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APPLICATION OF AN ENVELOPE TECHNIQUE IN THE DETECTION OF BALL BEARING DEFECTS IN A LABORATORY EXPERIMENT

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Abstract: To judge the diagnostic capabilities of a envelope technique (Bearcon Signature™; Carl Schenck AG, Germany) artificially damaged ball-bearings (SKF 6207) were run under oil-lubrication at different radial loads and speeds in a laboratory experiment. Respectively outer race, inner race and ball damages of different sizes were introduced by spark erosion and the response of the measuring system was analysed. The results showed, that vibration spectrum components of outer race defects showed up in the envelope spectra of undamaged bearings and that detectability of defects was primarily limited by the speed of the bearing, sometimes the automatic scaling facility of the analyser was a limiting factor. Inner race and ball defects showed the well known effects of load modulation in the defect-contact zône, which can become dominant in the envelope spectra at high loads and speeds. This phenomenon could be confirmed by computersimulation. The detection of ball-damage was hampered by the fact, that overrolling of the defect in purely radially loaded bearings takes place incidentally. This draw back could be mitigated by applying a trigger-technique to the envelope signal.

Key Words: Ball bearings; bearing damage; detection limits; diagnostics; envelope technique; triggering; vibration analysis.

INTRODUCTION: The widespread application of R.E. bearings and the fact that the failure modes of these components often show considerable lead times have in the past intiated many succesful efforts to develop diagnostic equipment for R.E. bearing damage. Many surveys of the literature on this subject are given of which [1] is an example.
In recent years much emphasis is given to the application of envelope techniques to the analysis of R.E. bearing vibration signals.[2-6]. It offers the opportunity to reduce interference of other vibration sources in the machinery under surveillance with the initially often relatively weak vibration signals, originating from bearing defects. Moreover it enables us to diagnose in more detail the location of the defect in terms of outer ring, inner ring or rolling element by means of the defect overrolling frequencies.

For the maintenance engineer the latter is not all that important as long as he knows which bearing in a train is suffering. However defect overrolling frequencies can be very specific for a bearing and hence enable us localise the bearing that shows an impending failure.
In routine monitoring practice it is important to understand the detection limits of the monitoring equipment in order to be in a better position to estimate the rest-lifetime of a damaged bearing.
For this reason the experiments described in this paper have been set up, obviously for a very limited set of operating conditions and with the application of Carl Schenck's Vibroport 41 vibration analyser with an enveloping facilty (Bearcon-Signature™). As the experiments have been run in a laboratory environment, it can be doubted whether the results can be improved in industrial practice.

THE "ENVELOPE TECHNIQUE": The overrolling of a defect in a race of a ball bearing will give rise to impulsive action on the bearing itself, on the surrounding mechanical structure and on a vibration pick-up in case this pick-up is properly connected to the structure. The impulsive action may result in resonancies in these three elements, or may become the origin of elastic stress-waves that are emitted into the structure as acoustic emission. Due to damping the resonances and acoustic emission will die out, until a next impuls takes place.
By making use of the resonance frequencies or the frequency of the acoustic emission as a carrier frequency, the repetion rate of the impulses can be shown. To do so, it is important to eliminate other, very often stronger vibration components in the signal caused by e.g. unbalance, gear mesh, mis-alignment etc., which normally will be found in the lower frequency regions. This can be done by proper band-pass filtering. The result is shown in the upper part of fig.1.
To determine the repetition frequency of the impulses the band-pass filtered signal is rectified and subsequently the envelope of the rectified signal in the time domain is produced. (see fig.1 - middle).
The next step is a Fast Fourier Transform of the envelope, which will result in a number of spectrum components in the frequency domain. The frequency components will represent the repetition frequency of a bearing defect overrolling and harmonics of this frequency. (see fig.1 - under)
Sometimes, due to modulation of the maximum amplitudes of the band-pass filtered signals, the modulation frequency itself and side-bands of the repetition frequency will appear at distances equal to the modulation frequency.
When geometry and speed of the bearing are known, defect overrolling frequencies can be determined for outer ring defects (ORDF), inner ring defects (IRDF) and rolling element defects (REDF) by means of bearing supplier resources, e.g. the SKF-Atlas computer program.
Thus comparing the envelope spectra with the calculated frequency values, enables us to diagnose the bearing defect.

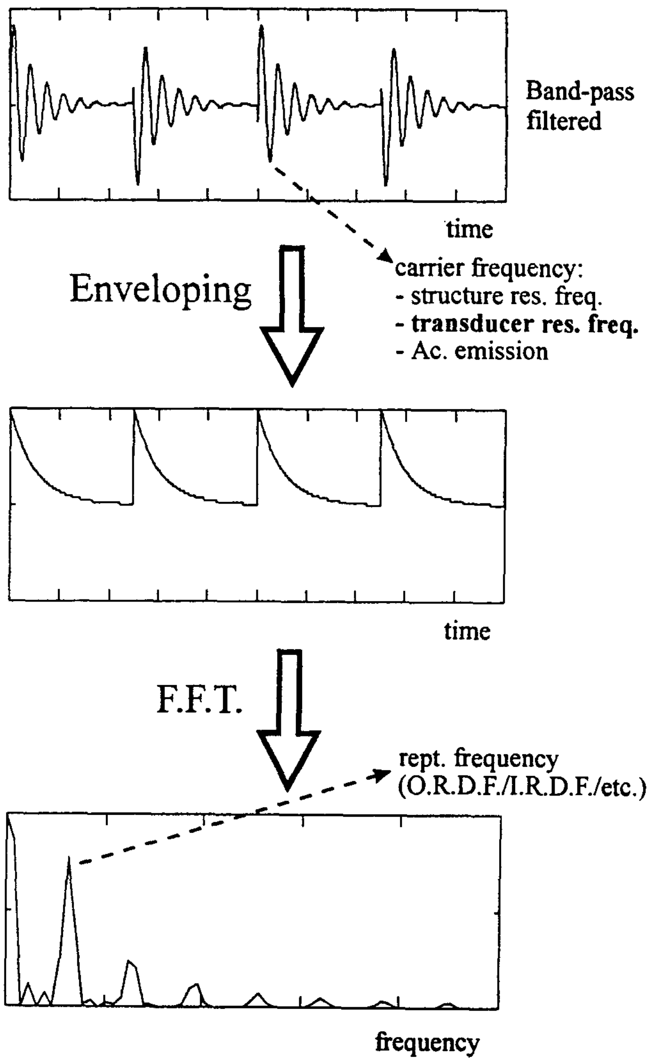
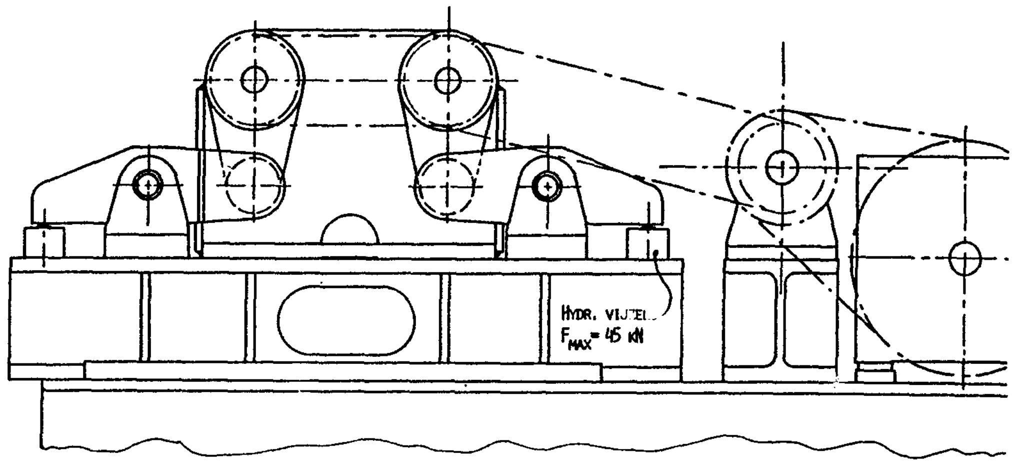


Fig.1 Three important steps of signal processing in th` envelope analysis.

As is already mentioned, different carrier frequencies are being used. The Bearcon Signature™ measurement utilises the resonance frequency of the vibration pick-up and the band pass filter is set from 13 kHz to 65 kHz.

THE EXPERIMENTAL SET-UP: The experiments are carried out on a test-rig, which is schematically shown in fig.2. It is extensively described in [5] and [7].
The bearing under test is a deep-groove ball bearing (SKF 6207), which is radially loaded in a static way bij means of a hydraulic actuator. Originally the set-up provides for 4 test-bearing positions of which only one is used for reasons of reproducability.
The bearings are lubricated with circulating oil (Shell Tellus 32) and kept at a constant temperature of approx. 40 °C.
Bearing defects were artificially introduced by spark-eroding a cylindrical hole through the inner and outer ring in the



Sideview

Fig.2 Test rig; schematically.

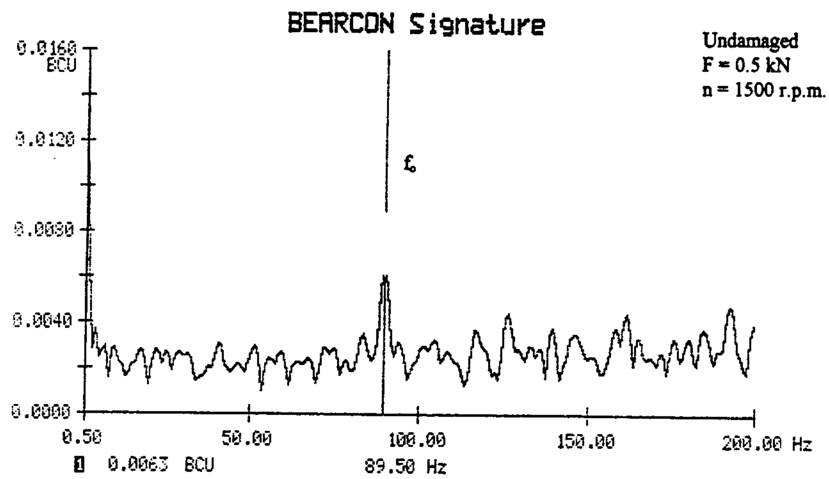
center of the races. A blind hole was eroded into a ball straight through the side of the metal cage.
The diameter of the holes varied from 0.2 mm to 2.0 mm for the outer rings and from 0.4 to 2.0 mm for the inner rings and the balls. The size of the defect needs to be judged in relation with the ball diameter, which is 11 mm, and with the load dependent contact area.
Two loads were chosen, viz. 0.5 and 5.0 kN. The dynamic load ratio of the bearing was 25.5 kN and the static load ratio 15.3 kN, hence we used a relatively low and high load on the bearings.The characteristic defect overrollingfrequencies for the bearings related to one damage in a bearing, are given in table I for the three speeds, used in the experiments.

Table I. Characteristic defect-frequencies of the bearings at speeds used in the experiments.

Inner ring speed (r.p.m.)	500	1500	4500
Inner ring speed (Hz)	8.33	25.00	75.00
Outer ring defect freq. (Hz)	29.71	89.14	267.41
Inner ring defect freq. (Hz)	45.29	135.86	407.59
Rolling element defect freq. (Hz)	38.40	115.20	345.59
Rolling element rot. speed (Hz)	19.20	57.60	172.79
Cage rot. speed (Hz)	3.30	9.90	29.71

Bearing SKF 6207; Contact angle 0.00°; Source SKF-Atlas-1989

Before the damages were introduced zero-measurements were taken on the same, undamaged bearings under identical conditions as compared with the damaged bearings. All measurements were taken in duplo, which meant that after the first measurement the bearing was dismounted and re-mounted for the duplo-measurement, taking care that the outer ring was mounted and fixed in the same angular position as before. The outer ring damage was always located in the center of the loaded zône.
Before measurements were taken the test-bearing was run in after mounting and re-mounting during 2 hours at a speed of 1500 r.p.m and a load of 5.0 kN. Measurements were taken with the Vibroport 41 of Carl Schenck AG and with an acceleration pick-up type AS-20, which was screwed in a position directly above the loaded zône of the bearing.



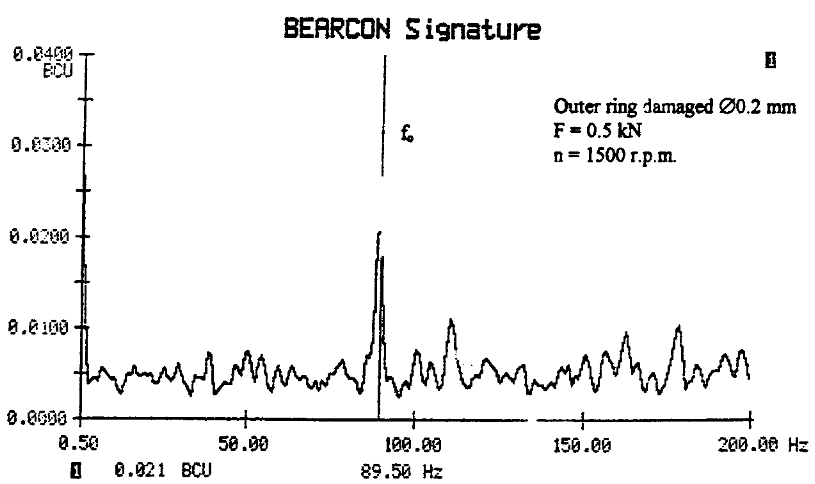


Fig.3 Envelope spectra of an undamaged and a slightly damaged (outer ring damage) bearing at similar operational conditions

RESULTS:

The Zero-Measurements: Obviously these measurements were taken as reference for the measurements on the damaged bearings. Sometimes we observed, particularly with the higher speeds, weak spectrum-components in the envelope spectrum (Bearcon Signature™), which normally are indicative of outer ring damage. Fig.3 shows two envelope spectra of an undamaged bearing (upper) and of a slightly damaged bearing (lower) for the same operational conditions.
Although the signal level of the outer ring defect frequency f_o of the slightly damaged bearing is somewhat larger than the f_o of the undamaged bearing, it is quite clear, that it is difficult to distinguish between the two and the indicated damage can hardly be diagnosed.
It appeared that this phenomenon was more dominant when geometrical discontinuities were present in the loaded zone of the bearing housing.

Bearings With Outer Ring Defects: Independent of the applied load on the bearing and of the size of the damage (up to 2 mm diam.) it was hardly possible to obtain clear damage indications at a speed of 500 r.p.m. At higher speeds the influence of the bearing load was small; in some cases an increase in damage indication was observed at the lower loads (0.5 kN). With higher speeds the influence of increasing damage diameter shows up clearly, which can be illustrated by comparing fig.3 (under, damage diam. 0.2 mm) with fig.4 (damage diam. 2.0 mm). The number of higher order frequency components (harmonics) in the latter case is striking.

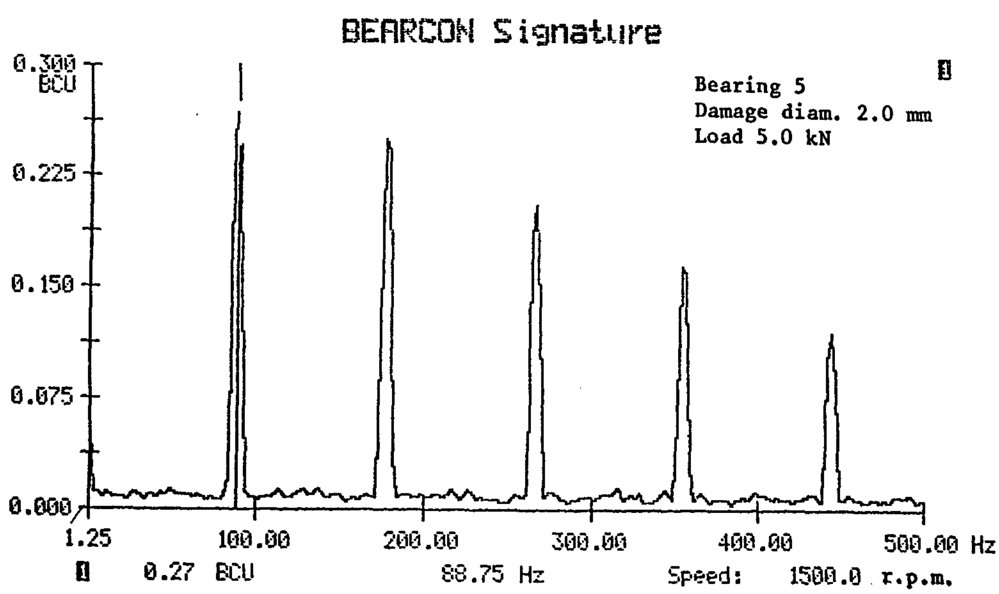


Fig.4 Envelope spectrum for outer ring defect diam. 2.0 mm

Plotting the levels of the outer ring defect frequency component f_o against damage diameter (fig.5) the influence of the increasing damage diameter is shown again. In fig.5 the results of the duplo-measurements are also shown as well as the results of the zero-measurements.

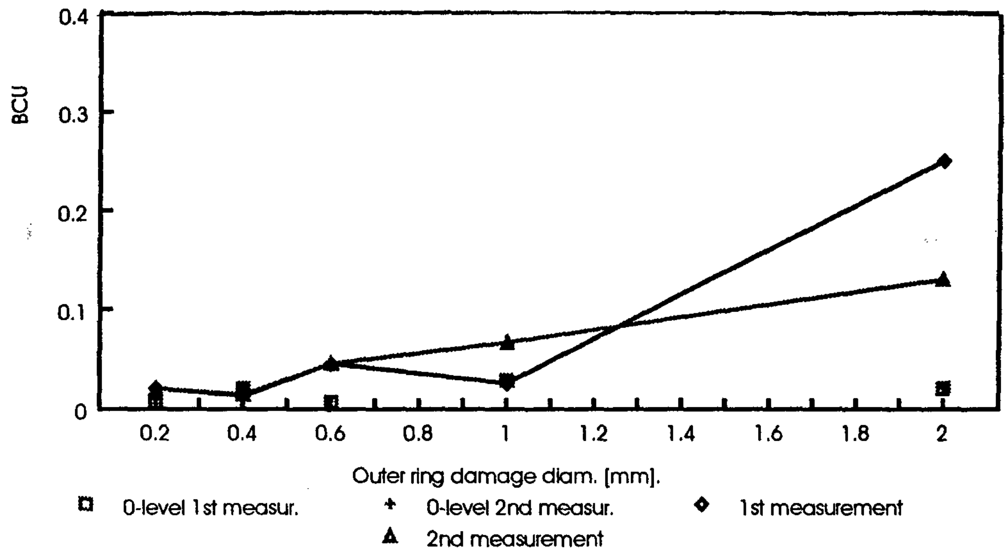


Fig.5 Vibration level of the f_o-component versus damage diameter at a load of 0.5 kN and a speed of 1500 r.p.m.

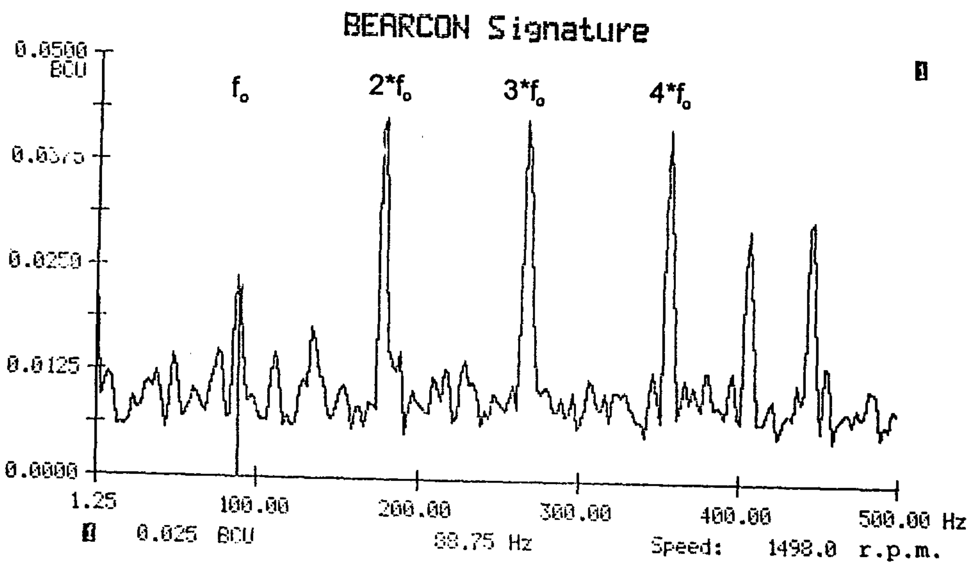


Fig.6 Envelope spectrum of an outer ring damage of 0.4 mm diam. at a load of 0.5 kN and a speed of 1500 r.p.m.

One would be inclined to conclude from fig.5 that it is not possible to detect outer ring damages of 0.4 mm diam. and smaller at a speed of 1500 r.p.m. However it appeared that sometimes harmonics of f_o had a much higher signal level, as is illustrated in fig.6, enabling clear detection of the damage.
Summarising it can be concluded that the detection limit with regard to the outer ring damage lies somewhere about 0.3 mm damage diam. under the given conditions, provided the speed of the bearing is not to low (over approx. 300 r.p.m.). (See also part on ball damage)
Bearings With Inner Ring Defects: The results of the experiments with the outer ring damages prompted to choose 0.4 mm as the smallest damage diameter for the inner ring damage, as weaker signals from inner ring damages were to be expected.
Here again it was difficult to determine inner ring damages at speeds lower than 500 r.p.m. irrespective of the size of the damage (up to 2.0 mm diam.).(See also part on ball damage)
Apart from the spectrum components that represent the inner ring defect frequency (f_i) and its harmonics, frequency components show up that correlate with the rotating frequency (f_n) of the bearing and side-bands of the f_i appear at a distance of f_n (see fig.7)

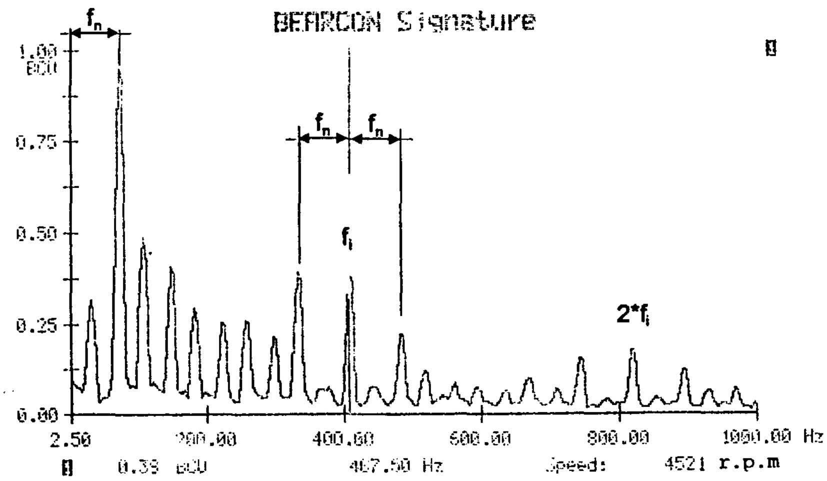


Fig.7 Envelope spectrum for an inner ring defect of 0.7 mm diam. at a load of 5 kN and a speed of 4500 r.p.m.

The f_n-component may completely dominate the envelope spectrum, particularly with the higher loads and speeds.
This can be explained by the fact that the excitation level of the carrier frequency will be modulated by the rotational frequency f_n as the defect overrolling passes through the loaded zône into the unloaded zône of a statically loaded bearing, with the rotating speed of the inner ring. Hence the effect will be stronger with higher bearing clearances and higher bearing loads.
The phenomenon can be easily simulated on a PC with e.g. a

Matlab program. The result of such a simulation is given in fig. 8. It shows in the upper part the excitation modulation of the amplitude of the carrier frequency, the corresponding envelope of the signal in the middle part and the resulting envelope spectrum in the lower part.

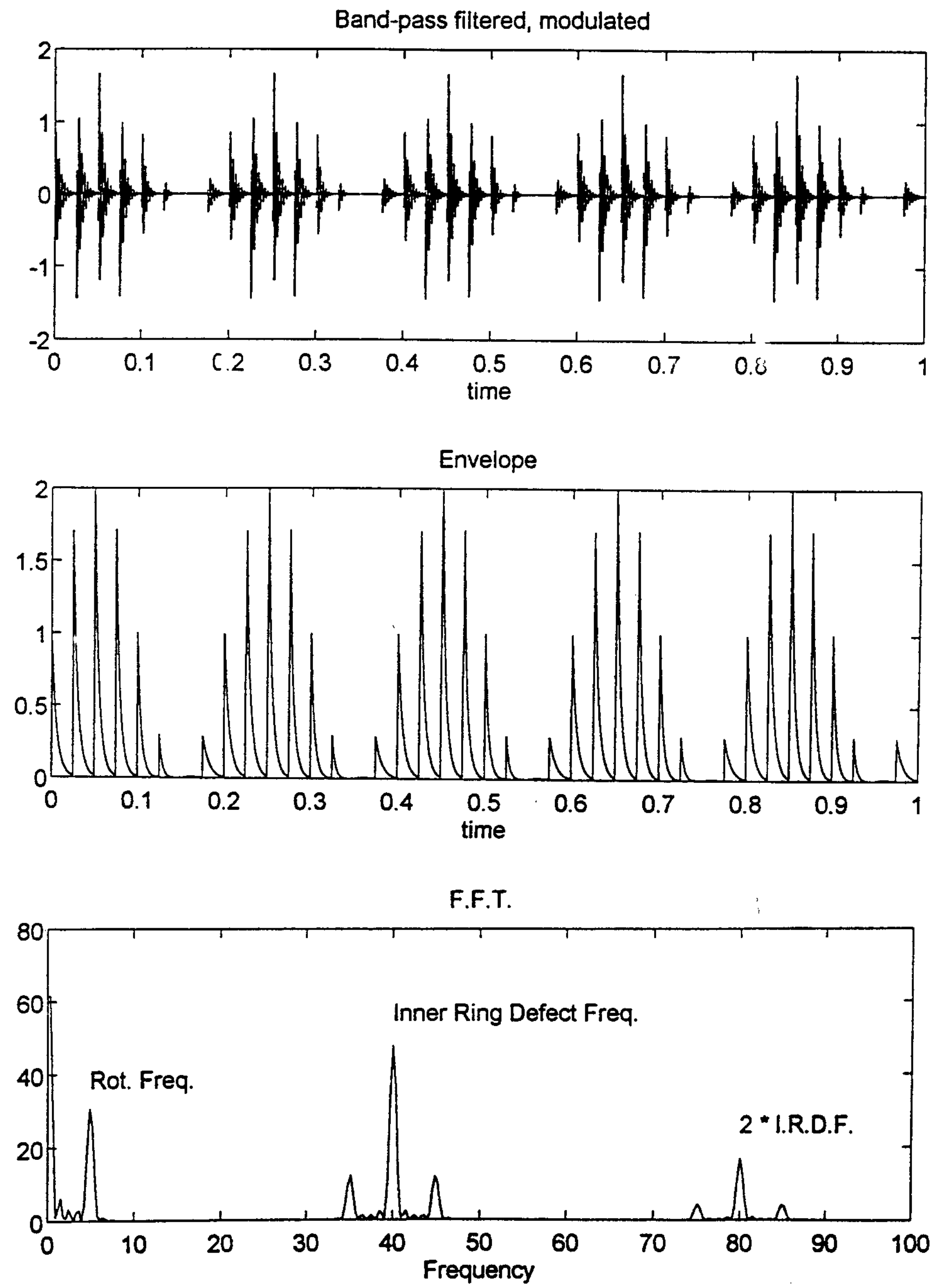


Fig.8 Simulation of an envelope spectrum with amplitude modulation of the carrier frequency with a Matlab program.

The inner ring defect frequency and its harmonic are flanked by side-bands at rotating frequency (f_n) distance and the f_n-component itself shows up clearly. The effect will be stronger with stronger modulation of the maximum amplitude of the carrier frequency, which was confirmed both in the simulation and in the real experiments. Similar effects can be expected with outer ring damage in a bearing supporting a shaft with high out of balance loading, where again modulation takes place with the frequency f_n, and with ball damage in a statically loaded bearing due to modulation with the cage rotation frequency (See part dealing with ball damage).
Returning to the detection limits it can be summarised from the experiments that:

- at the lower speed no detection of an inner ring defect was possible, irrespective of the size of the damage (up to 2.0mm).(See remarks in the part on ball damage)
- at a speed of 1500 r.p.m. inner ring damages of 0.7 mm diam. and larger could be detected and at a speed of 4500 r.p.m. damage with a diam. of 0.4 mm could easily be seen.
- sometimes the rotational frequency is a better damage indicator than the inner ring defect frequency. This holds particularly for the higher loads.

Bearings With Ball Defects: In a purely radially loaded ball-bearing with a ball defect it is a matter of coincidence when the defect will be overrolled and therefore the measuring technique had to be adapted to capture such an event. To do so the transducer signal was band-pass filtered and enveloped in a special module before feeding it to the analyser, which was set in the FFT-mode with a trigger level of 20% of f.s.d. and a short pre-trigger time.
It was observed, that the frequency of occurrance of defect-overrolling could be increased by applying light fluctuating axial loads on the bearing.
By doing so envelope spectra of bearings with a ball damage could be captured in a single shot and fig.9 gives an example of such a spectrum. The ball-defect frequency (f_b = 38 Hz) and four harmonics show up clearly and they are all flanked by two side-bands at a distance of the cage rotating frequency f_c. Moreover the f_c itself shows up very well. The whole picture shows a striking analogy with the simulated spectrum in fig.8 and with fig.7, the envelope spectrum for a bearing with inner ring damage. This obviously is not surprising as in the case af a ball defect in a statically loaded bearing the rotation of the cage, by pushing the damaged ball from the unloaded into the loaded zône, modulates the amplitude of the impacts that occur, when a defect is overrolled.
Again it could be shown experimentally that this modulating effect increases with higher loads and speeds and then very often the f_c-component in the envelope spectrum is the better indicator of a ball damage.
A striking difference with the spectra obtained with outer ring and inner ring damage is the far better sensitivity of the method used with the ball damage. Here a ball damage with

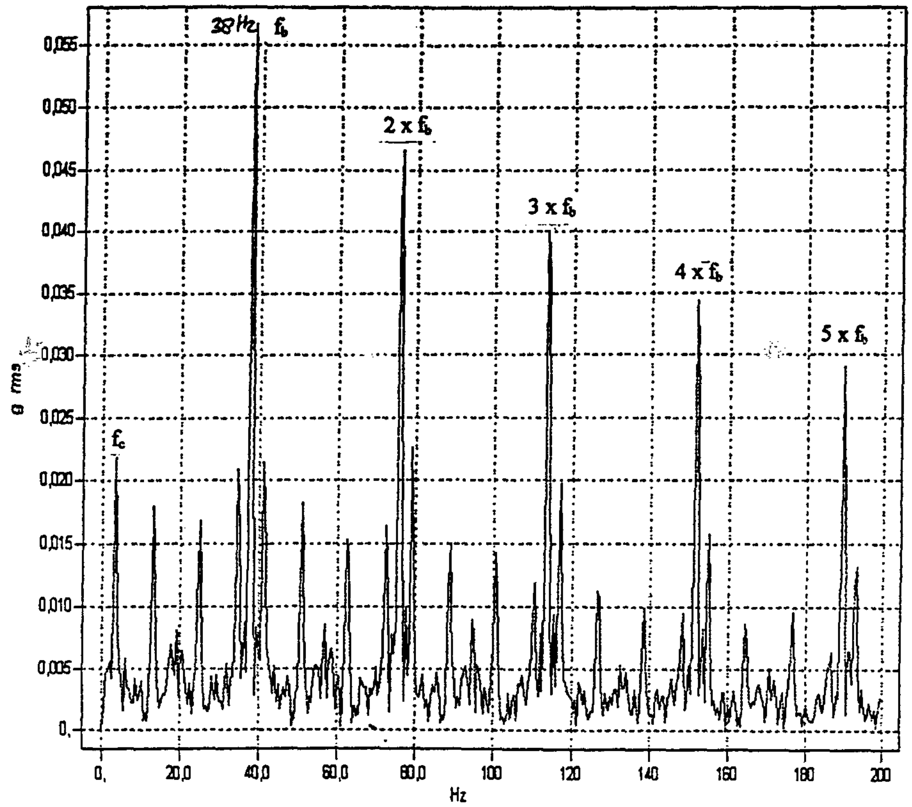


Fig.9 Triggered single shot envelope spectrum for a ball damage diam. 0.7 mm, load 0.5 kN and speed 500 r.p.m.

a diam. 0.7 mm and in a bearing running at 500 r.p.m. could be detected very clearly (fig.9), which was not possible with the outer ring and inner ring defects.
The explanation of this phenomenon could be, that the standard set-up of the Bearcon Signature™ measurement employs automatic scaling of the envelope spectra and in case of a relatively high starting peak in the spectrum (see e.g. fig.3) combined with a low f.s.d.-value, this starting peak determines the sensitivity. This was actually not the case with the single shot, triggered spectra.
It indicates, that the potential of the envelope technique with respect to detection limits, is better than reported here for the outer ring and inner ring damages.

CONCLUSIONS:

1. Signals of outer ring damage in undamaged bearings limit the detection of very small outer ring damage.

2. There is a low sensitivity of damage detection at low speeds. This is probably caused by the automatic scaling facility of the analyser.

3. Detection limits are hardly load dependent. Sometimes better results are obtained with the lower loads.

4. In a purely radially loaded ball bearing ball defects might be overrolled incidentally. This is a serious handicap for routine monitoring these defects. This handicap can be mitigated by applying a triggering technique.

5. Due to amplitude modulation the inner ring and cage rotational frequencies can be better indicators for respectively inner ring and ball defects than the defect overrolling frequencies.

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