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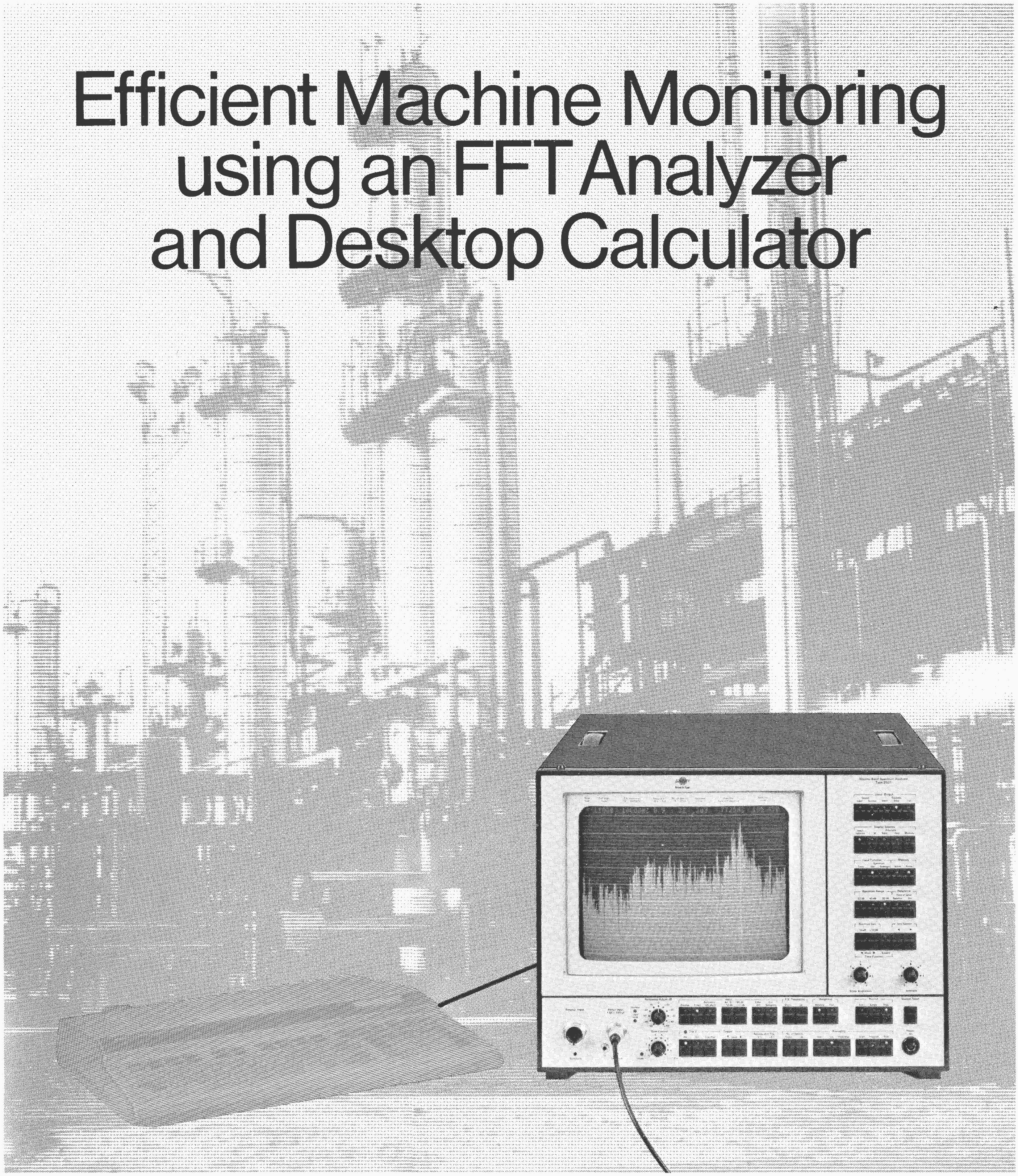
Efficient Machine Monitoring using an FFT Analyzer and Desktop Calculator



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Efficient Machine Monitoring using an FFT Analyzer and Calculator

by R.B. Randall

The monitoring and analysis of machine vibration signals has been found by many to be an excellent means of predicting incipient failures in sufficient time to allow repairs to be made at the most suitable time. (e.g. Refs. 1 - 6).

This is particularly valuable in the continuous process industries (e.g. (petro)-chemical and power generation) where loss of production is sometimes a more important economic consideration than damage to the machines themselves.

In this connection, it is worth noting that in order to significantly reduce production losses it is vital to have advance warning of impending failures up to several months in advance, so that the necessary planning and purchase of spare parts can be made. The latter also requires an advance diagnosis of the problem. Given that several months warning are required, it is quite a valid procedure to monitor the machines in question at intervals of one month or so, and use sophisticated analysis techniques to obtain the required information. The alternative procedure of continuous monitoring of important machines is aimed primarily at reducing consequential damage to the machines themselves in the final stages of breakdown, and will not necessarily avoid production loss. A combination of the two procedures is usually advisable, with the intermittent monitoring covering a larger number of machines.

However, in power stations and large chemical complexes there can be a problem of data handling because of the large number of machines to be surveyed, and several people have demonstrated that it can be an economical propostion to do this automatically using a minicomputer based system. (e.g. Refs. 7 - 9).

The development in recent times of very powerful real-time analyzers, based on the FFT principle, plus the parallel development of desk-top calculators, has meant that the benefits of digital processing can now be obtained much more cheaply, and thus extended to a wider range of users. One very important factor in this development is the appearance of an internationally standardized interface (IEC/IEEE) which permits immediate connection of equipment from different manufacturers.

The purpose of this article is to demonstrate how a modern FFT analyzer (B & K Type 2031) connected to a desk-top calculator (Fig.1) can be used to make automatic spectrum comparisons and thus detect significant changes in machine condition, while at the same time being insensitive to nonsignificant changes due to small speed variations etc. The cassette recorder included in the calculator can be used for mass storage of reference spectra and other data for a large number of measurement points.

Other applications of the instrument system to machine health monitoring will also be described.

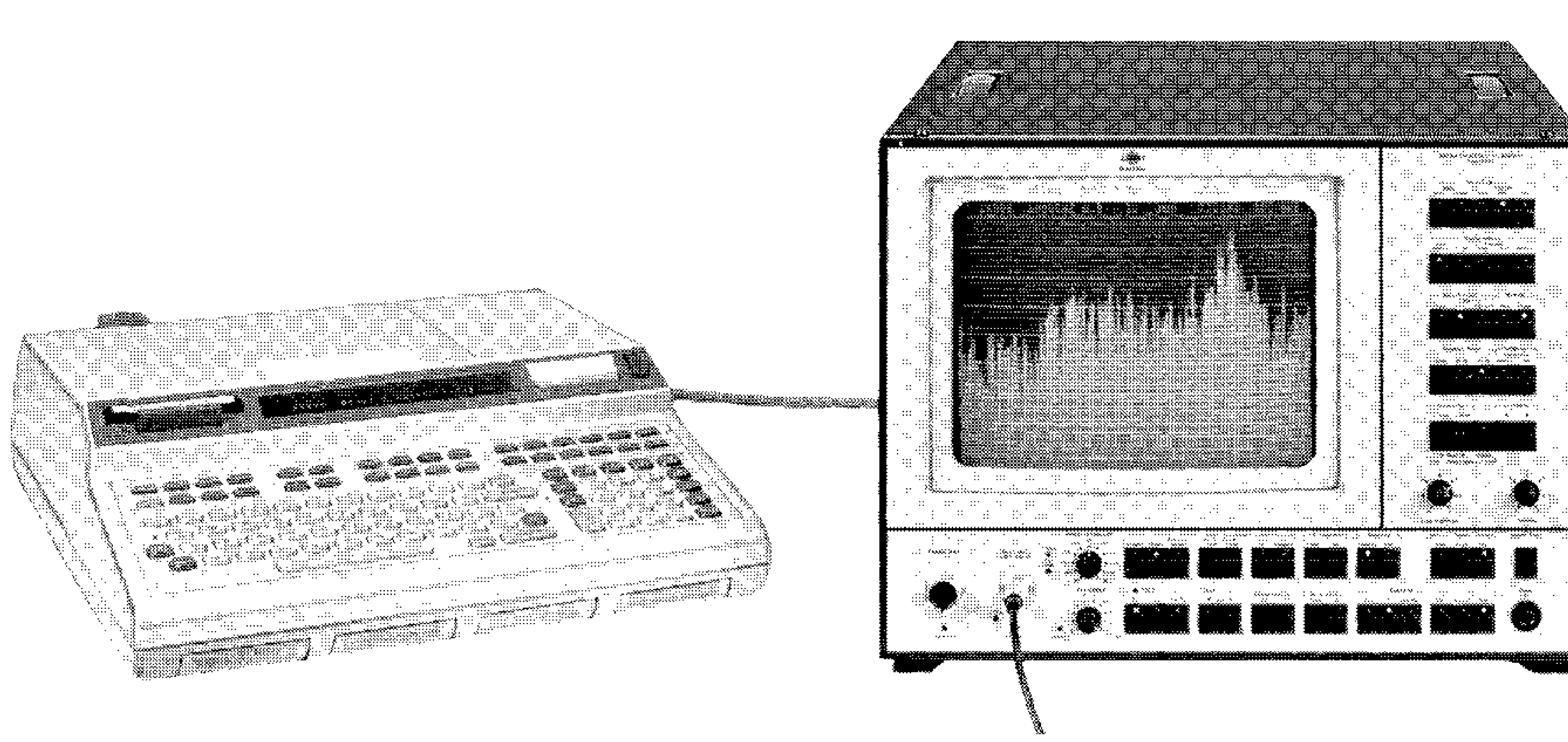


Fig.1. FFT Analyzer (B & K Type 2031) together with a Desktop Calculator

Machine Vibration - Which parameter should be measured?

Machine vibration is measured in two fundamentally different ways:

1) As a relative motion, usually displacement, between rotating and stationary components.

2) As the absolute vibration (displacement, velocity or acceleration) of the stationary parts, on which it is simplest to mount the transducers.

As pointed out in Ref.1, the choice between these two measurement methods depends on what is being guarded against. Relative displacement is optimal where closure of a certain available gap would be catastrophic, e.g. in protecting the seals around hydraulic turbine runners or avoiding rubs when starting up large steam turbines (Ref.10). On the other hand, where large forces can be present with imperceptible relative displacements, such as in gears and rolling element bearings, the absolute vibration of bearing housings gives the best measure of these forces. There is a certain amount of overlap, for example in the detection of unbalance and misalignment where either technique can be used, but roughly speaking it can be said that while both are used as permanent monitoring techniques for indicating the current condition, for long-term advance information it is necessary to measure the absolute vibration of the housing expressed either as velocity or acceleration. This is primarily because the first indications of impending failure often occur at high frequencies and are thus not detectable in the displacement signal (Ref.5) (the limit is generally not the frequency range of the electronics but the noise level of the system due to mechanical and electrical runout).

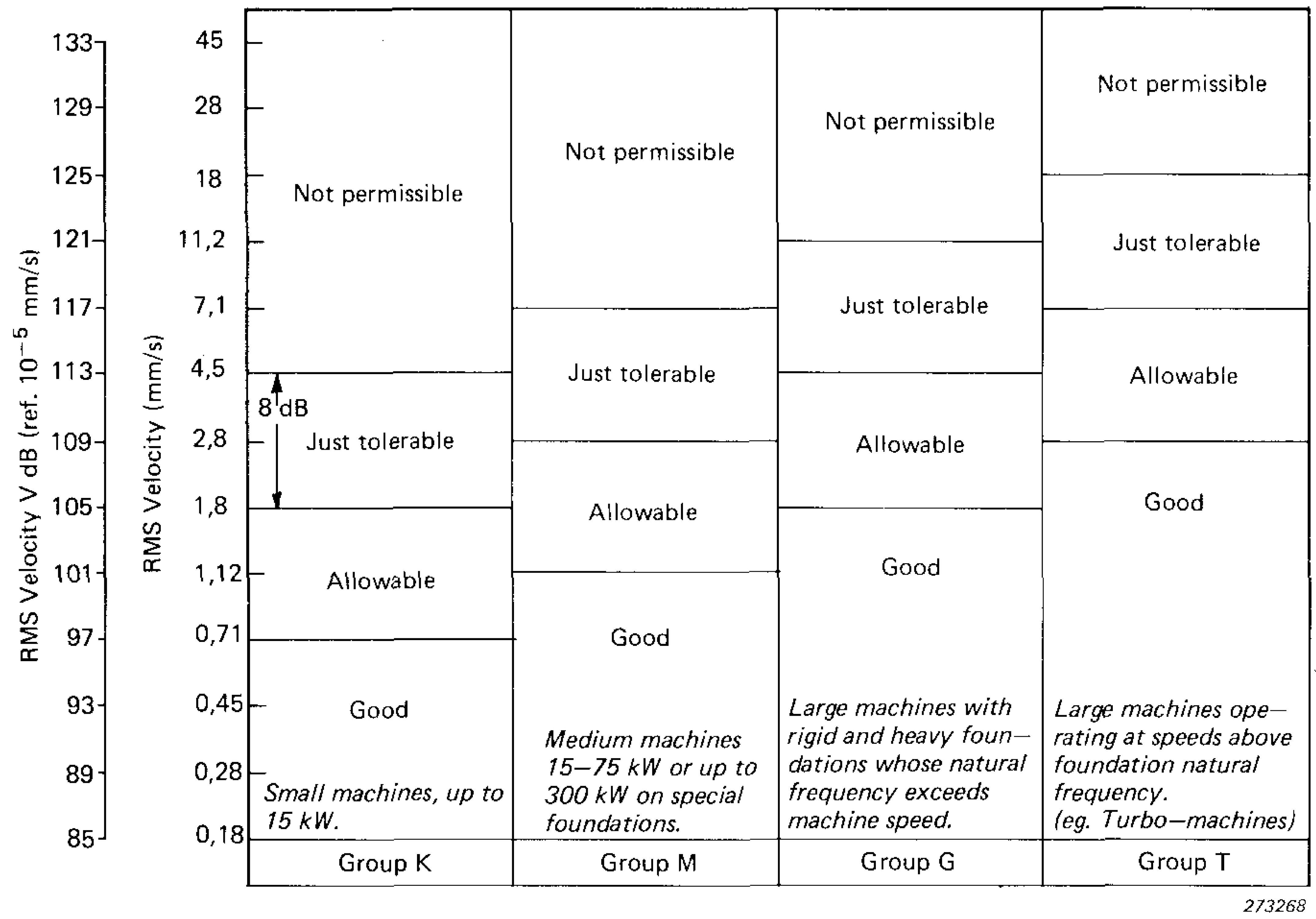


Fig.2. Vibration Criterion Chart (from VDI 2056)

Vibration criteria exist (e.g. Refs. 11, 12) which give recommended allowable vibration levels in absolute terms, and most of them are in agreement that it is the RMS vibration velocity which best represents vibration severity over a wide frequency range. Fig.2 expresses in a concise way the recommendations of Ref. 11, which have been derived largely by experience with "typical" machines. Ref. 1 warns against placing too much confidence in such absolute criterion levels, however, because of the wide variability between different machines of the same class, and a better criterion of failure is the degree of departure from the normal condition. The standard criteria can still be used to give an indication of what constitutes a significant change. For example, Fig.2 illustrates that independent of machine class, the separation of severity classifications is 8 dB and a change of 20 dB would always go from "Good" to "Not permissible". Note that the logarithmic scale of Fig.2 implies that it is the change in decibels rather than absolute units which is significant. It should always be kept in mind that it is not really the externally measured vibrations but the internal forces which are of primary interest, and these are connected via the mechanical impedance of the transmission path. A good illustration of this point is given by Fig.3, which shows the vibration spectra from two measurement points on the same machine (a large gearbox). For each measurement point, the spectra are represented on both a linear and a logarithmic amplitude scale. The spectra from both measurement points are equally representative of the internal condition of the machine, and when expressed on an 80 dB logarithmic scale, there is not much to choose between them. Even though they have a somewhat different shape, they both contain the same basic information, and a change at any frequency would be equally well detected. In the linear spectra, on the other hand, different sections of the spectra are unduly emphasized, and they no longer resemble each other very closely. Moreover, the same internal change would show up very differently in the two spectra, depending on where it happened to fall in the frequency range.

To summarize, the best parameter to use for comparison of machine vibration spectra is usually the vibration velocity expressed on a logarithmic or dB scale, and a change of 6 - 8 dB is significant while a change of 20 dB is serious.

Automatic Spectrum Comparison

Modern narrow-band spectrum analyzers such as the B & K Type 2031 typically give a 400-line spectrum having constant bandwidth on a linear frequency scale (see for example Fig.3). Each of the 400 lines is available as a digital value, but to find the significant differences between two such spectra it is generally not sufficient to simply subtract the two sets of digital values. There are a number of reasons for this:

1) Even relatively small speed changes can mean that the same vibration component falls in different line numbers in the two spectra. In the typical case of a 400-line spectrum from an FFT analyzer, a 1% speed change would mean that the same effective components would be separated by 4 lines at full-scale frequency, 2 lines at half-scale, etc.

2) Even where major components fall in the same line number, the digital sampling of the spectrum is very sensitive to small speed changes within one line spacing, in particular in the steeply sloping flanks of discrete frequency components. Fig.4 illustrates a typical case where two virtually identical spectra (Figs.4(a), 4(b)) when directly subtracted from each other (Fig.4(c)) show differences up to 12,8 dB, which are without real significance.

There are two basic ways of tackling the first problem, of which the first consists in normalizing the spectra to a harmonic order rather than an absolute frequency scale. This requires:

a) Addition of a tracking unit to the analyzer

b) A tacho signal from each machine to trigger the tracking unit. This is often difficult to arrange.

c) In the case of intermediate recording on tape, an extra channel would have to be used to record each tacho signal.

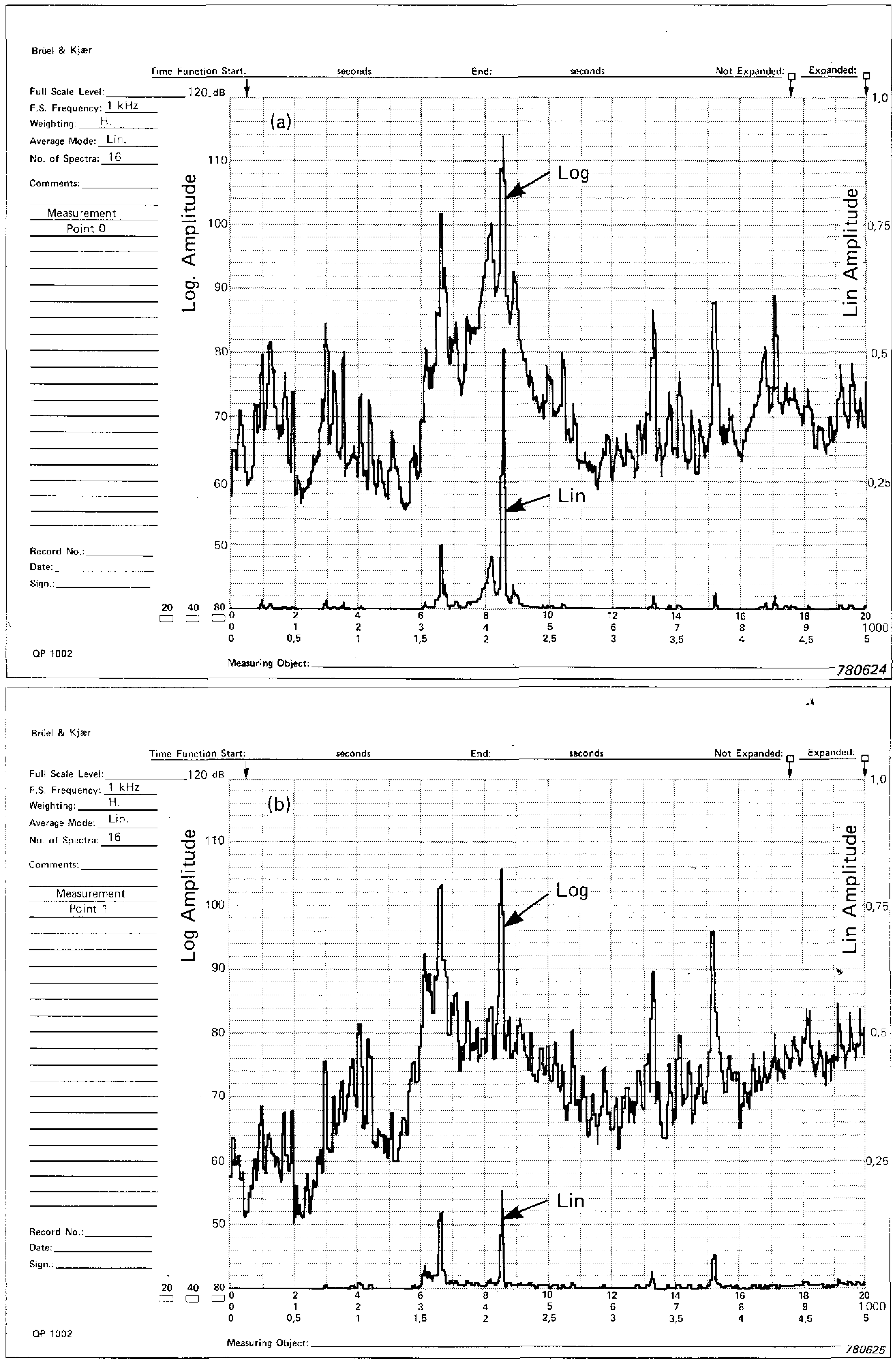


Fig.3. Comparison of linear and logarithmic amplitude scales for spectra from two measurement points

The alternative method, which is normally to be preferred, involves conversion of the spectra to a logarithmic frequency axis whereafter a lateral shift is sufficient to eliminate the effect of the speed change. The need for a tacho signal is eliminated, and information can usually be obtained from the spectrum itself as to the actual machine speed in each case. This conversion to a logarithmic frequency axis gives two other benefits at the same time:

a) It enables a wide frequency range to be covered in the one spectrum, provided that constant percentage bandwidth is used.

b) With both axes logarithmic, conversion between the various parameters (acceleration, velocity, displacement) is simply a linear change of slope, and for example it is a simple matter to evaluate a velocity spectrum in terms of acceleration by superimposing a number of constant acceleration lines (see Fig.5(a)).

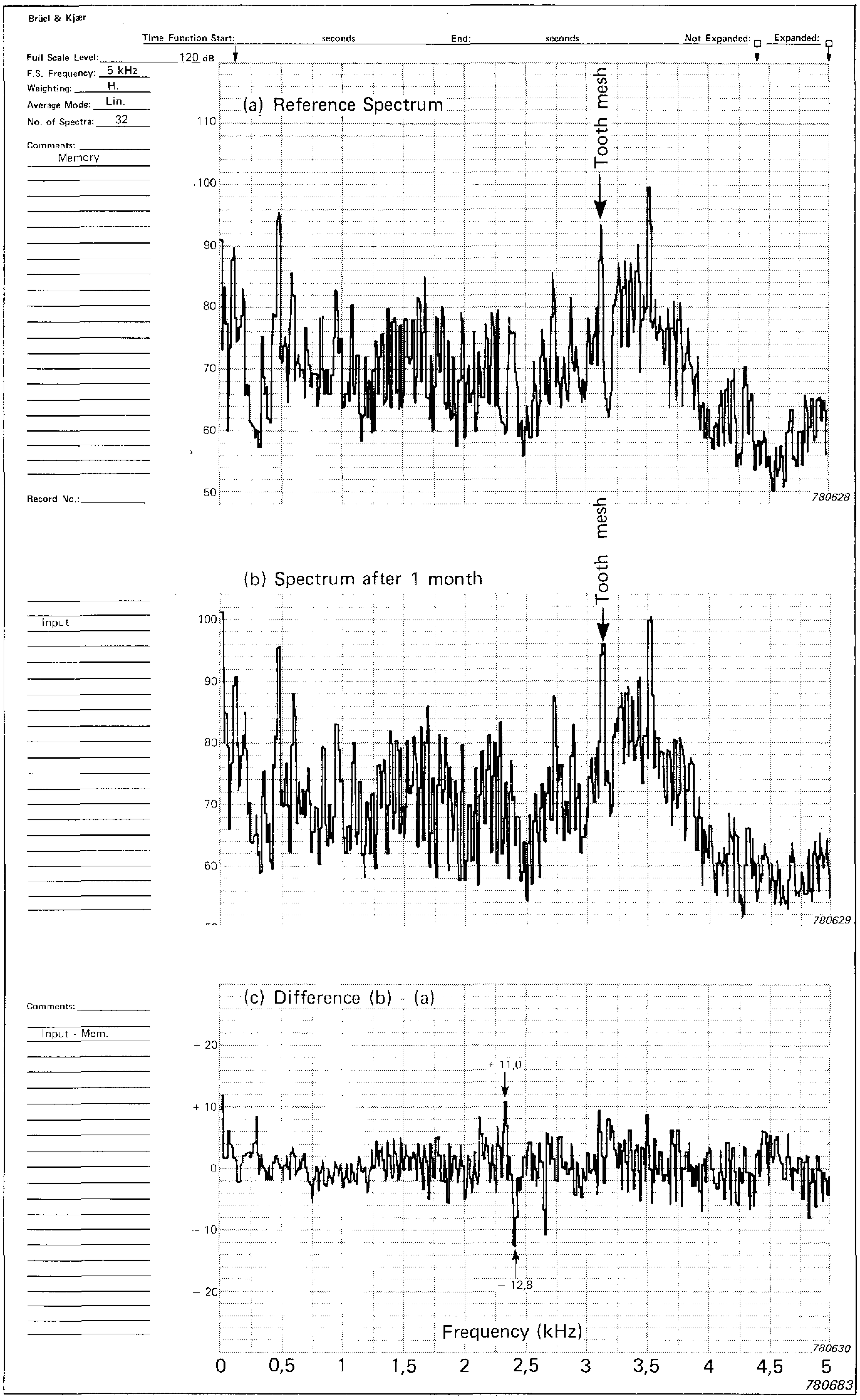


Fig.4. Illustration of large numerical differences between apparently similar spectra

There are many machines where a wide frequency range, e.g. 3 decades, should be surveyed in order to guard against all possible faults. For example, Fig.5(a) shows the spectrum (4% bandwidth) of a gearbox vibration signal over the 3 decades from 20 Hz to 20 kHz. The lower limit is governed by the necessity to guard against oil whirl (at approx. 45% of the lowest shaft speed, 50 Hz), while the upper limit is necessary to include a number of harmonics of the tooth meshing frequency (3150 Hz) which indicate gear condition. The constant percentage bandwidth spectrum of Fig.5(a) has been produced by the calculator using three individual linear spectra from the analyzer each separated by a decade in frequency, i.e. with full-scale frequencies of 200 Hz, 2 kHz and 20 kHz, respectively. The generation of the three spectra was controlled automatically by the calculator, however, and did not require operator intervention other than initial specification of the desired percentage bandwidth, maximum frequency, and number of spectra to be averaged in each frequency range. For comparison purposes, the equivalent linear frequency spectrum up to 20 kHz (the one used in fact to generate the final third of Fig.5(a)) is shown in Fig.5(b). It will be appreciated that even though this gives more information for the upper decade from 2 - 20 kHz, most of the lower frequency information is lost. It would be impossible, for example, to detect oil whirl at 23 Hz, because the first line in the spectrum has a width of 50 Hz (and in fact a bandwidth of 75 Hz because Hanning weighting was used, see Ref.13). This explains why it is necessary to convert each decade separately.

The exact frequency of rotation of the machine can be determined (manually or automatically) from the narrow band spectrum in the lowest decade, and this information used to shift the spectrum laterally before comparing with the standard. The maximum error will then be 1/2 bandwidth. For a 4% bandwidth spectrum such as Fig.5(a) it is only changes greater than 2% which will require compensation anyway.

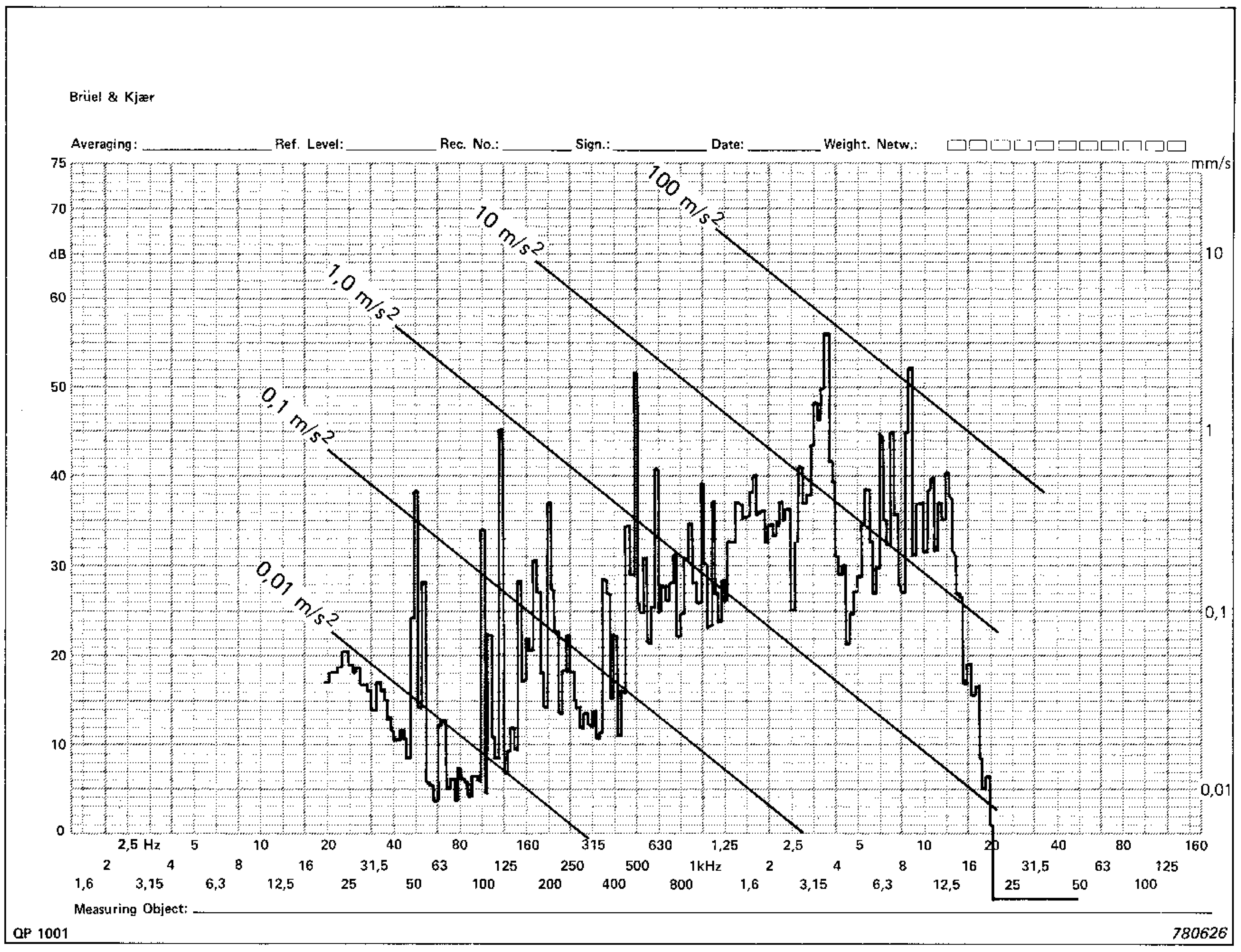
One way of tackling the second problem (due basically to shifts within one bandwidth), which has been found useful by the author, is to broaden the width of peaks in the reference spectrum by the following procedure. The actual spectrum used for comparison is the upper envelope of the three spectra obtained from the reference spectrum by shifting it one step to each side. At the same time it is advisable to limit the dynamic range of the reference spectrum to, say, 40 dB so that insignificant changes in the base noise level will not give false alarms.

An example should illustrate the feasibility of the procedure:

Fig.6(a) shows the vibration spectrum of a newly installed machine (a gear-box between a motor rotating at 50 Hz and a centrifugal compressor rotating at 121 Hz) and Fig.6(b) the reference spectrum derived from this by the described procedure.

Figs.6(c) to 6(e) are spectra obtained at approx. one month intervals from the machine as its condition deteriorated. Superimposed on each spectrum is a list of significant differences (> 6 dB) found by an automatic comparison program in the calculator. For the first month (Fig.6(c)) there is no significant change. One month later (Fig.6(d)) the component at the rotating speed of the high speed shaft (121 Hz) has increased significantly (14 dB) and a month later again (Fig.6(e)) a further worsening to 22 dB indicates that the situation is serious. Shortly afterwards the machine was shut down for repair. The immediate reason for the increase of the 121 Hz component was a developing misalignment, but the basic problem with the machine was an axial resonance of a disc coupling which was excited by the 4th harmonic of the shaft speed. Note the development of this component at 484 Hz in the spectra of Fig.6 (the development was in fact more obvious at other measurement points closer to the coupling).

It should be noted that the shaft speed in Fig.6(e) is 126 Hz compared with 121 for the others, but this difference has been taken care of without problems by the program so that only the significant changes are detected. For comparison purposes, Fig.7 shows the effect of a direct comparison of narrow band linear frequency scale spectra between the same two signals (i.e. those corresponding to Fig.6(a) and 6(e)). A full-scale frequency of 5 kHz has been used in an attempt to include as many significant components as possible. A direct subtraction of the two spectra results in differences of up to 30 dB throughout the spectrum, among which the actual significant differences are hidden.



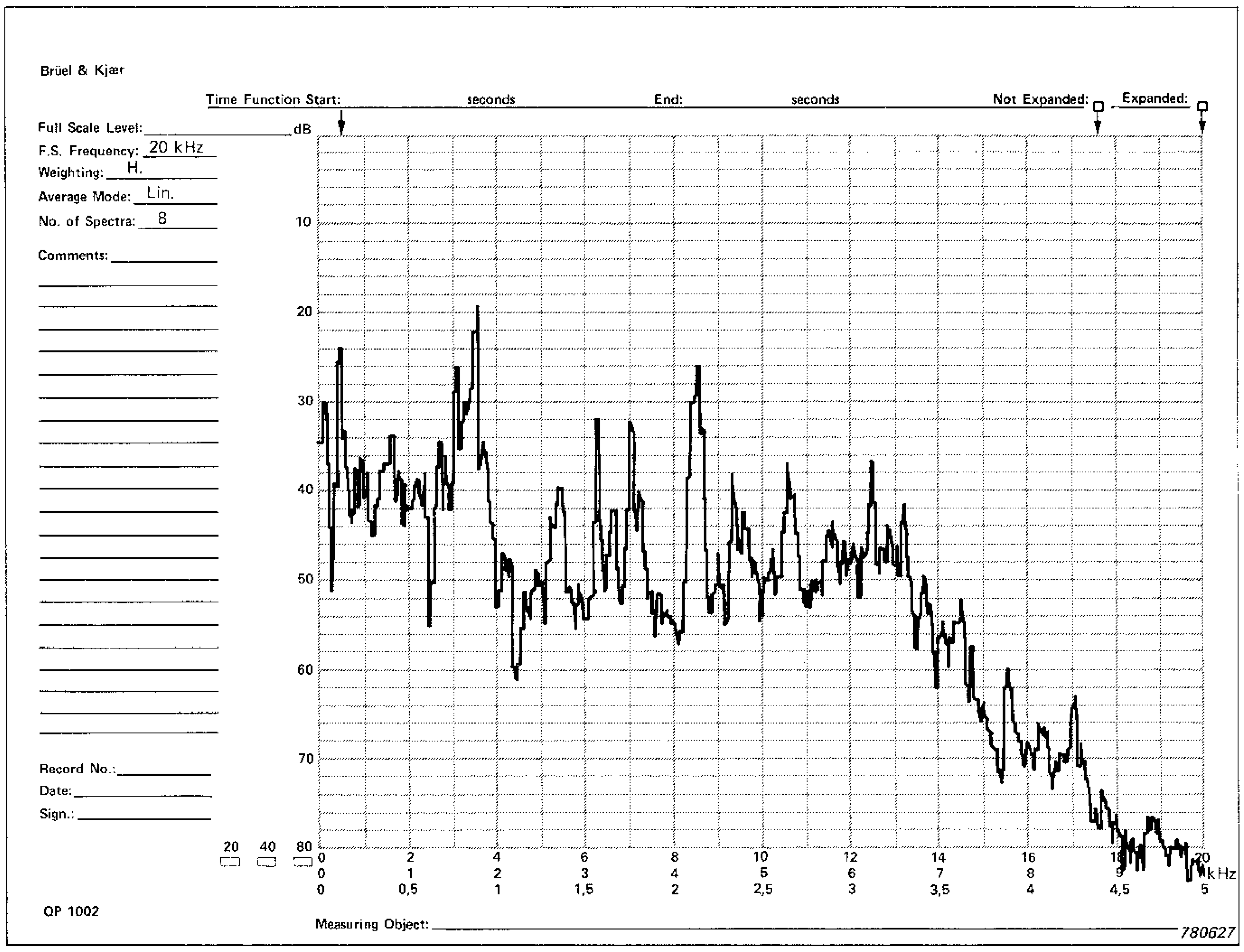


Fig.5. (a) Constant percentage (4%) bandwidth spectrum on logarithmic frequency scale (20 Hz — 20 kHz)
(b) Constant bandwidth (400 line) spectrum on linear frequency scale (0 — 20 kHz) for same signal

Choice of Bandwidth

The bandwidth used in Fig.6 (4%, actually 1/18 octave) results in a spectrum comprised of 180 values over 3 decades, and gives a very high degree of certainty that changes anywhere in the spectrum will be detected. It is about the minimum which can be achieved with a 400-line FFT analyzer (the line spacing one decade down from full-scale frequency is 2,5 % and bandwidth 50% greater when Hanning weighting is used).

The possibility of using a broader bandwidth (at the fault detection stage) should be kept in mind in the interests of economy (e.g. Ref. 9). As an example, Fig.8 compares the same signals as Fig.6 on a 1/3-octave or 23% basis. This has the following advantages:

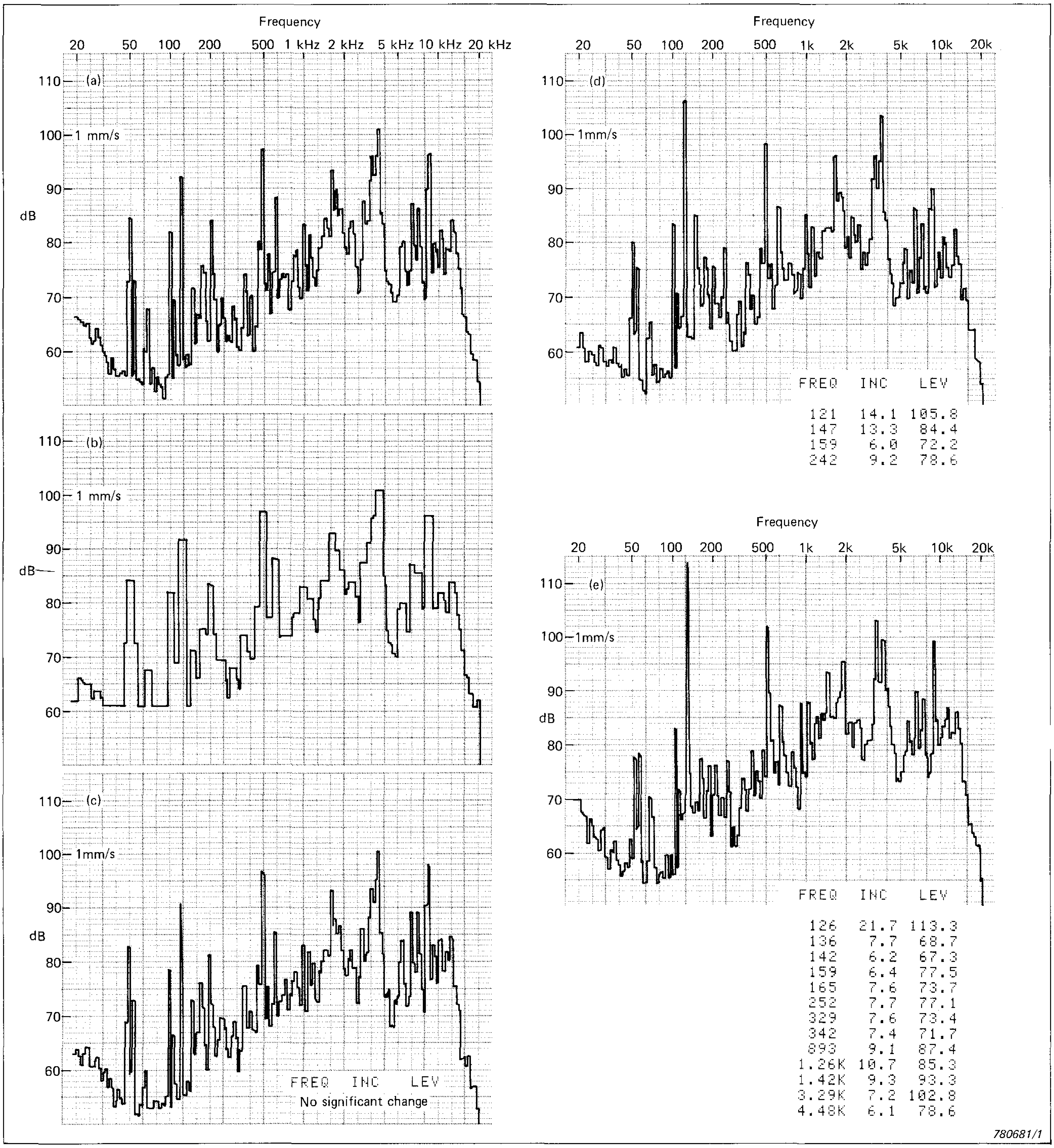


Fig.6. (a) Spectrum soon after installation
(b) Reference spectrum derived from 6(a)
(c) Spectrum one month later
(d) Spectrum two months later
(e) Spectrum three months later

1) Only 30 values are required to cover the same frequency range, thus reducing the data handling problem.

2) The bandwidth of 23% means that it is not normally necessary to compensate for speed variations and thus a direct subtraction of the digital values can be used in this situation.

The most significant change (in the 121 Hz component) is detected in this case also, but it will be seen that the likelihood of detecting changes elsewhere has been reduced. For example, because the separate components at 3150 Hz and 3550 Hz fall in the same 1/3-octave band, the relative changes in these two are not detected (cf. Fig.6(d), (e)).

Thus, the advantages of the broader bandwidth must be weighed against the fact that some of the advance warning is lost.

Fault Diagnosis

Detection of a significant change is only the first step in the overall process (but that which involves most analysis time, because it is only perhaps in 2 - 5% of cases that significant changes will be found). Diagnosis of the reason for the change is the next very important step, but one which is very difficult to automate fully (a parallel can be drawn with medical diagnosis). Ref. 14 contains a detailed discussion of the ways in which many typical faults can be diagnosed, based on the frequency at which they manifest themselves (see also Refs.1 - 5).

For diagnostic purposes, it is most often best to express the spectrum on a linear frequency scale with constant bandwidth, the normal presentation of an FFT analyzer. This facilitates the visualisation of a harmonic or sideband pattern, these often being important factors in diagnosis (Ref.14).

As another example, Fig.9 shows vibration spectra measured at the bearings of a rotating compressor before and after a maintenance shutdown. Before the shutdown only the low harmonics of the running speed (approx. 165 Hz) were evident, but after the shutdown not only a half-order subharmonic, but also the "interharmonics" of order $1\,^1/_2$, $2\,^1/_2$, $3\,^1/_2$ etc. are present. Sohre (Ref.15) states that exact half-order components arise typically as a result of lack of tightness of mechanical assembly of (journal) bearing components. In the author's experience such mechanical looseness ("rattling") tends to give rise to interharmonic components, also. Sohre points out the importance of distinguishing between this case and that of "oil whirl" where the frequency of the vibration is at just less than half the rotational speed (42 — 48%). Expressing the results on a linear scale with constant bandwidth immediately allows this distinction to be made purely from the pattern of the result.

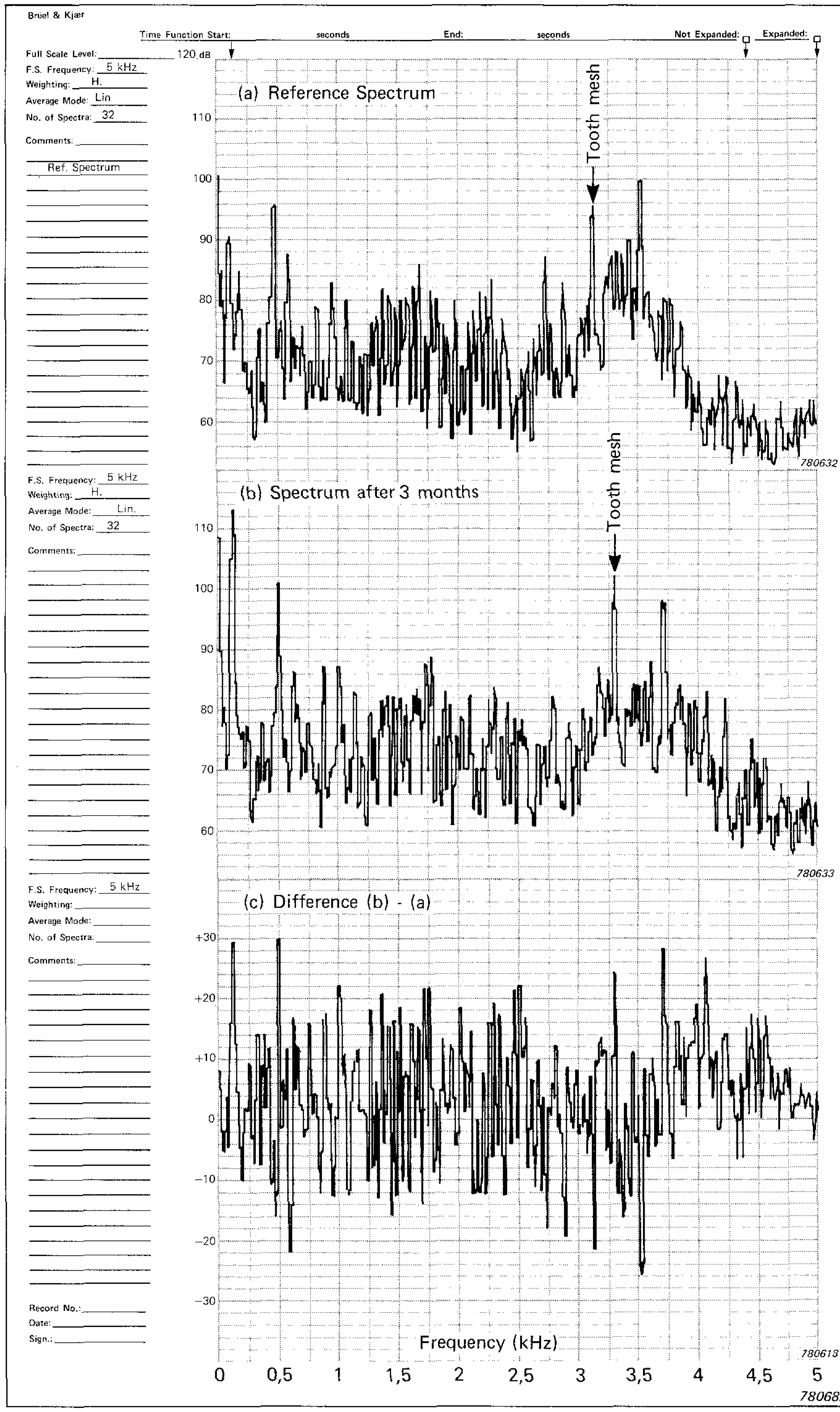


Fig.7. Direct comparison of linear frequency spectra from same signals as Figs.6(a) and 6(e)

Even though it will normally be necessary for an engineer to make the diagnosis, the calculator could be useful for suggesting various possibilities. This need not only be general faults, as mentioned above, but could also include faults specific to the machine in question. This type of information, based on the past history, could be stored on the calculator cassette together with the reference spectra for each measurement point.

Another application of the analyzer/calculator combination, unique to the B & K Type 2031, is to perform cepstrum analyses, as described in Ref.14. The cepstrum, obtained by performing a further frequency analysis on the logarithmic (i.e. dB) spectrum, is useful for detecting and separating different families of harmonics and sidebands. The first application is useful in detecting missing blades in large turbines (Refs. 16, 17), while the second is useful in diagnosing various faults in gearboxes (Ref. 14). Fig.10, for example compares spectra and cepstra for a large gearbox before and after repair. The major differences between the two spectra with increasing wear are:

1) An increase in the overall level of the spectrum.

2) A relatively greater increase of the higher harmonics of the toothmeshing frequency (333 Hz), indicating a greater distortion of the toothmeshing vibrations.

3) A vast increase in the number and level of sidebands around the toothmeshing frequency and its harmonics, due to modulation of the basic toothmeshing vibration. In the spectrum before repair, it is difficult to separate the various sidebands, but in the cepstrum it is evident that these have typical spacings of 8,3 Hz (indicating a modulation at the speed of the input pinion) and its third harmonic 25 Hz (indicating that the gear was slightly "triangular"). In the cepstrum after repair, these components are much lower indicating that there is no significant modulation.

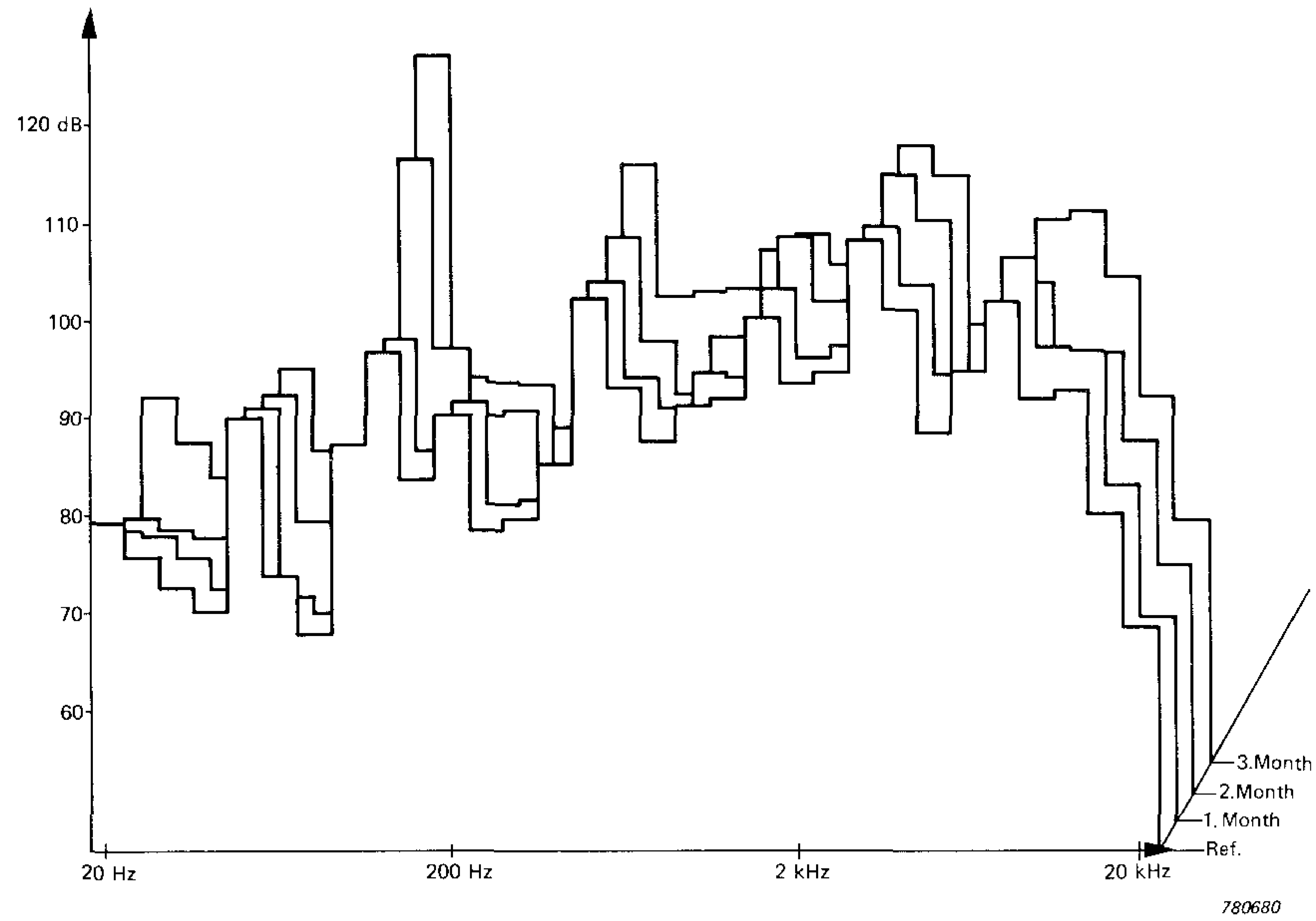


Fig.8. Three-dimensional representation of 1/3-octave spectra corresponding to Fig.6.

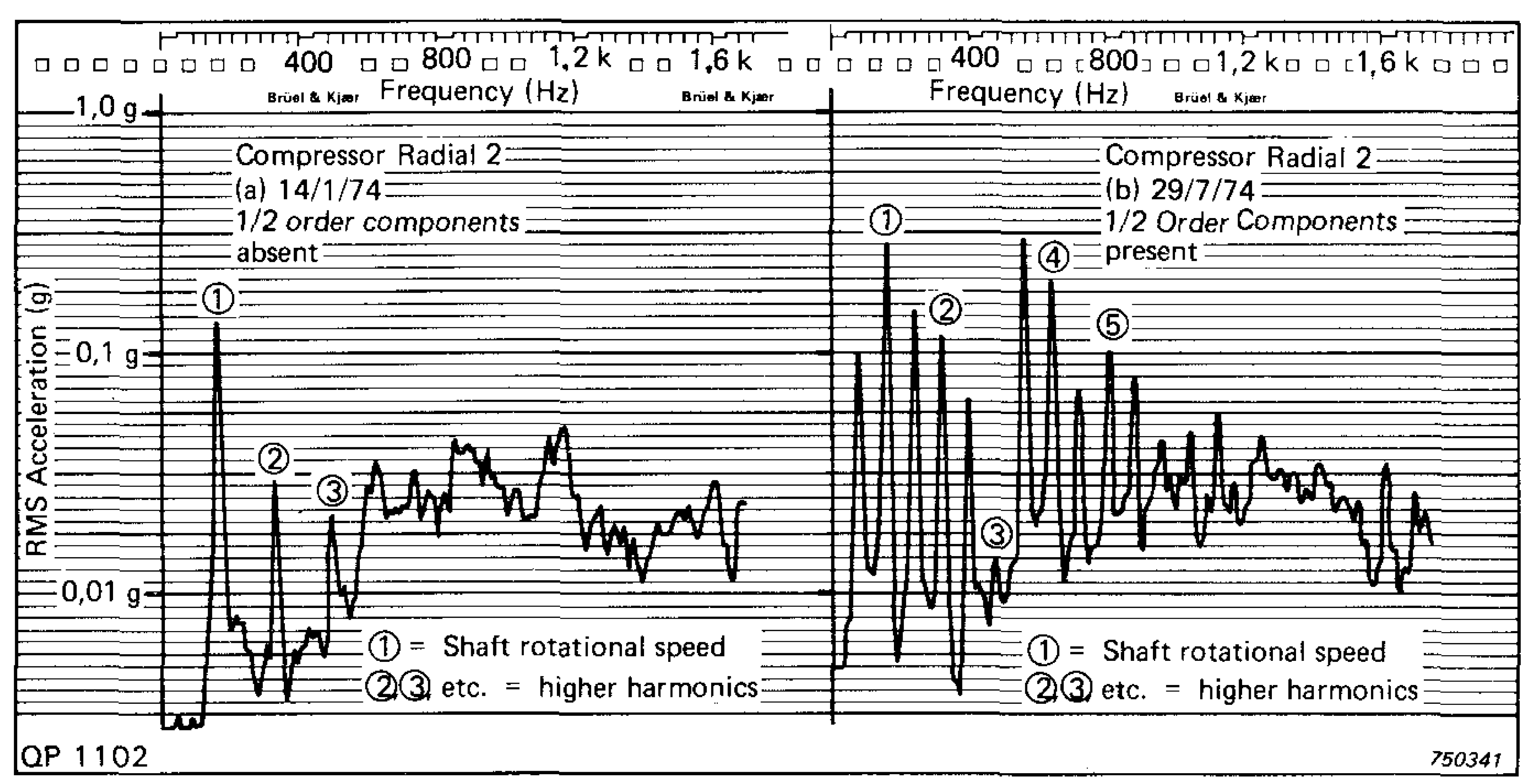


Fig.9. Inter-harmonic components resulting from insufficiently tight assembly of bearing components

Statistical Calculations

The calculator will be found very useful for making statistical calculations. For example, in deciding on the significance of a particular change from the standard condition, it is useful to be able to judge it in relation to the standard deviation of variations in the normal condition, and this sort of statistical calculation can be performed in the calculator. Another such method is trend analysis, to assist in making prognoses as to the most likely time of failure. Yet other calculations can be made on the raw time signal (which is also available from the analyzer) e.g. probability distributions and signal eduction by synchronous averaging.

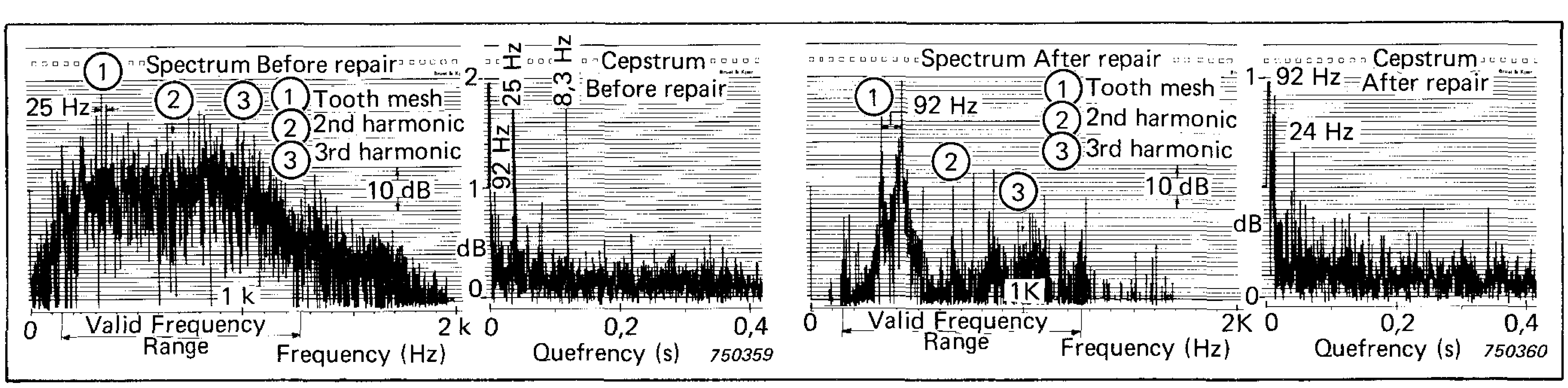


Fig.10. Spectra and cepstra from gearbox vibration signal before and after repair

Data Presentation

Addition of a digital plotter gives the possibility of making the following 3-dimensional plots, which can be useful in some cases:

1) Frequency spectra vs. time — These can either show the variation within the process cycle of a slow-speed reciprocating machine (see Ref.18) or the changes from month to month at the same measurement point (e.g. Fig.8).

2) Frequency spectra vs. RPM — This enables the separation to be easily made between harmonics (radial lines) and resonances (vertical lines) when several spectra are taken at equal intervals of machine speed during a run-up or rundown. Speed ranges to be avoided can also be determined most easily by this method.

Data Treatment and Storage

One of the major advantages of the analyzer/calculator combination is the efficient way in which large quantities of data can be handled and stored, eliminating the need for files filled with paper. A typical cassette could accommodate reference data from several hundred measurement points, and to cover a larger number it is only necessary to change the cassette. The processing time for each signal is about 30 s of which about 20 s is required measurement time. For maximum speed, the signals should be processed in the same order that the reference files are recorded on the cassette, which means that the regular tape recordings should always be made in the same order. The easiest way to achieve this is to use printed data sheets which are filled in by the operator making the recordings in the field. Most data would be permanently printed, and only variable factors, such as scaling factors during recording would be filled in manually, and entered into the calculator during the subsequent processing.

B & K can supply a software package for a limited number of calculators, for performing conversion to constant percentage bandwidth, automatic spectrum comparison, cepstrum analysis etc. Conversion of the software for other calculators (having the IEC/IEEE interface) is a relatively simple matter. One of the advantages of modern desktop calculators is that the high-level languages used to program them are simple to learn, and thus a user can easily modify the standard software to suit his own purposes.

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Brüel & Kjær
DK-2850 NÆRUM, DENMARK
Telephone: + 45 2 80 05 00
TELEX: 37316 bruka dk