness statistical analysis is plotted against the results from the Kurtosis statistical analysis. The high order statistical sampling process has the ability to determine whether the flexible assembly 106 is in good working order or if individual flexible elements 108 have been fractured. Referring to figure 13, the Skewness-Kurtosis threshold provides an indication on the performance of the coupling 100.

In a third embodiment, the signal processor 212 analyses the digital signals using the Fast Fourier Transformation process combined with the high order statistical sampling process of the second embodiment to

provide an indication on the health of the flexible assembly106. Using the following equation, the health of flexible assembly106 can be determined:

$$\text{Coupling Health} = \frac{1}{(C3 \times C4)^2 \times e^{\frac{(FFT_{shaft1} - FFT_{\Sigma Z}) + (FFT_{shaft2} - FFT_{\Sigma Z}) + \dots + (FFT_{shaftn} - FFT_{\Sigma Z})}{n}}}$$

Where:

$$FFT_{\Sigma Z} = \frac{\sum_{i=1}^Z f_i}{Z}$$

is the average *FFT* (Fast Fourier Transformation) for first *Z* frequency bands, whereby *Z* is an integer

FFT_{shaft1} is the Fast Fourier Transformation for the first frequency of the coupling shaft

FFT_{shaft2} is the Fast Fourier Transformation for the second frequency of the coupling shaft

FFT_{shaftN} is the Fast Fourier Transformation for the n^{th} frequency of the coupling shaft, whereby *n* is an integer and $n < Z$

C3 is the Skewness value

C4 is the Kurtosis value

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The above equation is a typical example of mathematical statistical function used to determine coupling health. Other combinations of values in mathematical statistical function may provide similar results and may be used without departing from the scope of the invention.

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As indicated above, the combined Fast Fourier Transformation and high order statistical sampling method allows to determine the condition of the coupling for any operational speeds of the coupling 100. Therefore, such method may be applied to couplings 100 that operate on variable or fixed speeds.

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Referring to figure 14, using the inverse the coupling health values, the condition of the coupling 100 is illustrated in graphical format together with

- the threshold of the coupling health by the diagnostic module 214 for highlight potential problems. As shown in figure 14, coupling condition boundaries are set to determine the health of the coupling 100. Values between 0.1 and 1 indicate that the flexible assembly 106 is in good working order, values between 1 and 10 indicate that the flexible assembly 106 has a potential problem, e.g. fretting between individual flexible elements 108, and values above 10 indicate that the coupling has failed or cracks are present in the flexible elements 108.
- 10 In a forth embodiment, the signal processor 212 samples the digital signals by calculating the RMS values of the digital signals over one shaft revolution. Referring to figure 15, the diagnostic module 214 displays the RMS values of the signals on a graph. Although there is little to distinguish the signals of an intact coupling from the signals of a failed coupling, threshold points may be set by the user such that the diagnostic module 214 would give an indication of a potential total coupling failure.

Various modifications may be made without departing from the scope of the present invention. For example while the above embodiments have been described with reference to an envelope modulator for reducing noise, the invention is equally applicable to be used with any signal processors or signal filters that are capable of reducing background noise.

While the invention has been described with reference to an acoustic emissions detection system for determining fatigue induced failure of an assembly comprising at least one transducer, this is only as an example and the invention may be used for single or multiple transducers.

In addition, the sampling processes may sample the signals continuously or intermittently over a specified time frame without depart from the scope of the invention.

Claims

1. An apparatus for detecting fatigue induced failure of assembly having a series of flexible elements stacked in juxtaposed engagement, for transmitting power from one component to another, the assembly having a cyclic operating speed frequency, said apparatus comprising;
- at least one sensor mounted in proximity to said assembly, the sensor providing an analogue signal corresponding to an airborne acoustic signal emitted by the assembly;
- means for amplifying the analogue signal;
- filter means to reduce background noise in the analogue signal;
- an analogue to digital converter for converting the analogue signals to a digital signal;
- means for sampling the digital signals in respect of the operating speed frequency of the assembly; and
- means for analysing the digital signals and providing an output upon the occurrence of one or more specific signal patterns in an operating cycle.
2. An apparatus according to claim 1 in which the sensor is sensitive to frequencies in the range of the acoustic signals emitted by the flexible elements of the assembly.
3. An apparatus according to claim 1 in which the sensor is positioned to sense airborne acoustic signals in the frequency range between 25 and 90kHz.
4. An apparatus according to any one of the preceding claims in which the sensor is a piezo-electric transducer.

5. An apparatus according to any one of the preceding claims in which the filter means is an envelope demodulator which averages the peak analogue signals over a time frame and replaces them with mean value analogue signals.

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6. An apparatus substantially as described herein with reference to and as shown in figures 1 to 3 of the accompanying drawings.

7. A method of detecting fatigue induced failure of assembly having a series of flexible elements stacked in juxtaposed engagement, for transmitting power from one component to another, the power transmission assembly having a cyclic operating speed frequency, said method comprising;

10 providing a sensor for monitoring the airborne acoustic emissions of said assembly, said sensor converting acoustic signals emitted by the assembly into analogue signals;

15 amplifying the analogue signal;

filtering the analogue signal to reduce background noise;

converting the analogue signals to digital signals;

20 sampling the digital signals in respect of the operating speed frequency of the assembly; and

analysing the digital signals to determine the occurrence of one or more specific signal patterns in an operating cycle, said occurrence of one or more specific signal patterns indicating a failure of one or more of the flexible elements of the assembly.

8. A method according to claim 7 in which the analogue signal is filtered by passing it through an envelope demodulator which averages the peak analogue signals over a time frame and replaces them with mean value analogue signals.

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9. A method according to claim 7 or 8 in which the digital signals are sampled using a Fast Fourier Transformation process, whereby the signals are analysed in a spectrum with respect to the operating speed frequency of the assembly, the failure of one or more of the flexible
5 elements of the assembly producing harmonic frequencies in the Fast Fourier Transformation spectrum.
10. A method according to claim 7 or 8 in which the amplitude of the harmonic frequencies increases with the number of flexible elements to
10 have failed.
11. A method according to claim 7 or 8 in which the digital signals are sampled using a combination of Skewness and Kurtosis statistical values to provide an indication of the failure of one or more of the flexible
15 elements.
13. A method according to claim 7 or 8 in which the digital signals are sampled using the Fast Fourier Transformation process combined with Skewness and Kurtosis statistical values to provide an indication of the
20 failure of one or more of the flexible elements.
14. A method according to claim 7 or 8 in which the digital signals are sampled by calculating the Root Mean Square (RMS) values of the digital signals over one cycle of the assembly.
25
15. A method substantially as described herein with reference to and as shown in figures 1 to 15 of the accompanying drawings.

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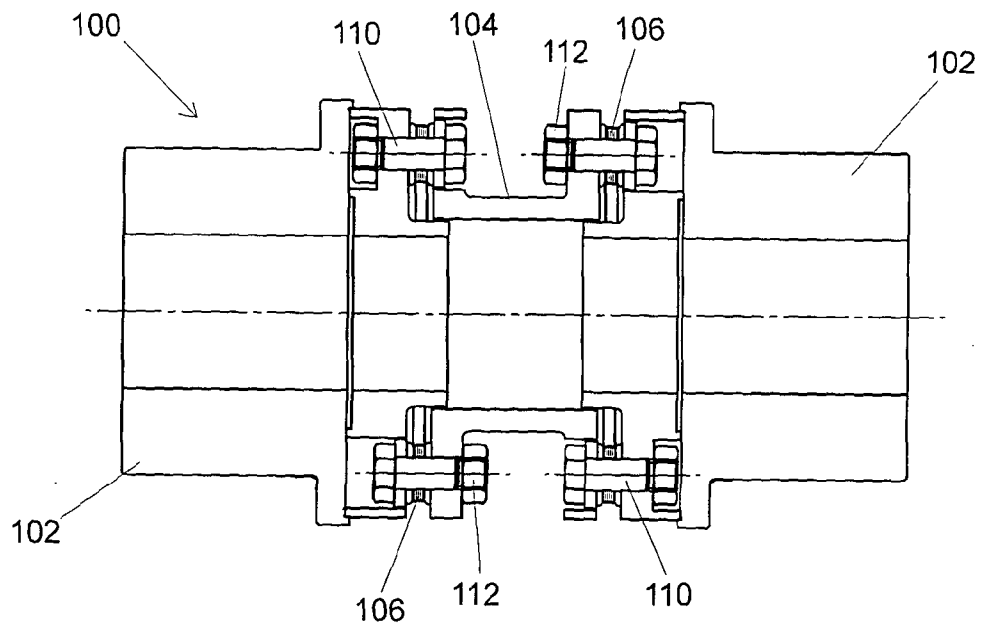


Fig 1.

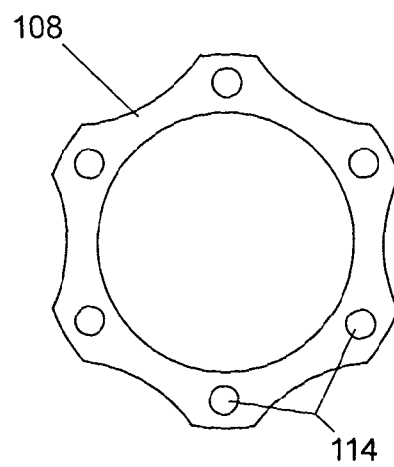


Fig 2.

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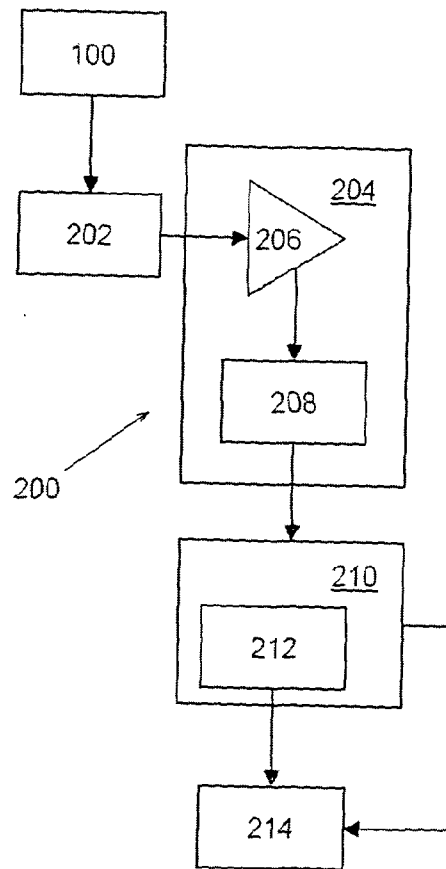


Fig 3.

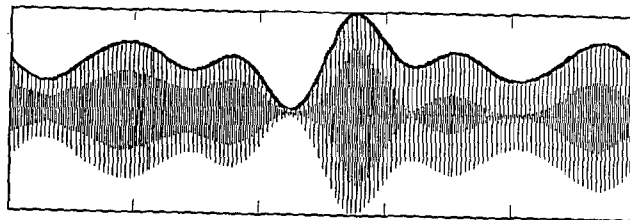


Fig 4.

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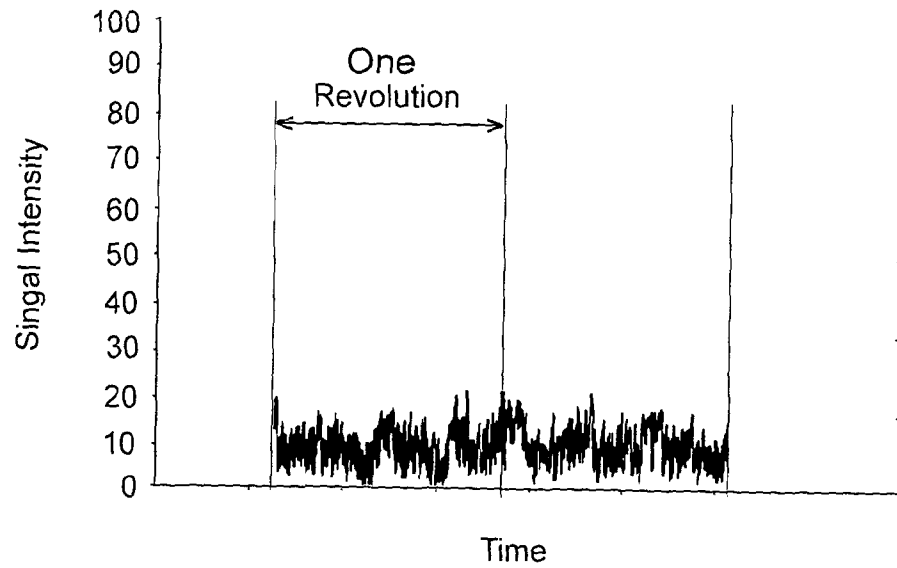


Fig 5.

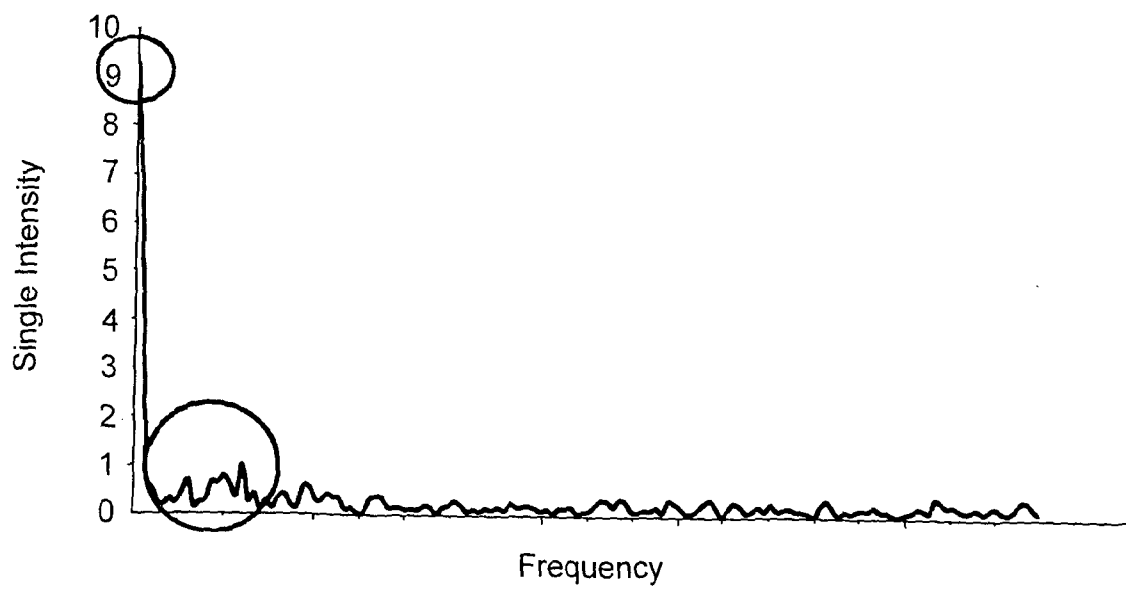


Fig 6.

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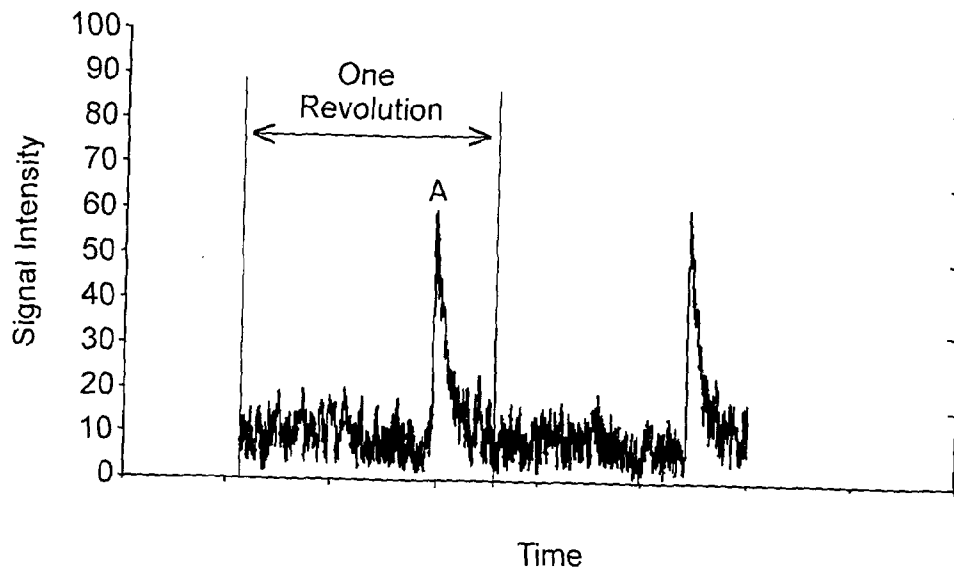


Fig 7.

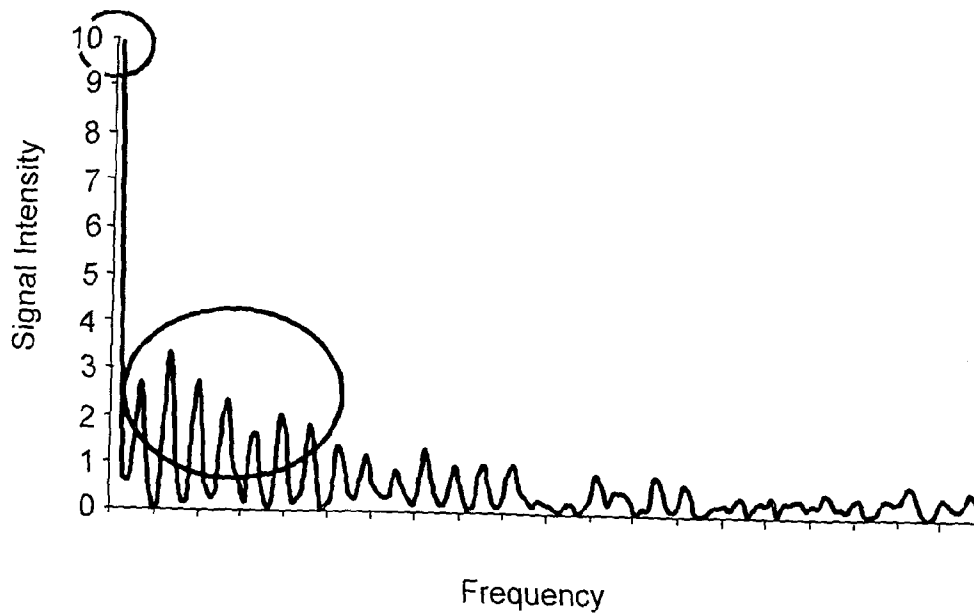


Fig 8.

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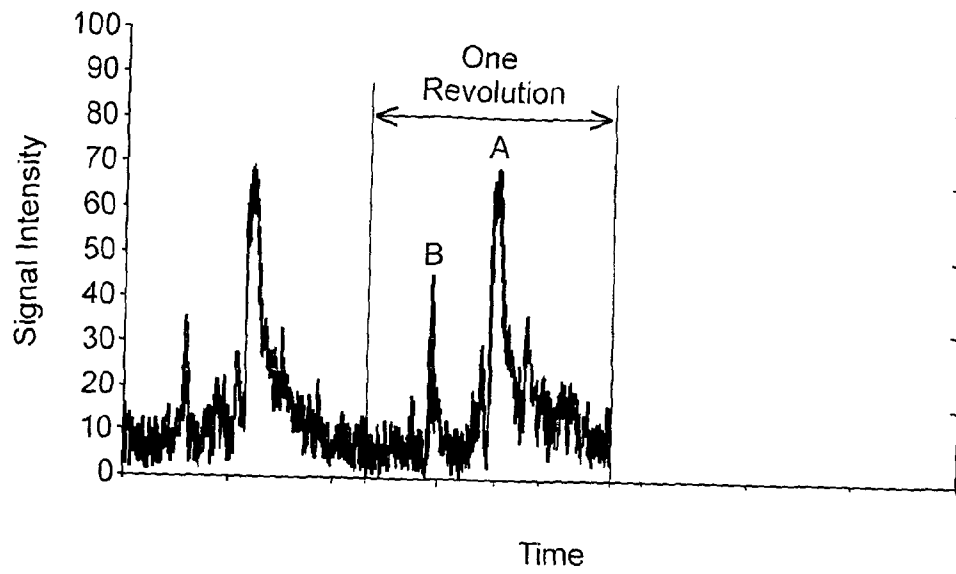


Fig 9.

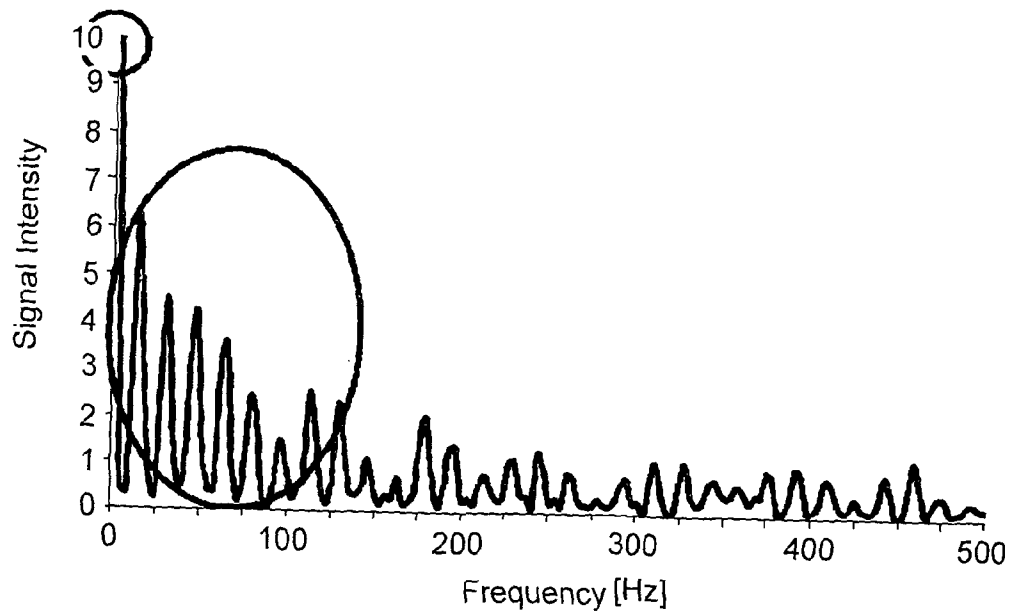


Fig 10.

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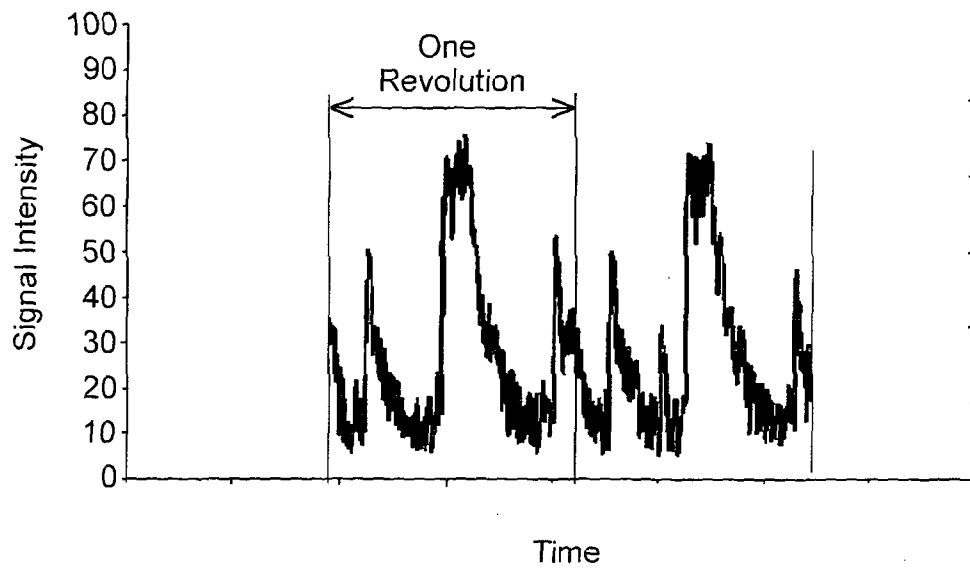


Fig 11.

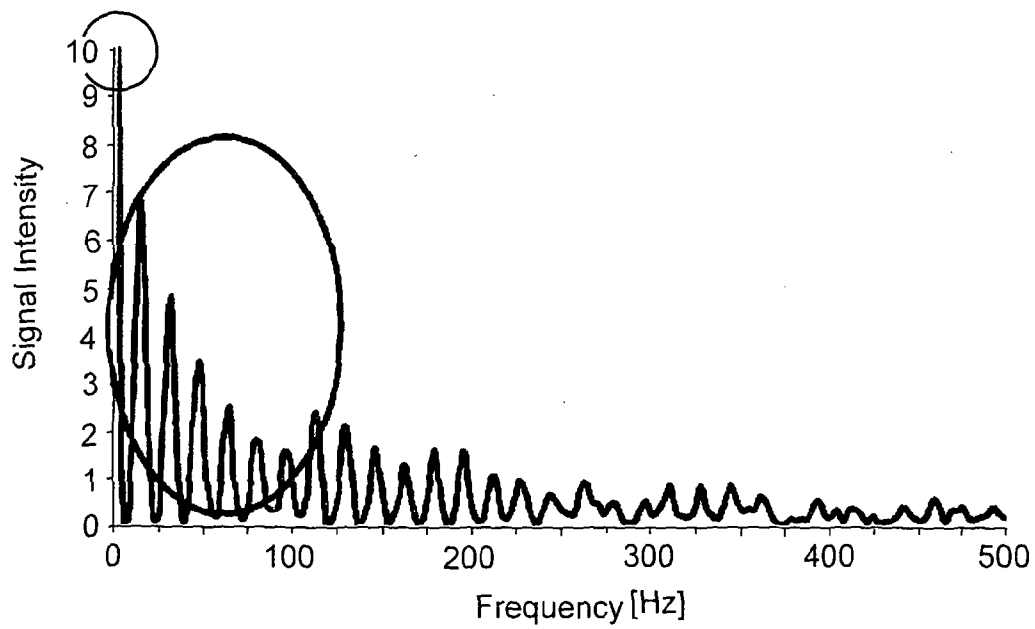


Fig 12.

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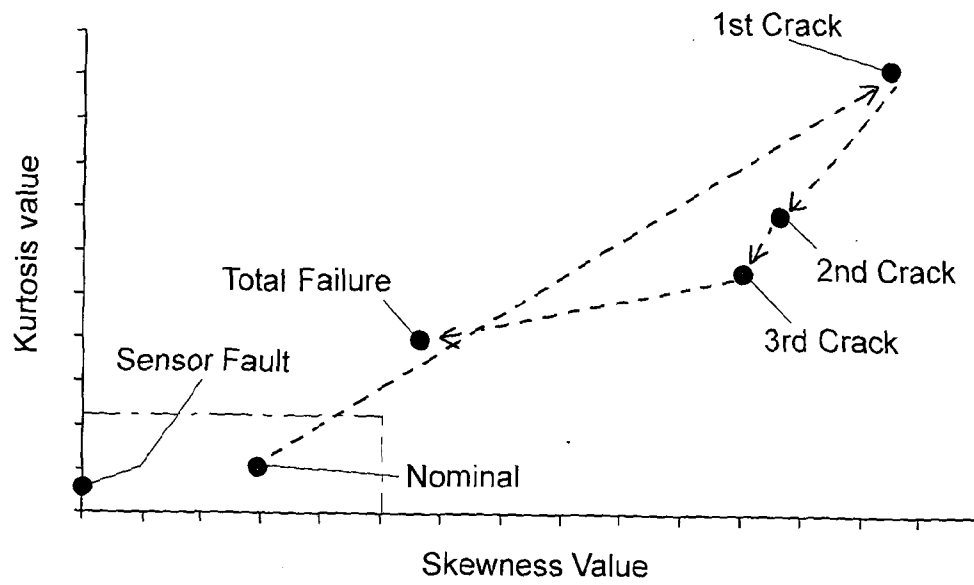


Fig 13.

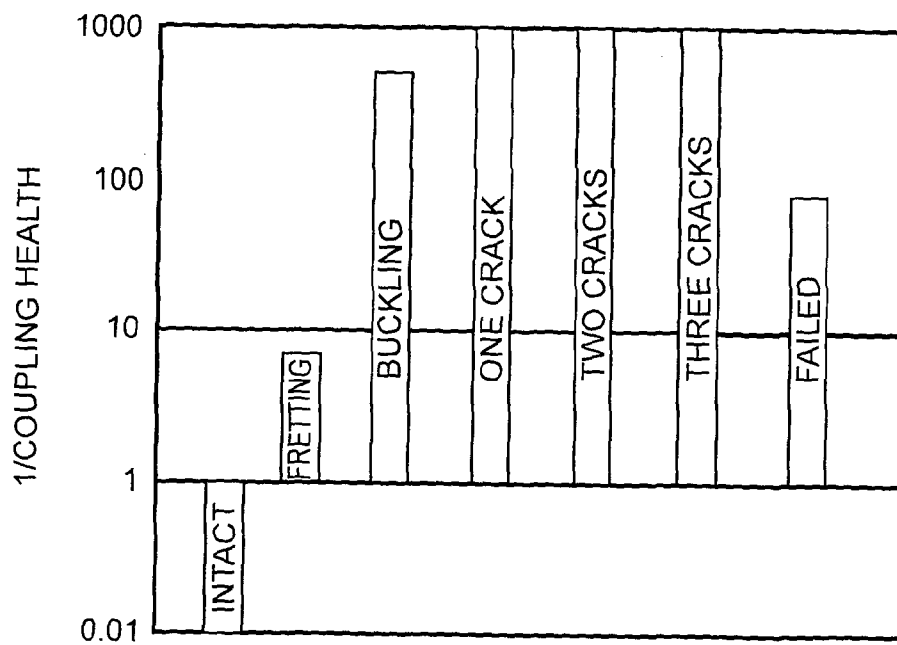


Fig 14.