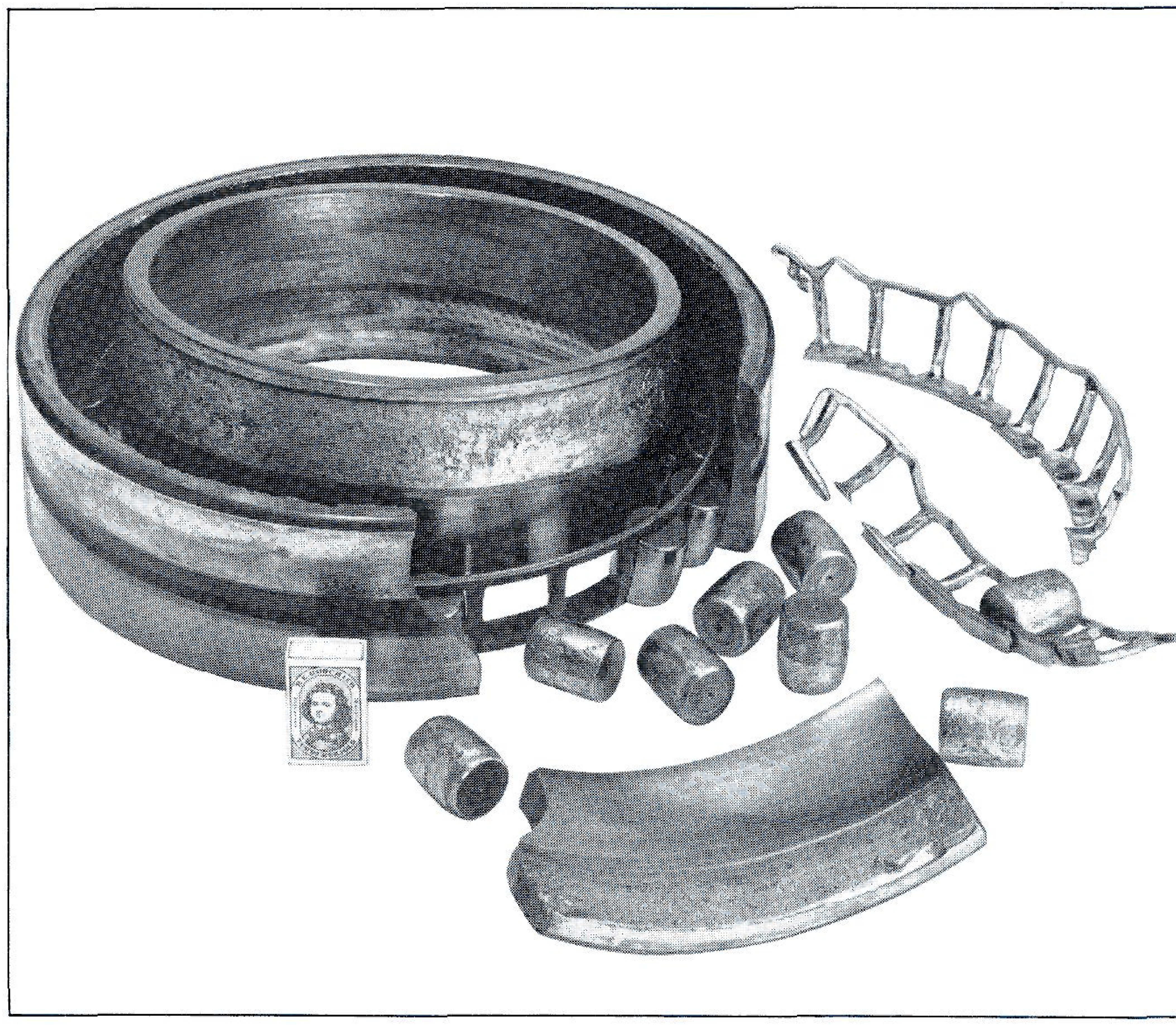
Brüel & Kjær application notes

Detecting faulty rolling-element bearings

Faulty rolling-element bearings can be detected *before* breakdown.

The simplest way to detect such faults is to regularly measure the overall vibration level at the bearing housing. A similar but significantly more effective way is to measure the crest factor of the vibration. However, the earliest possible warning is given by regularly comparing constant-percentage-bandwidth (CPB) spectra of the vibration. Bearing faults show up in such spectra as increases in a band of high-frequency components.

The more you know about the fault the greater the confidence with which you can predict breakdown. You can find out more about the fault using one or more of the following diagnosis techniques: zoom; cepstrum; and envelope analysis.



Unexpected breakdown of a rolling-element bearing, like that above, can cause injury, damage or lost production. Faulty rolling-element bearings can be detected long before breakdown by monitoring machine-vibration

What is a rolling-element bearing ?

Rolling-element bearings support and locate rotating shafts in machines. The term "rolling-element" bearing includes both ball bearings and roller bearings. Rolling-element bearings operate with a rolling action whereas plain bearings operate with a sliding action.

Why do they fail ?

Rolling-element bearings fail because of: manufacturing errors; improper assembly, loading, operation, or lubrication; or because of too harsh an environment. However, even if a bearing is perfectly made, assembled, etc. it will eventually fail due to fatigue of the bearing material.

How do they fail ?

Most modes of failure for rolling-element bearings involve the growth of discontinuities on the bearing raceway or on a rotating element. With time, the discontinuities spread and, if the bearing survives long enough, may eventually be worn smoother.

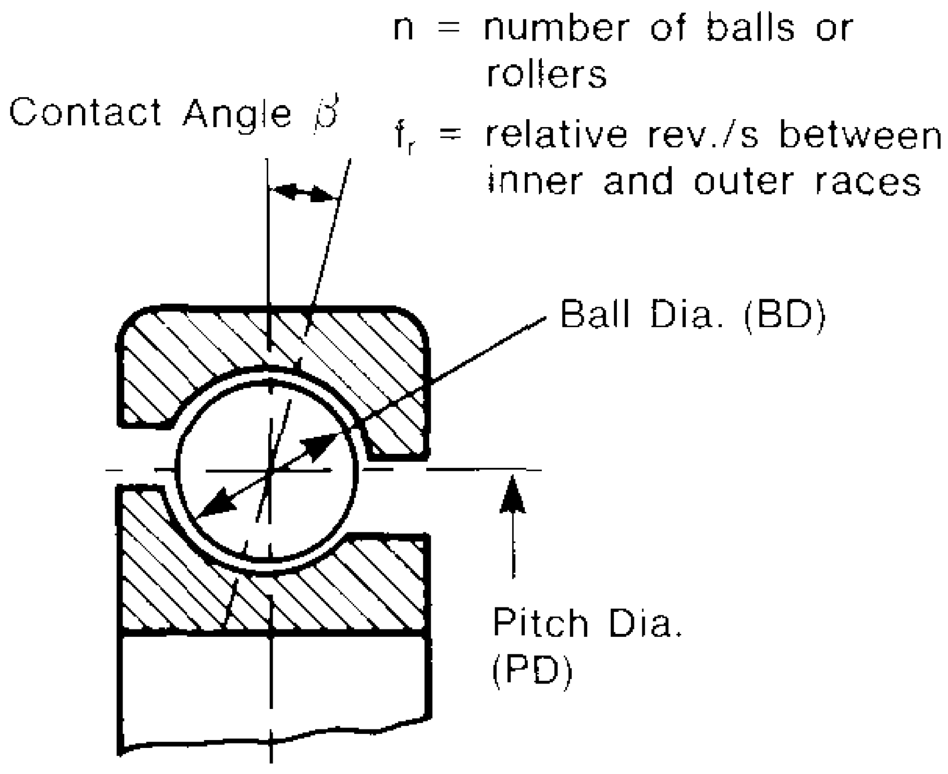
How do they vibrate ?

The vibration produced by a healthy, new bearing is low in level and looks like random noise.

As a fault begins to develop, the vibration produced by the bearing changes: Every time a rolling-element encounters a discontinuity in its path a pulse of vibration results. The resulting pulses of vibration repeat periodically at a rate determined by the location of the discontinuity and by the bearing geometry. These repetition rates are known as the *bearing frequencies.* More specifically: the ball-passing frequency outer-race (BPFO) for a fault on the outer-race; the ball-passing frequency inner-race (BPFI) for a fault on the inner-race; the ball-spin frequency (BSF) for a fault on the ball; and the fundamental train frequency (FTF) for a fault on the cage. The bearing frequencies can be calculated from the bearing geometry using the formulae given in Fig. 1. However, note that the relationships assume pure rolling motion, while in reality there is some sliding. Thus, the equations should be regarded as approximate.

Unfortunately, in frequency spectra of vibration from rolling-element bearings, the components associated

Rolling-element bearing frequencies



Impact Rates f(Hz) (assuming pure rolling motion)

For an outer race defect: $f(Hz) = \frac{n}{2} f_r \left(1 - \frac{BD}{PD} \cos \beta\right)$

For an inner race defect: $f(Hz) = \frac{n}{2} f_r \left(1 + \frac{BD}{PD} \cos \beta\right)$

For a ball defect: $f(Hz) = \frac{PD}{BD} f_r \left[1 - \left(\frac{BD}{PD} \cos \beta\right)^2\right]$

For a cage defect: $f(Hz) = \frac{1}{2} f_r \left(1 - \frac{BD}{PD} \cos \beta\right)$

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Fig. 1. Formulae for calculating bearing frequencies

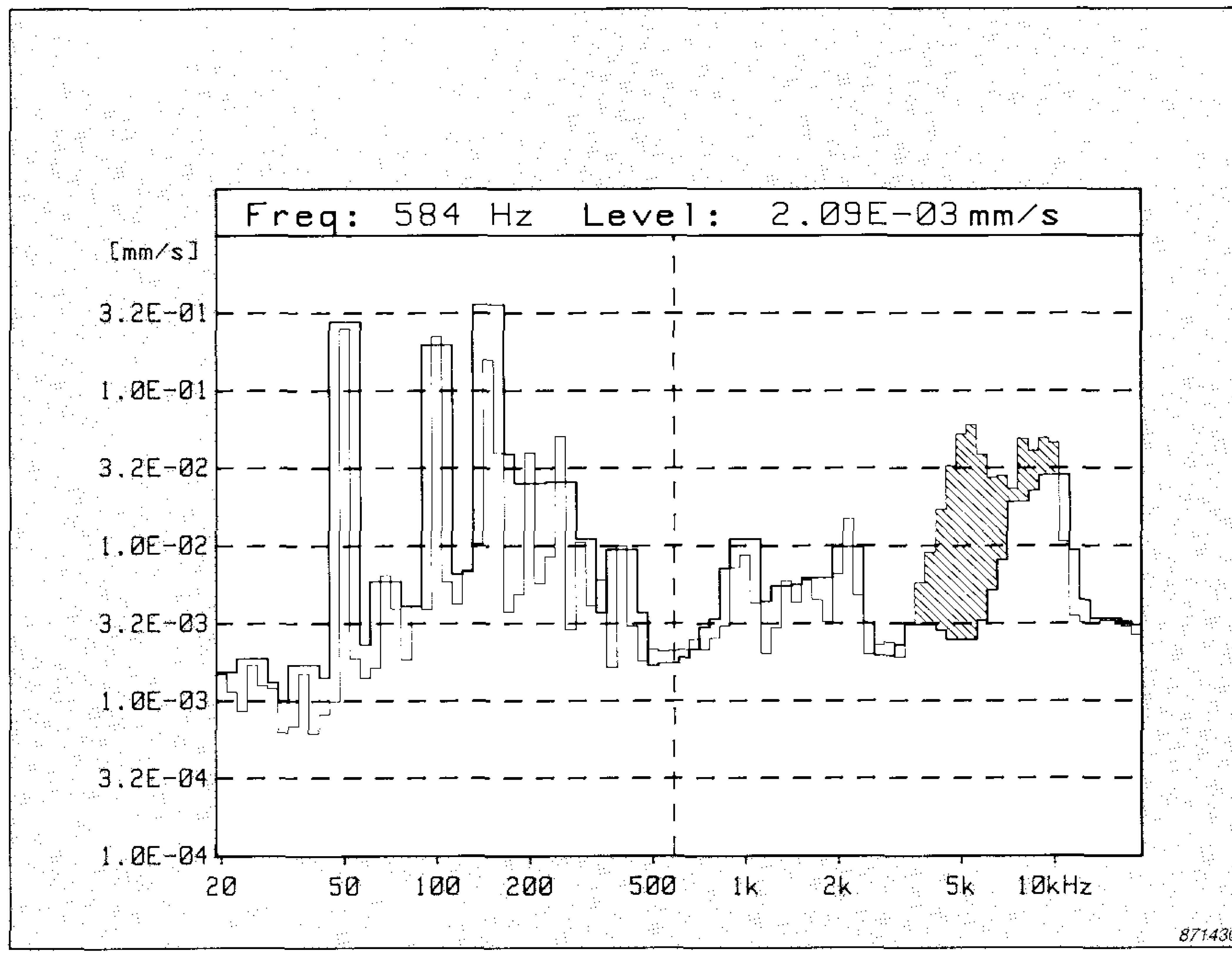

Fig. 2. CPB spectrum comparison for the vibration of a 110kW motor. The dark line is the "good-condition", reference mask against which the current spectrum (light line) is compared. Significant increases in a band of high-frequencies (shaded) indicated a damaged rolling-element bearing

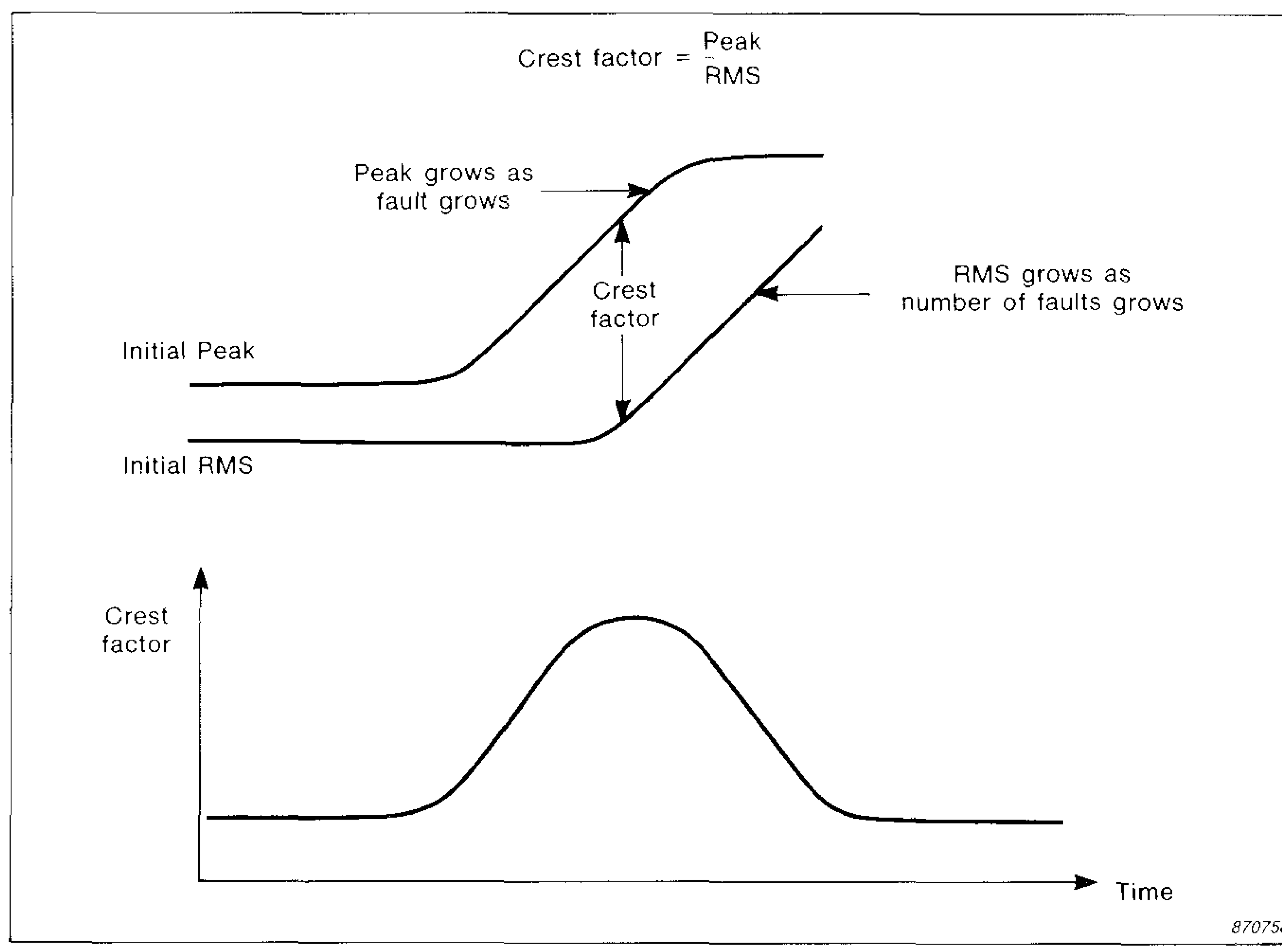

Fig. 3. The Crest Factor principle

with the bearing frequencies are usually "buried" in much higher-level components such as those associated with rotor unbalance.

However, in Fig. 2, which shows a vibration spectrum measured from a motor six weeks before a rolling-element bearing burnt out, increases in two bands of high-frequency vibration can clearly be seen. Experience has shown that such increases in bands of high-frequencies are an indication of a faulty rolling-element bearing. Why?

Consider the following: The impact as the rolling-element encounters a discontinuity is analogous to a bell being struck with a hammer. The structure consisting of the bearing, its housing and the machine-casing together acts like a bell which is made to "ring" (i.e. resonate) by the impact. The ringing frequency or *resonance* is a property of the structure and is not affected by how often or how hard it is struck. The resonances of such structures are generally between 1 kHz and 20 kHz and, unlike the resonance of a bell, are not concentrated in particular frequencies but rather in frequency bands. See Fig. 2. Thus, rolling-element bearing defects show up in frequency spectra as increases in one or more frequency bands between 1 kHz and 20 kHz.

How can you detect a bad bearing ?

Overall Vibration Level

The simplest way is to regularly measure the root-mean-square (RMS) average of the *overall vibration level* at the bearing housing. This technique involves measuring the root-mean-square (RMS) average of the vibration level over a wide range of frequencies. Measuring acceleration over a range of high frequencies (e.g. 1000 to 10000Hz) gives best results. Such measurements can be made using an accelerometer and a pocket-sized vibration meter fitted with an appropriate filter. Measurements are compared with general standards or with established reference values for each bearing. By plotting the measurement results over time the trend in vibration can be followed and extrapolated to give a prediction of when the bearing needs replacement. However, because a rolling-element bearing's overall vibration often increases only in the final stages of failure, this method gives late warnings of failure.

Advantages:
- Quick
- Simple
- Low capital outlay
- Single-number result

Disadvantages:
- Detects fewer faults
- Detects faults later

Crest Factor

You can get an earlier warning of bearing failure by using the same type of equipment used for measuring overall vibration, to regularly measure the *crest factor* of the bearing vibration (Fig. 3). The crest factor is the Peak-to-RMS ratio of the vibration. The vibration pulses produced by a bearing defect are measured by the peak detector in the vibration meter. Measuring acceleration over a range of high frequencies (e.g. 1000 to 10 000Hz) gives best results.

The curve in Fig. 3 shows a typical trend for crest factor as bearing condition deteriorates. Initially, there is a relatively constant ratio of peak to RMS value. As a localised fault develops, the resulting short bursts increase the peak level substantially, but have little influence on RMS level. The peak level will typically grow to a certain limit. As the bearing deteriorates, more spikes will be generated per ball-pass, finally influencing RMS levels, even though the individual peak levels are not greater. Towards the end of bearing life, the crest factor may have fallen to its original value, even though both peak and RMS levels have increased considerably. The best way to trend the data is as illustrated; RMS and peak levels on the same graph, with crest factor inferred as the difference between the two curves.

Advantages:
- Quick
- Simple
- Low capital outlay

Disadvantages:
- Prone to interference from other vibration sources
- Does not detect as wide a range of faults as CPB spectrum comparison

CPB Spectrum Comparison

The method which also detects other types of machine faults such as unbalance, misalignment, looseness, etc., is *CPB* (constant-percentage-bandwidth) *spectrum comparison*. See Fig. 2. The constant-percentage-resolution (8% in Fig. 2) along the frequency axis of CPB spectra means that you can have a frequency-range wide enough to detect rolling-element bearing faults, while still having sufficient resolution to detect low-frequency faults such as unbalance or misalignment.

Overall vibration level is largely determined by the level of the highest peak in the spectrum of the vibration. Thus, the overall vibration level only increases after an increasing component has become the highest peak in the spectrum. See Fig. 4. In this way, CPB spectrum comparison gives earlier warnings than overall-vibration monitoring.

Advantages:
- Detects a wide range of machine faults
- Provides *frequency information* that can be used for fault diagnosis
- Same equipment can usually be used to do further fault diagnosis

Disadvantages:
- Larger capital outlay

How can you find out more about the fault ?

All of the above methods can result, manually or otherwise, in a prediction of when the machine needs to be maintained. The more you know about the fault the greater the confidence with which you can make the prediction. You can find out more about the fault using one or more of the following diagnosis techniques: *zoom*; *cepstrum*; and *envelope analysis*.

Zoom

"Zooming" on an area of a frequency spectrum greatly increases the resolution with which that part of the spectrum is displayed. Thus, by zooming, what is displayed as a single peak in the ordinary spectrum may be revealed as two or more components in the "zoomed" spectrum. Zooming also lowers the displayed noise-floor, allowing lower-level components to be seen more clearly.

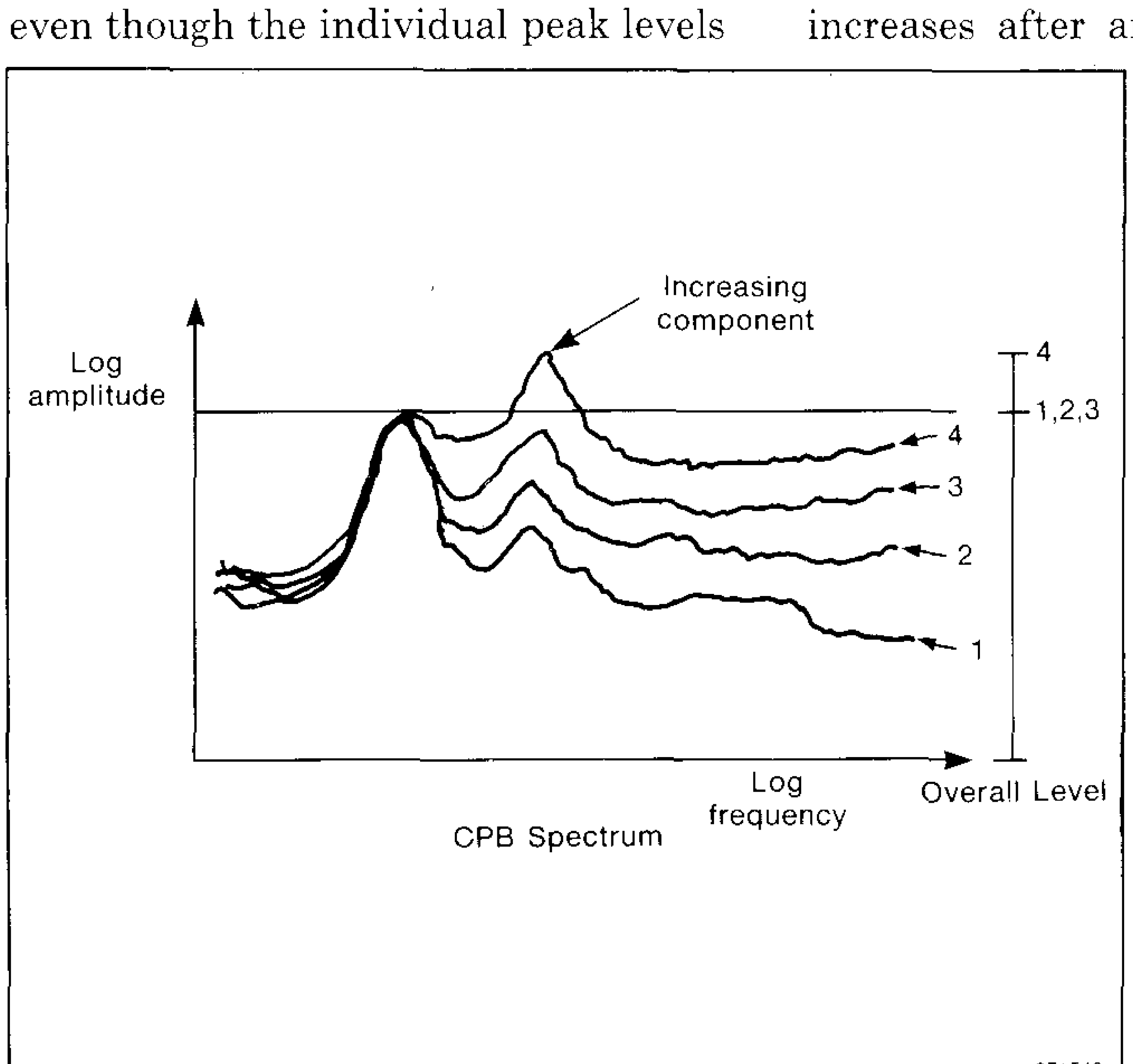

Fig. 4. A CPB spectrum comparison gives earlier warnings than monitoring of overall vibration – the level of overall vibration only increases after an increasing component has become the highest peak in the spectrum

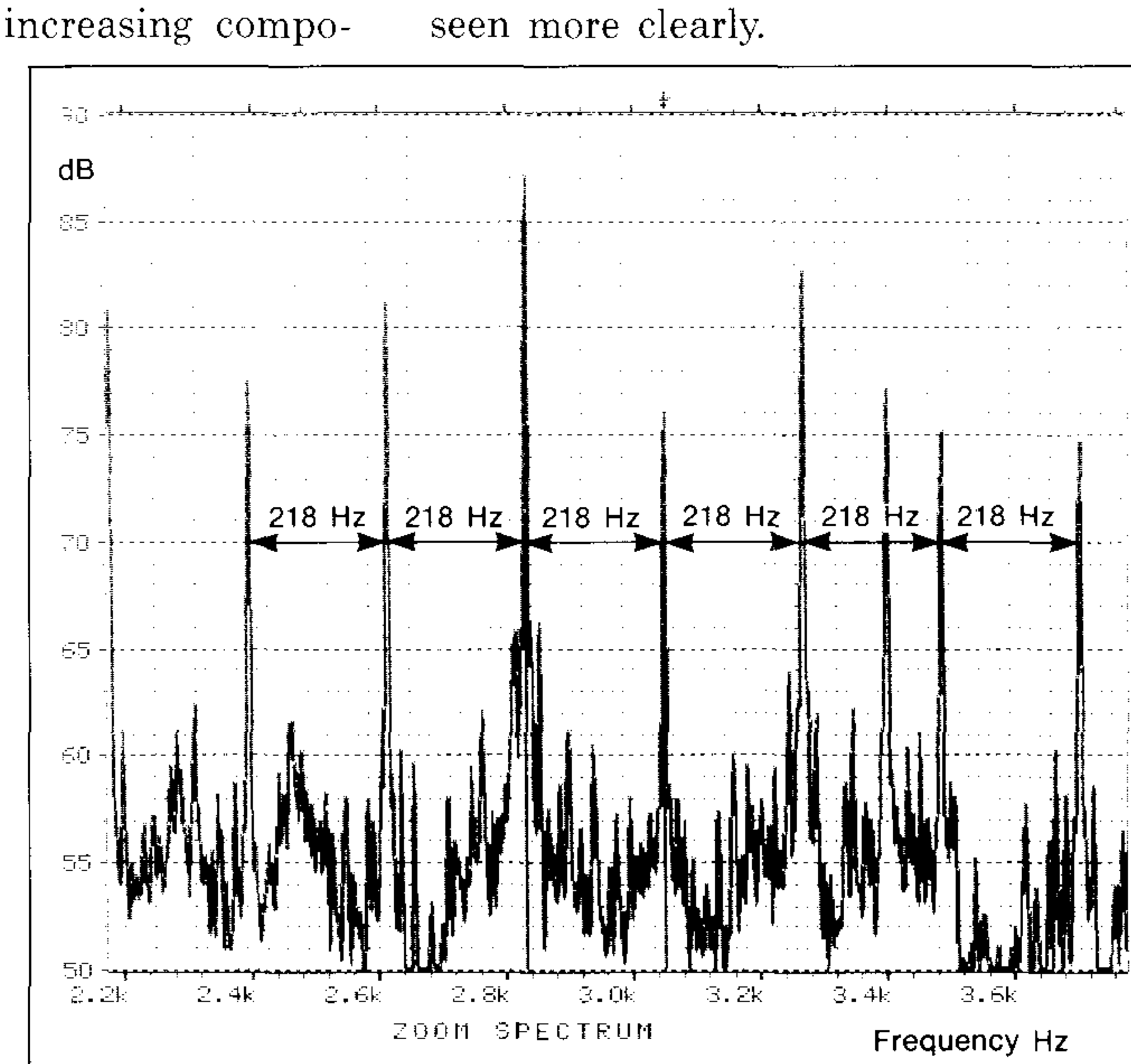

Fig. 5. A zoom spectrum showing harmonics corresponding to the ball-pass frequency outer race (BPFO). When the bearing was stripped down, eight months after the fault was first detected, a spall was discovered on the outer race

Zooming on the toothmeshing frequencies of a gearbox may reveal sideband components whose spacing corresponds to one or more shaft speeds of the gearbox. Increases in the number or level of such sidebands can indicate a faulty bearing on the corresponding shaft, shaft misalignment or a deteriorating gearwheel.

Sometimes, zooming can reveal harmonics of a bearing frequency (Fig. 5). Increases in such components can indicate a faulty rolling-element bearing. Normally, however, these components are "smeared" by the small variations in the running speed of the bearing or else they are hidden by higher-level components.

Cepstrum

As mentioned above, a faulty bearing, gearwheel or misaligned shaft in a gearbox can reveal itself as an increase in the number or level of sidebands around the component corresponding to the toothmeshing frequencies in the spectrum. Cepstrum analysis identifies families of sidebands and harmonics in a spectrum and reveals their relative importance. See Fig. 6. The greater the number of, or average level of, a family of sidebands/harmonics the higher the corresponding peak in the cepstrum. Cepstra are relatively insensitive to changes in machine load and so can be useful for trending. Cepstra for measurements made at different points on the same gearbox are likely to be very similar, i.e. cepstra are relatively insensitive to changes in the transmission path between the accelerometer and the source of the vibration. Cepstra are also useful for the accuracy with which they display the spacing of the sidebands or harmonics.

Envelope Analysis

Envelope analysis can extract periodic impacts, such as those made within a deteriorating rolling-element bearing, from a machine's vibration signal. It can do this even when the impacts may be low in energy and "buried" within the other vibrations from the machine. In envelope spectra, such as that in Fig. 7, regular impacts in the bearing show up as a peak (possibly with some harmonics) at the bearing frequency (see Fig. 1) corresponding to the location of the fault, e.g. the inner race, outer race, cage or a ball. Envelope analysis can thus differentiate between the periodic impacting of a rolling-element bearing fault and the random impacts of other phenomena such as cavitation (in a pump).

See the Brüel & Kjær application note BO 0187 "Envelope analysis—the key to rolling-element bearing diagnosis".

Why Brüel & Kjær?

Because any predictive maintenance program can quickly lose credibility through false alarms or missed breakdowns, the quality of the measuring equipment is critical to its success. Brüel & Kjær make a complete range of vibration monitoring equipment and, in the world of measurement, the name Brüel & Kjær is synonymous with quality. The unique Delta Shear® design of Brüel & Kjær accelerometers makes them particularly insensitive to environmental influences which might otherwise distort the vibration signal and cause false alarms. Vibration Analyzer Type 2515 is built to withstand the sort of treatment a toolbox receives. With Type 2515, you can make a CPB spectrum comparison to check the condition of a machine and if there is a significant increase, use the diagnosis techniques mentioned above* to locate the source of the problem. By examining the trend of the increase, using Machine-Condition Monitoring Software Type 7616, you can schedule maintenance in advance of a predicted breakdown.

* For envelope analysis Type 2515 requires modification WH 1936 and Envelope Detector WB 1048.

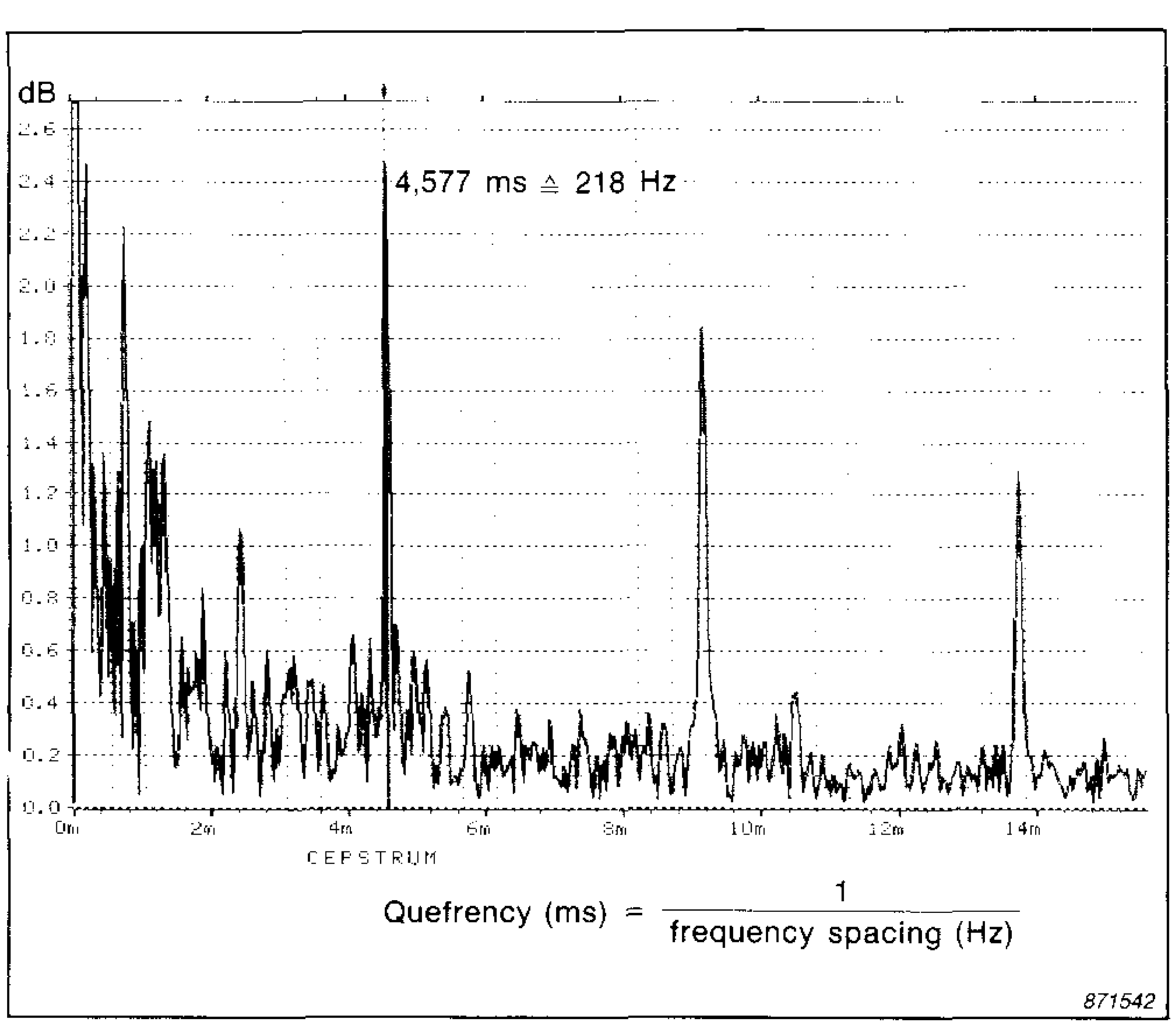

Fig. 6. The family of harmonics in Fig. 5 show up in the cepstrum as a distinct peak whose quefrency corresponds to the frequency spacing of the harmonics. A number of rahmonics (equivalent to harmonics in a normal spectrum) are also present

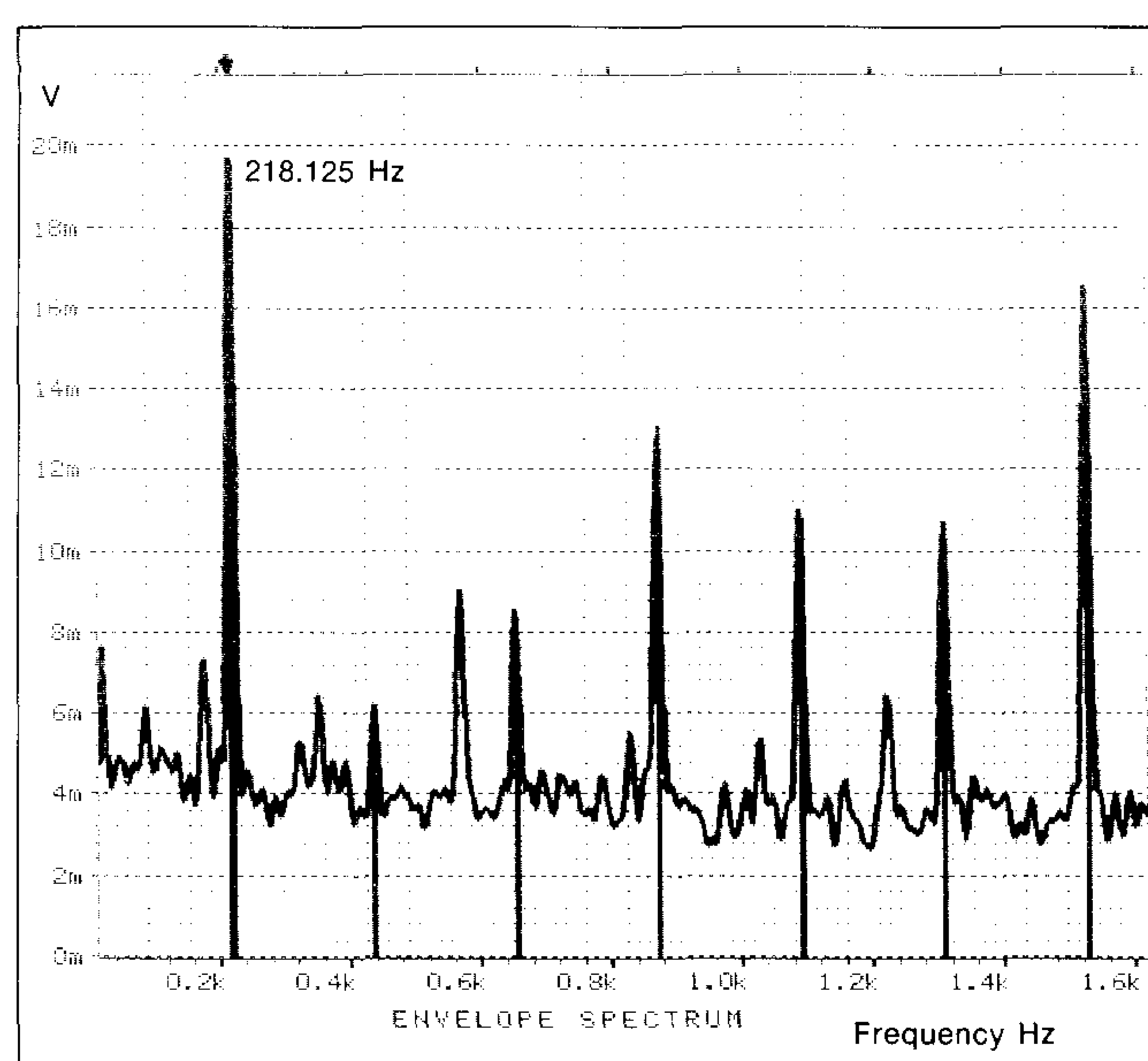

Fig. 7. The envelope spectrum corresponding to Figs. 5 and 6, showing a harmonic series of the BPFO

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