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Vibration Signature Analysis — Techniques and Instrument Systems

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VIBRATION SIGNATURE ANALYSIS – TECHNIQUES AND INSTRUMENT SYSTEMS

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Vibration signals measured at the external surfaces of a machine contain a great deal of information as to the internal processes and a number of monitoring and analysis techniques can be applied to extract information from these signals.

This paper discusses the area of applicability of the various techniques, which fall into three main categories:

(i) Field measurement with portable instruments.
(ii) Field recording followed by detailed analysis.
(iii) Permanent on-line monitoring.

Principles for the selection of suitable instrumentation and data processing systems are discussed, with respect to the types of information which can be extracted, the degree of complexity of the machine, and the amount of data to be handled.

The most important analysis technique is narrow band spectral analysis, and this can be carried out by normal swept-frequency techniques, high-speed swept frequency techniques or real-time analysis techniques. Where required, the spectrum can be obtained in digital form from analogue analyzers or by direct digital analysis. Other useful techniques include time domain averaging and cepstrum analysis.

Practical cases associated with machine health monitoring in a number of chemical plants are included as illustrations and a comprehensive bibliography is given in the paper.

It is a well-known fact that an experienced mechanic can detect by ear the development of many faults in for example an automobile engine, to the extent that the sound "signatures" of many such faults have acquired standard names: "piston slap", "bearing knock", "pinging" etc.

The concept of "vibration signature analysis" is in principle very similar: machines in good condition generally tend to have a fairly stable vibration pattern, which can be considered as a "signature". Changes in the internal conditions are often reflected by changes in the vibration pattern which can then be detected by externally mounted pick-ups while the machine is in operation.

The ability to monitor the condition of machines while in operation is very useful in preventive or "predictive" maintenance of continuously operating plant such as in the power generating and chemical industries, but the technique could also be of considerable use in machine development. The present paper is a general discussion of the many measurement and analysis techniques which have been and can be applied in "vibration signature analysis". The emphasis is laid on vibration rather than sound measurement because in the majority of cases this can be used to eliminate the further transmission process from the machine surface to the microphone. Furthermore, most of the information will be present in the vibration signals measured at the bearings, since it is here that most of the dynamic forces are transmitted from the moving parts to the housing. ("Bearings" are taken to include sliding bearings such as cylinder walls in reciprocating machines).

The three main ways in which vibration measurement and analysis can be used for machine monitoring are:

(i) Field Measurement with portable equipment.
(ii) Detailed laboratory analysis usually involving tape recording in the field.
(iii) Continuous monitoring with permanently installed pick-ups.

Before going into each of them in detail, it is as well to give a general indication of their areas of applicability and thus to put them in perspective.

Portable measuring instruments have the advantages of being relatively inexpensive and simple to operate and although they are limited to the measurement of overall vibration level or perhaps selective measurements at a few individual frequencies, this is adequate for the vast number of simple machines on most plants, eg. motors, pumps, fans etc.

The signals from more complex machines such as gearboxes, turbines, compressors and reciprocating machines will generally require more sophisticated analysis, at least to realise the full detective and diagnostic power which vibration monitoring can offer. This will mostly be justified with the more valuable and critical machines in the continuous process industries, where there are considerable benefits to be gained from more advance knowledge of impending failure and a better indication of its nature so that shutdown time can be minimized.

Finally, continuous monitoring will find application with the most critical machines, to guard against rapidly deteriorating situations and allow shutdown before catastrophic failure occurs. It is also useful for guarding against unstable areas of operation such as critical shaft speeds and oil whip in journal bearings.

Intermittent detailed analysis can often be used to advantage to supplement continuous monitoring on the same machine, the former giving more information about normal wear processes and the latter giving protection against sudden failure. In fact, in some industries it will be beneficial to employ all three types of vibration monitoring in parallel in the same plant.

TRANSDUCERS AND PREAMPLIFIERS.

Regardless of the further processing of the vibration signal, it has first to be converted to an electrical signal by a suitable transducer. Three types of transducers are currently in common use, which measure acceleration, velocity and relative displacement respectively.

For measurement of absolute motion, acceleration transducers, known as "accelerometers", are to be preferred for the following reasons.

(i) They have a very wide frequency range and dynamic range.
(ii) They have small mass and physical dimensions.
(iii) They are very rugged, and have no moving parts.
(iv) The acceleration signal can easily be integrated electronically to obtain a signal proportional to velocity or displacement, whereas the inverse process of differentiation is of dubious validity.

Velocity transducers were the first to be developed but have now been superseded by accelerometers in virtually all respects.

Relative displacement transducers are quite commonly built into large machines, but are primarily useful in cases where for example maintenance of working clearances is of greatest importance (1) and their use for signature analysis is limited by the frequency restriction inherent in displacement measurement.

Accelerometers have a high internal impedance, but this problem is now easily solved by using transistorized preamplifiers which convert from a high to a low impedance and which at the same time can be used for signal conditioning such as amplification and integration. Two types of preamplifiers are in use, "voltage preamplifiers" and "charge preamplifiers". The latter, though more expensive, are normally to be preferred as they give an output voltage which is independent of the cable length from the accelerometer. For further information see Ref. (2).

PORTABLE INSTRUMENTS.

When monitoring with portable instruments, it is desirable to simplify the operation as much as possible so that it can be carried out by people with a minimum of training.

It has been found from experience covering many types of rotating machinery that velocity is the best indicator of vibration severity over a wide frequency range. One explanation of this is that constant RMS velocity represents constant vibrational energy ie. components at different frequencies are weighted according to their energy levels. A common method of determining the vibration severity of a machine therefore, and one embodied in several standards((3), (4), (5)), is to measure the RMS value of the velocity over a wide frequency band (e.g. 10 - 1000 Hz) in order to include the effects of a large number of possible sources, and cater for a wide range of machines operating at different speeds.

These standards, in addition to specifying the method of measurement, also give recommended criterion levels, as illustrated in Fig.1. One must be careful not to give these absolute levels too much weight, however, since they are derived as averages over large numbers of machines and do not necessarily apply to any particular one. Reference (1), for example, describes how measurements of mechanical impedance at the bearing housings of a number of machines in the same class revealed a very wide range (>10:1) indicating that the forces resulting in a given velocity level would also vary over this range.

Another approach is to use the vibration level when the machine is known to be in good condition as a standard and take departures from this as the criterion of deterioration. The standard criteria (eg. Fig. 1) are still useful as a guide here, since the separation between the different grades there is 8 dB, and an increase of 20 dB is sufficient to change the classification from "Good" to "Inadmissible".

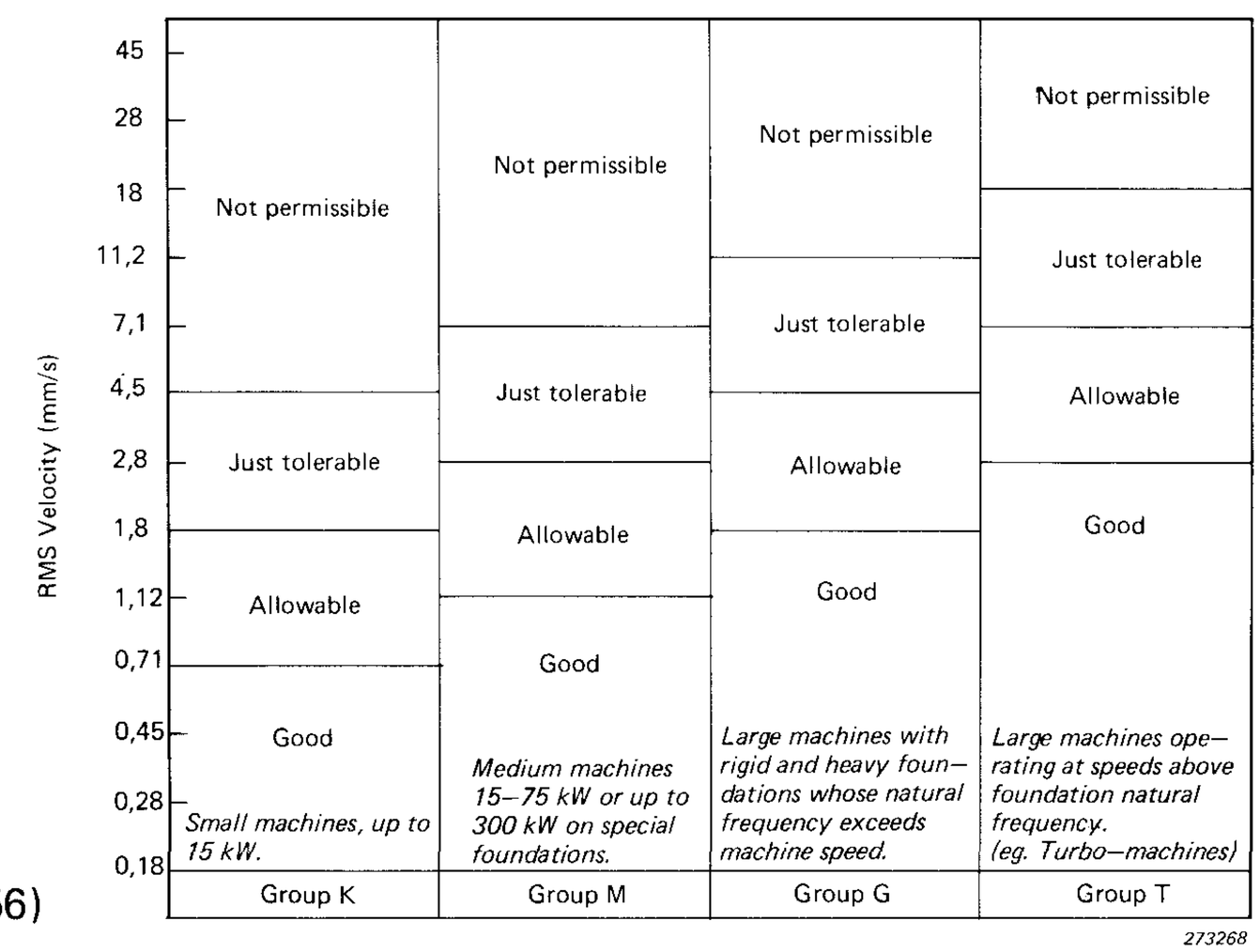


Fig. 1 Vibration Criterion Chart (VDI 2056)

Frequency Analysis

It is also possible to do some frequency analysis using portable equipment, and this is useful for two reasons:

(i) A rise in overall RMS level will indicate that something has changed internally but not give any information as to the cause. Frequency information can often indicate the source of a change as discussed under "Detailed Analysis".

(ii) Changes in minor spectral components, which may be the first indication of incipient failure, will not always affect the overall RMS level, but can be picked up by spectrum monitoring.

The two requirements are to some extent in conflict, since the first requires a narrow band resolution which would result in too many readings if it were desired to cover the complete spectrum for the second purpose. In practice therefore, some compromise must be made, with emphasis on one or the other factor.

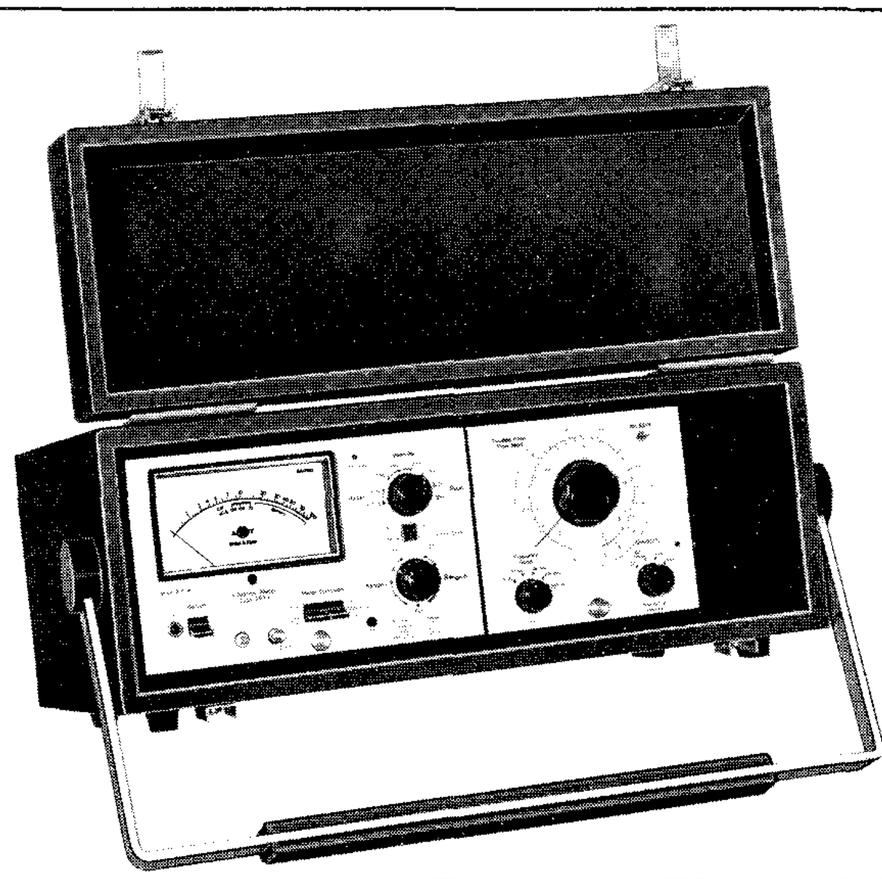


Fig. 2 Portable Vibration Set

A suitable portable battery-operated vibration monitoring set is illustrated in Fig. 2, housed in a rugged carrying case. It consists of a vibration meter with inbuilt charge preamplifier, capable of measuring RMS velocity according to the above-mentioned standards, but also acceleration and displacement. In addition there is a tunable narrow-band filter with bandwidths of 7% and 15%. With respect to the filter, it should be mentioned that bandwidth is not the only factor determining the resolution capability. The steepness of the filter characteristic outside the passband, as indicated by the "shape factor" or "Octave selectivity", is also very important.

Alternatively, some people prefer to monitor over a frequency range of 3 decades or so (6), so as not to miss changes which could occur at any frequency. Where the results from a large number of machines have to be noted down manually, it is not practicable to do this in bandwidths less than one octave. For this case a standard sound level meter with octave band filter set can be used, particularly if it has an integrator allowing measurement of velocity and displacement. The fact that the sound level meter is very useful in its own right will often influence this choice. Use of a 1/3-octave filter set represents a mid-way compromise.

DETAILED ANALYSIS

Using a portable tape recorder it is possible to bring the vibration signals into the laboratory where more detailed analysis can be carried out on them. The laboratory instruments are sometimes taken on-plant or to a control room to which the signals are led by long cables, and this may be suitable for individual measurements but it is not practicable for a regular monitoring scheme.

Tape Recording and Playback

The tape recording is an important part of the procedure, so it is worth discussing it in some detail. Firstly, the tape recorder itself should be chosen with care. Two recording principles are in common use viz. Direct Recording (DR) and Frequency Modulation (FM). Their relative merits are listed in Table 1.

	DR	FM
Dynamic Range (narrow band - typical)	70 dB	60 dB
Lower Frequency Limit	2.5 Hz*	DC
Upper Frequency Limit (typical)	50 kHz	10 kHz
Amplitude Stability	acceptable	excellent
Phase Linearity	poor	good
Preservation of Recorded Information	acceptable	good

*Playback speed 10x recording speed.

Table 1. Comparison of DR and FM recording techniques.

Perhaps the best compromise is a recorder with two channels FM (for most measurements) and two channels DR (for frequencies >10 kHz). It should of course be portable and battery-operated.

Since the tape recorder is likely to be the most limiting factor in determining the dynamic range of the system, it is wise to choose that parameter for recording (acceleration or velocity) which has the flattest spectrum, regardless of which is to be used for final evaluation. Conversion between the parameters is of course straight forward once a narrow band spectral analysis has been carried out.

There are several possibilities for playback of the signals for analysis:

(i) Continuous playback from the original tape reel. This will require unreasonably long recording times where analysis time is long.

(ii) Make up loops by cutting up the original tape reel. This is impractical for large numbers of signals.

(iii) Record directly on loop cassettes in the field. Also impractical for large numbers of signals.

(iv) Record over from the original tape reel to another recorder with permanently mounted tape loop for analysis. Requires two recorders.

In all cases where analysis is made from a tape loop, it may be found desirable to use a special weighting function to eliminate the effects of the tape splice (8, 9).

A better solution than (iv) would generally be to use a Digital Event Recorder in place of the second tape recorder since this eliminates the noise of the splice as such and allows a considerable reduction of analysis time by frequency transformation (9), as discussed later.

Spectral Analysis

The most usual analysis performed on the signals will be spectral analysis for the reasons already given, and in the laboratory it is possible to perform relatively narrow band analysis over the whole frequency range. It has been found that for many machines, the vibration power spectrum is very stable from time to time and even between different machines of the same type. This is the basis of a scheme developed by the U.S. Navy for onboard maintenance, and reported in Ref. (7). Shutdowns were based on departures from the envelope of standard signatures (Fig. 3) and the method was found to be justified by a statistical study of a large number of cases.

The question arises, however, as to the best way of presenting the results of such an analysis, and once again there is a conflict between covering a wide frequency range and requiring a fine resolution for diagnostic purposes.

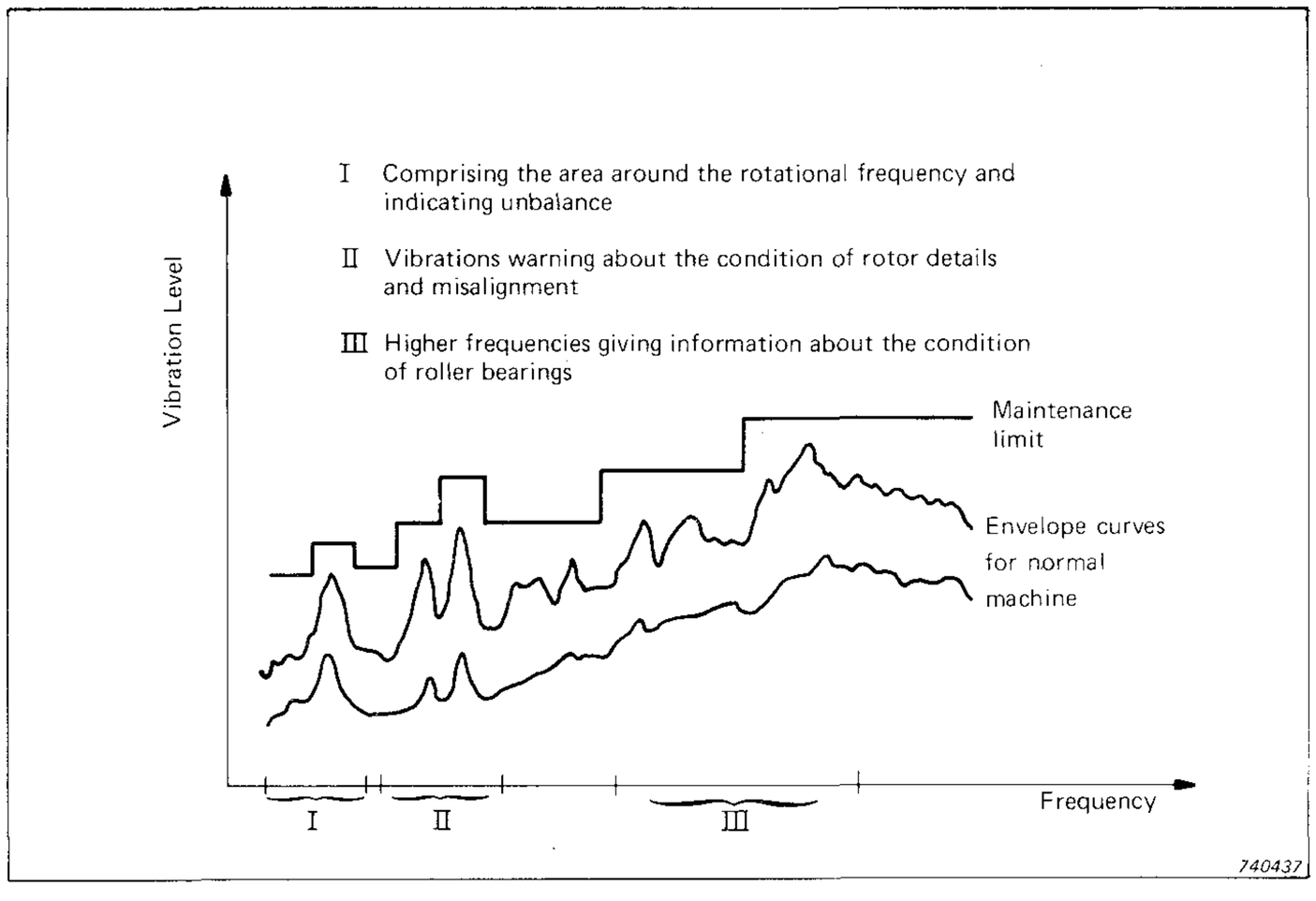


Fig. 3 Vibration Spectrum Envelopes

To cover a wide frequency range it is natural to use a logarithmic frequency scale, and then use of a constant percentage bandwidth (which gives uniform resolution) is almost unavoidable. Other reasons for using a logarithmic frequency scale (though not necessarily constant percentage bandwidth) are:

(i) Small changes in machine speed from time to time will only cause a lateral shift in the spectrum thus simplifying comparison.
(ii) Some relationships can most easily be seen in a log-log representation.

On the other hand if the signal being analyzed has a high harmonic content (e.g. gearbox vibrations) then it can be an advantage to obtain the analysis on a linear frequency scale with constant bandwidth which gives uniform resolution and equal separation of the harmonics. This point is discussed further under "Cepstrum Analysis".

The answer perhaps lies in using (approximately) constant percentage bandwidth analysis on a logarithmic frequency scale for detection of change, and constant bandwidth on a linear frequency scale for detailed diagnosis of changes. The same analyzer can perform both functions if its "constant" bandwidth can be made to step up automatically with increasing frequency, and if it has both linear and logarithmic frequency sweeps.

Analysis Methods

There are three main ways in which the power spectrum can be obtained:

(i) Using a narrow band sweep frequency analyzer (constant or constant percentage bandwidth). Analysis time typically 10 to 60 min. (See Ref. (10) for details).

(ii) High speed analysis using the same equipment as in (i) but with the addition of a Digital Event Recorder with which large speed transformations can be made on playback, thus increasing analysis speed considerably (9). Fig. 4 shows a typical instrument setup. Analysis time typically ½ to 3 min.

(iii) Real-time analysis using either the time compression principle (similar to (ii) or Fast Fourier Transform (FFT) techniques, and where the spectrum is continuously displayed on a screen. Fig. 5 shows a 400 line time compression analyzer.

Method (i) is only practicable where not many analyses have to be made, but it is worth examining the relative merits of (ii) and (iii), which are discussed in some depth below:

High Speed Analysis (ii) is somewhat cheaper in instrument cost than real time analyzers, typically ½ the cost of a Time Compression Analyzer and 1/4 the cost of an FFT analyzer. The saving is considerably more for people who already have the basic analysis system (i). It is also somewhat more flexible, the same setup offering both constant and approx. constant percentage bandwidth, log and linear frequency scales, and variable resolution up to the equivalent of 2500 lines. It can also be an advantage to be able to use the individual instruments separately; eg. the Digital Event Recorder has a multitude of other uses, and on the few occasions where 2500 line resolution is not adequate it is still possible to revert to a normal analysis setup to obtain any desired degree of resolution.

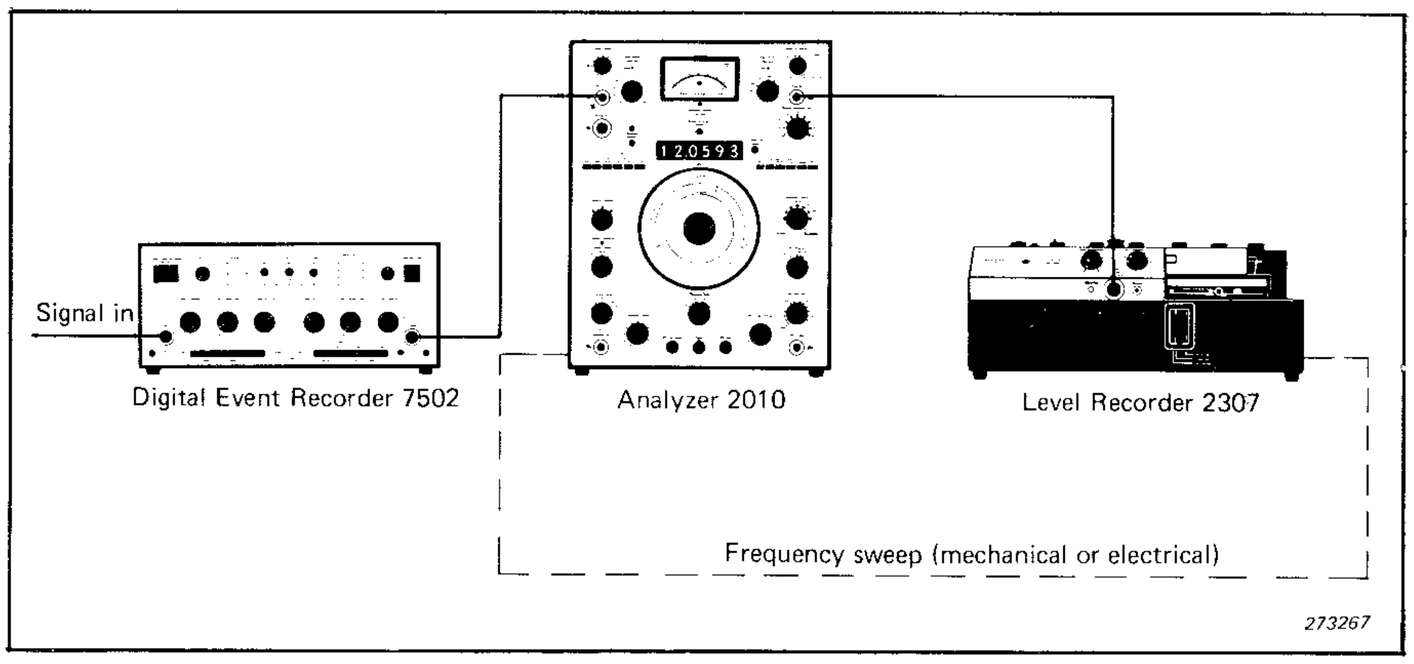


Fig. 4 Instrument Set-up for High Speed Analysis

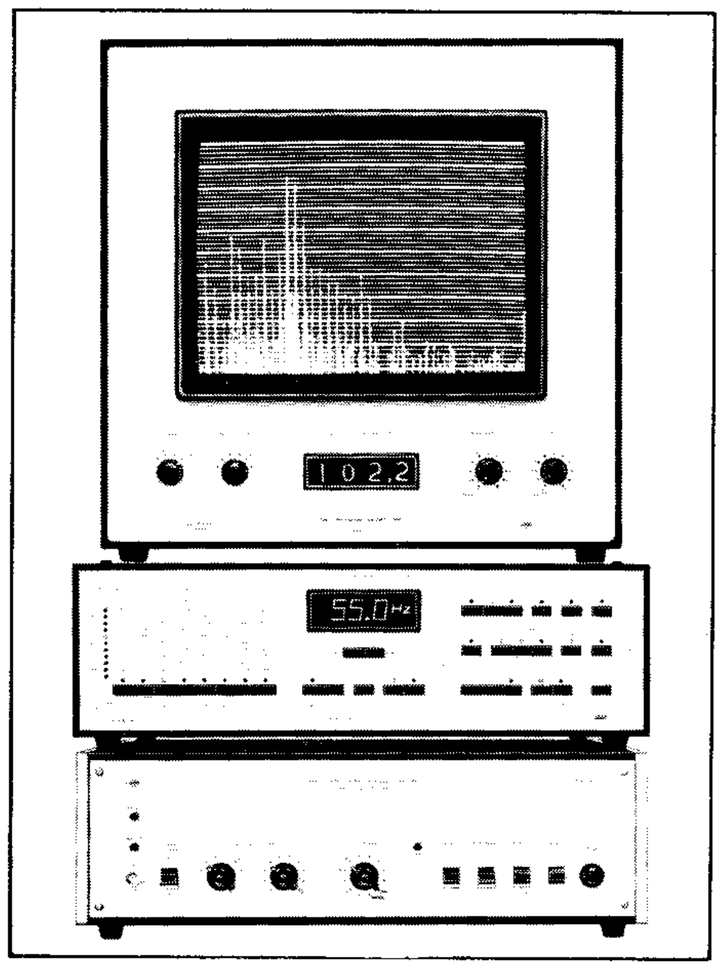


Fig. 5 Time Compression Analyzer

The same flexibility can be obtained with a real-time analyzer in combination with a general purpose computer, but this is of course even more expensive.

Real-Time Analysis (iii) has the principal advantage of being real-time, thus allowing the effects of changing conditions to be observed as they occur. In some cases, a transient phenomenon contains most information about the occurrence of damage, eg. turbine blade failure (11).

The use of digital averaging of a number of successive spectra to give adequate statistical reliability in the case of random signals can also be a considerable advantage in some cases. With the method (ii) the statistical reliability can only be improved by increasing bandwidth, but even so a 250 line (bandwidth) spectrum can be achieved with an RMS deviation $<1\frac{1}{2}$ dB. (BT product 10).

FFT analyzers have the additional advantage of being able to calculate cross correlations, cross spectra, transfer functions etc. thus providing considerable additional diagnostic power. (12).

Spectrum Diagnosis

The frequency at which a change in the spectrum occurs gives very important information as to the likely source, which is often related for example to the running speed.

The types of faults which can be detected and perhaps diagnosed from a frequency analysis (see also (1), (6), (7), (11), (13), (14), (15)) include unbalance (at shaft speed, primarily radial), misalignment and bent shafts (shaft speed and low harmonics, radial and axial), oil whip (just less than half shaft speed) and developing turbulence (blade and vane passing frequencies). Changes in natural frequencies can indicate crack growth or build-up of fouling. Local faults in rolling element bearings manifest themselves at frequencies corresponding to the rates of impact of the fault but also at higher frequencies (typically 20 - 60 kHz) corresponding to component natural frequencies (16, 13). Fig. 6 (from Ref. (16))shows the effect of induced pitting in an inner race.

Growth of sidebands indicates modulation at frequencies corresponding to the sideband spacings. This can for example indicate faults which cause modulation of the tooth meshing pattern in a gearbox (see later example). As another example, blade natural frequencies tend to frequency modulate the corresponding blade passing frequencies, providing another means of detecting these natural frequencies.

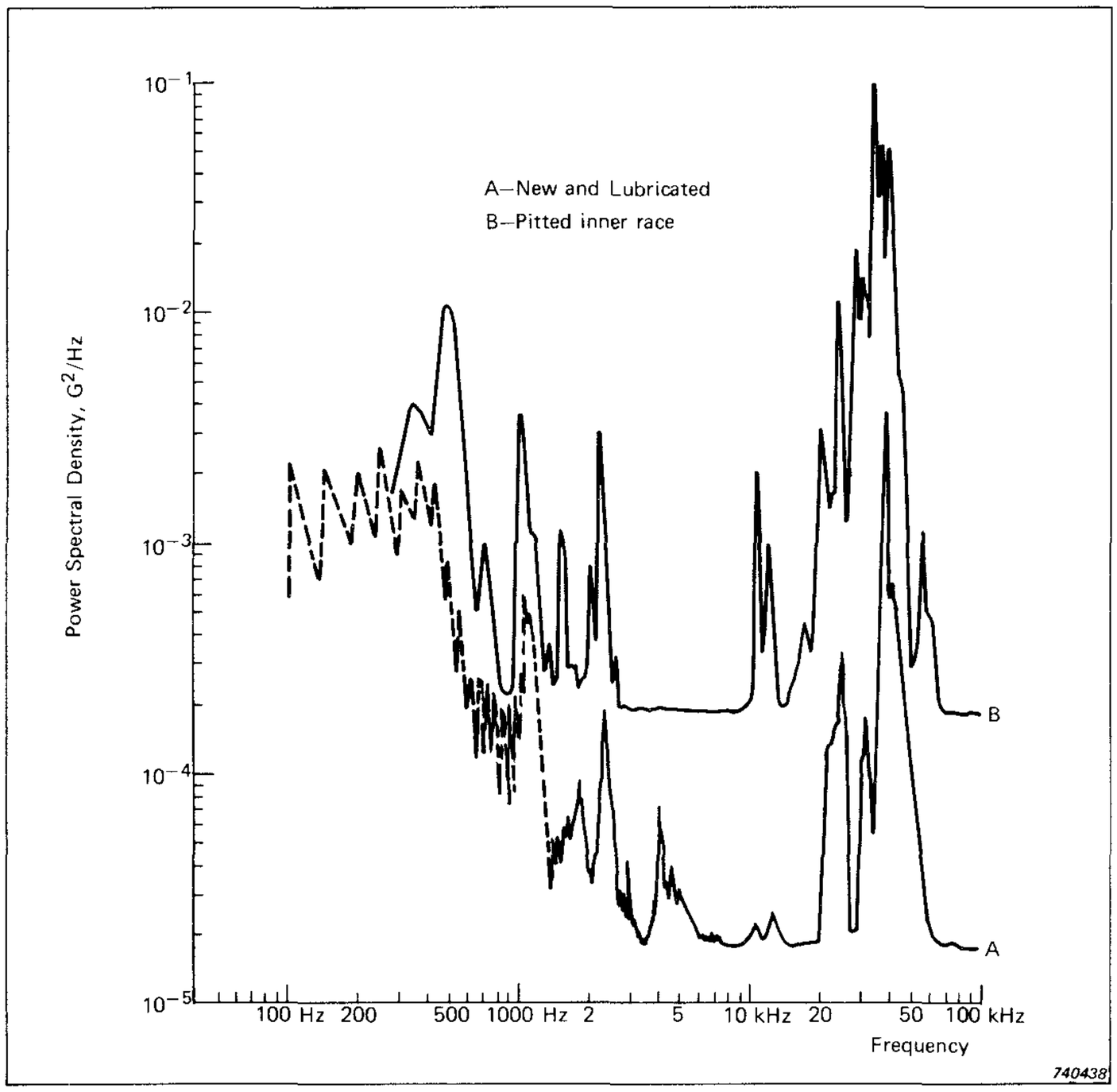


Fig. 6 Ball Bearing Vibration Spectra (Ref. 16)

Cepstrum Analysis

Since in a complex spectrum it may still be difficult to see the growth of sidebands by eye, and in particular to judge the relative importance of various modulating frequencies, this provides an application for "Cepstrum Analysis". In simple terms this is a method for detection of periodic components in a spectrum (eg. harmonics, sidebands) and consists in carrying out a frequency analysis of the (logarithmic or dB) power spectrum itself. The spectrum must be on a linear frequency scale with constant bandwidth. Reference (18) contains a detailed discussion of the basic concepts, methods of obtaining the cepstrum, and the application to gearbox fault diagnosis. Fig. 7 shows how the instruments from Fig. 4 can be used, while numerical (FFT) computation in a general purpose computer can alternatively be used (18).

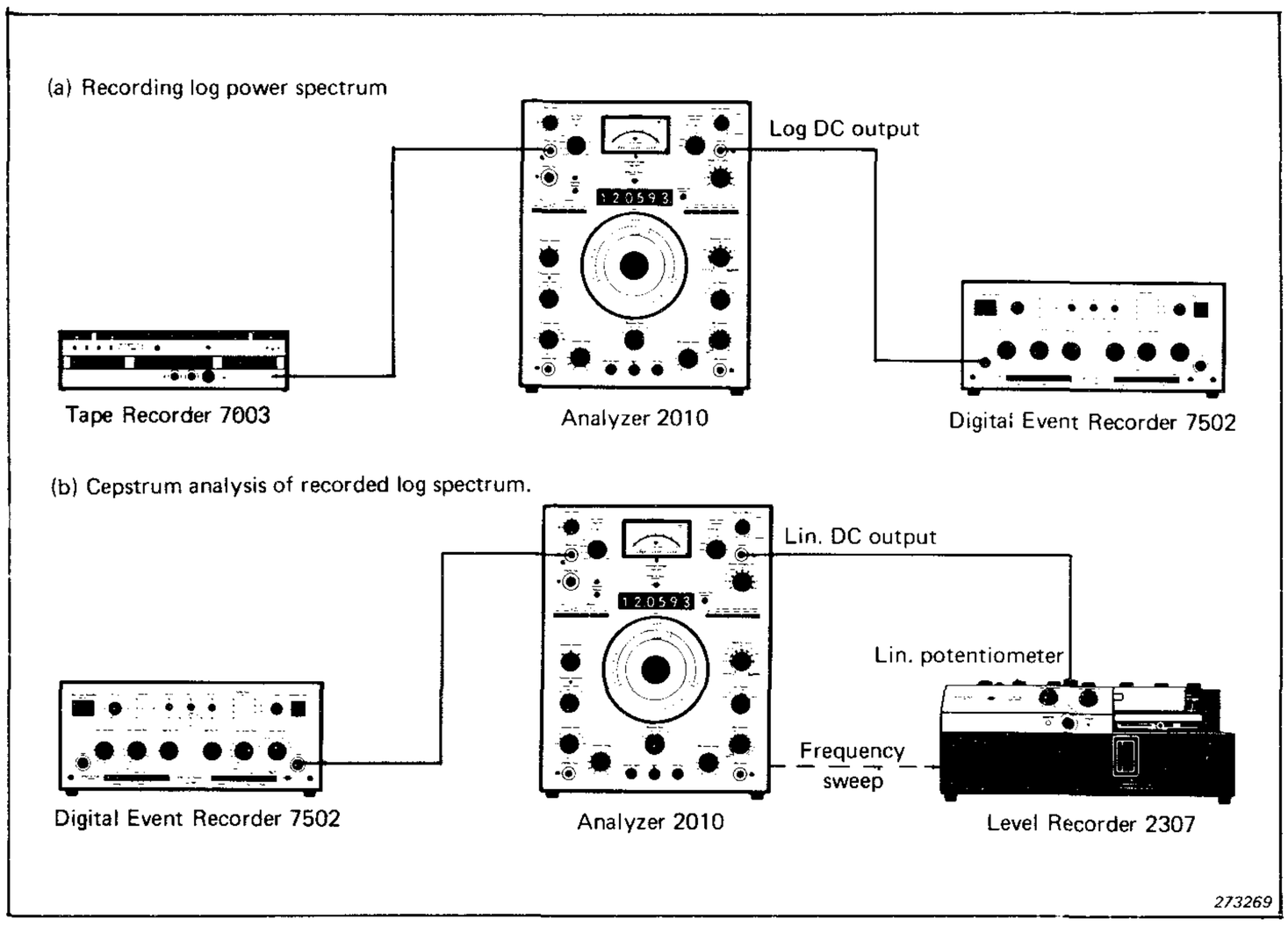


Fig. 7 Instrument Set-ups for Cepstrum Analysis

Example

The following example illustrates several of the concepts discussed. The measurements were made on a gearbox (mounted between a gas turbine and a generator) immediately prior to and shortly after a maintenance shutdown. The gearbox was primarily shut down to replace the internals, since fretting between the gearwheels and the shaft had been detected during an inspection 6 months earlier. The vibration signals before overhaul had also indicated misalignment, which was confirmed and corrected during the shutdown.

Fig. 8 shows 3% bandwidth analyses of the two signals compared as velocity, and it can be seen that the realignment has improved the VDI 2056 classification from "Just tolerable/Not permissible" to "Allowable", the overall RMS velocity being dominated by the components at the two shaft speeds (50 and 85 Hz).

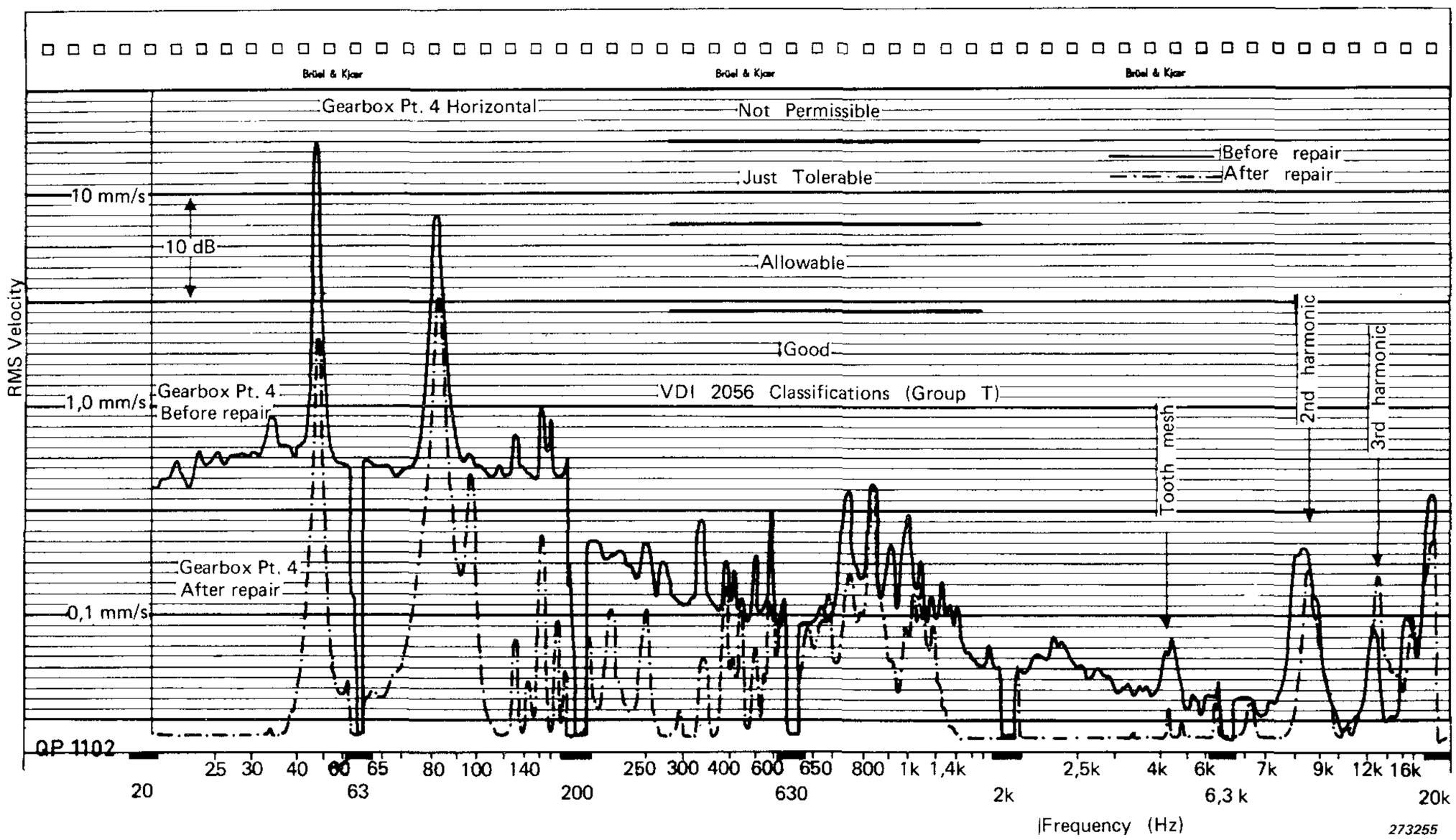


Fig. 8 3% Bandwidth Gearbox Vibration Spectra

It should be noted that the first signal "Before repair" was recorded as acceleration and integrated to velocity on playback. The noise level of the tape recording can clearly be seen, confirming that it is best to record the parameter with the flattest spectrum.

Another point of interest is that at the tooth meshing frequency and its harmonics it is difficult to determine from these 3% spectra that a significant change has occurred. The third harmonic has even risen in level slightly after repair. Fig. 9 shows constant bandwidth analyses of the same two signals on a linear frequency scale (this time as recorded since the overall slope of the spectrum is of secondary importance). The presence of sidebands around the tooth meshing frequency and its harmonics is now much more in evidence in the signal taken "Before repair", whereas the three harmonics stand out clearly "After repair". Fig. 10 shows cepstra corresponding to the spectra in Fig. 9 and this shows up the difference even more clearly and at the same time confirms that virtually all the modulation is occurring at the speed of the high-speed shaft (85 Hz).

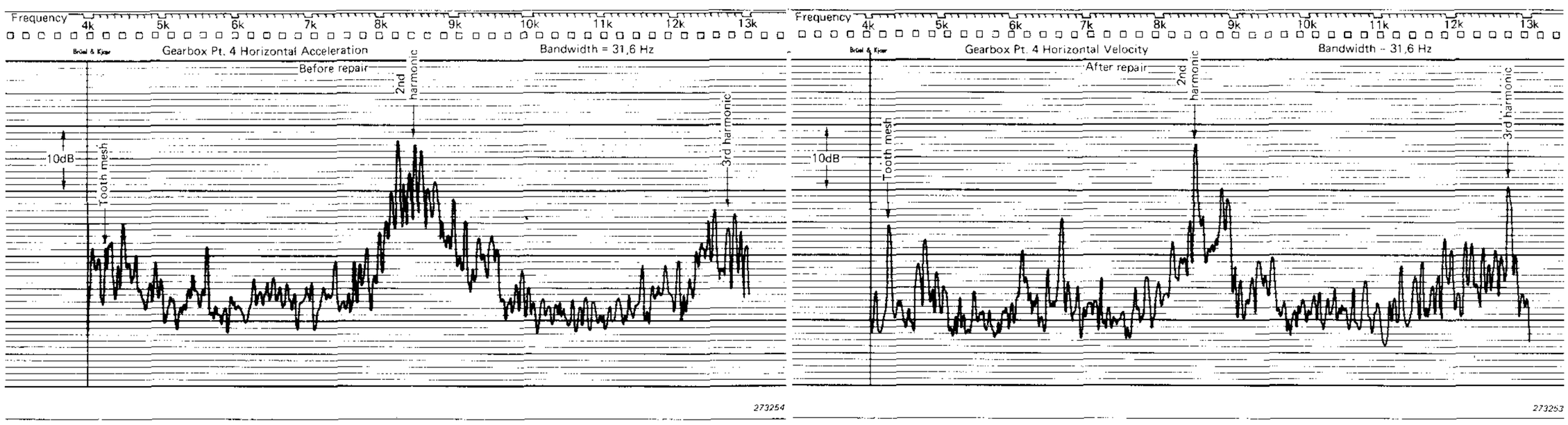


Fig. 9 Constant Bandwidth Gearbox Vibration Spectra

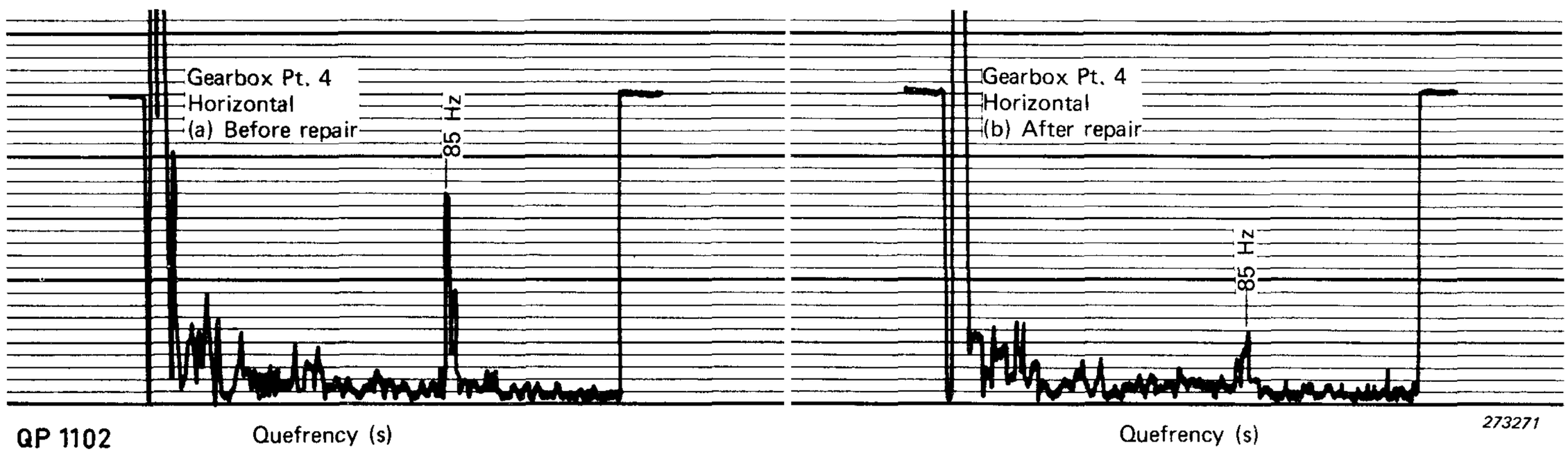
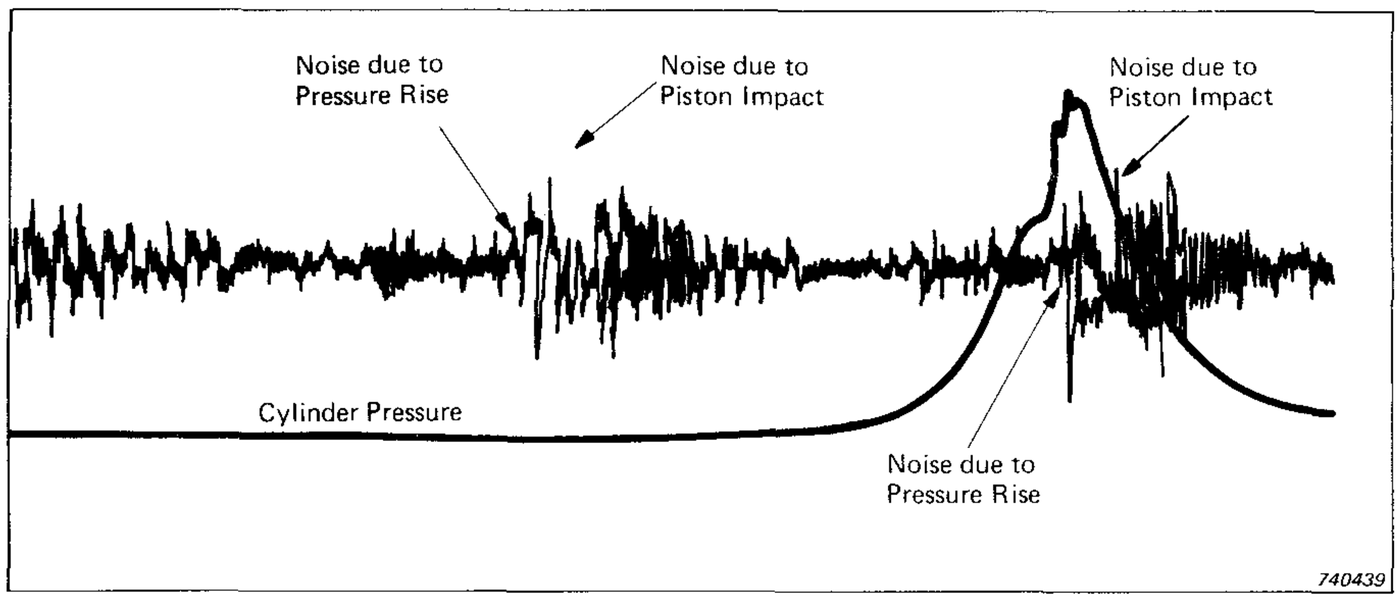


Fig. 10 Cepstra corresponding to Fig. 9

Time Domain Analysis

Spectral analysis, though very powerful, does not appear to be a universally applicable tool. For example, in the paper by Priede & Grover from Ref. (15) it is mentioned that with reciprocating machines, and in particular diesel engines, the vibration exciting forces tend to be impulsive in nature, thereby exciting the natural frequencies of the engine structure. Faults are therefore more likely to show up as changes in the various parts of the time signal rather than as a change in the spectrum (Fig. 11). The time signal also contains information on individual components (eg. particular gear teeth) which is averaged out in the frequency spectrum (13). A technique which can be useful in cases such as these is to overlay digitally the vibration signals from many machine cycles, triggering at the same point each time, and thus enhancing the regularly repeating phenomena with respect to random fluctuations (13, 14).



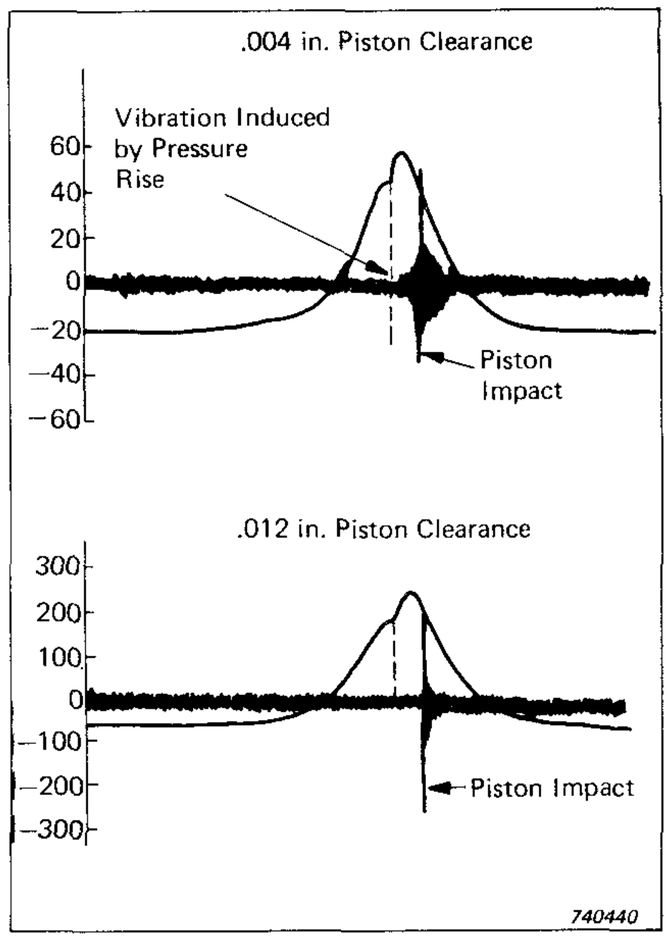


Fig. 11 Diesel Engine Time Signal (Ref. 15)

Data Handling

Where it is desired to monitor a large number of machines, it would be very time consuming to carry out visual comparison of the appropriate vibration characteristics (eg. spectra) and there will be considerable advantage in digital processing of the data. Real-time analyzers normally have the option of a digital output either to a computer or paper tape punch. It is also possible to obtain the spectrum in digital form from the high-speed analysis system shown in Fig. 4 by the addition of a Digital Encoder and Tape Punch (19). The analysis speed is then normally limited by the puncher and is thus as fast as when the output is obtained in this form from a real-time analyzer. One advantage of intermediate storage of data on paper tape is that it can provide a means of interfacing with large computers (eg. via a time-sharing terminal) with stringent requirements on data format. Where possible, however, considerable time can be saved by direct read-in of the data into the computer.

Ref. (19) gives one approach to the problem of programming for automatic spectrum comparison.

Other advantages of digital processing of spectra are:

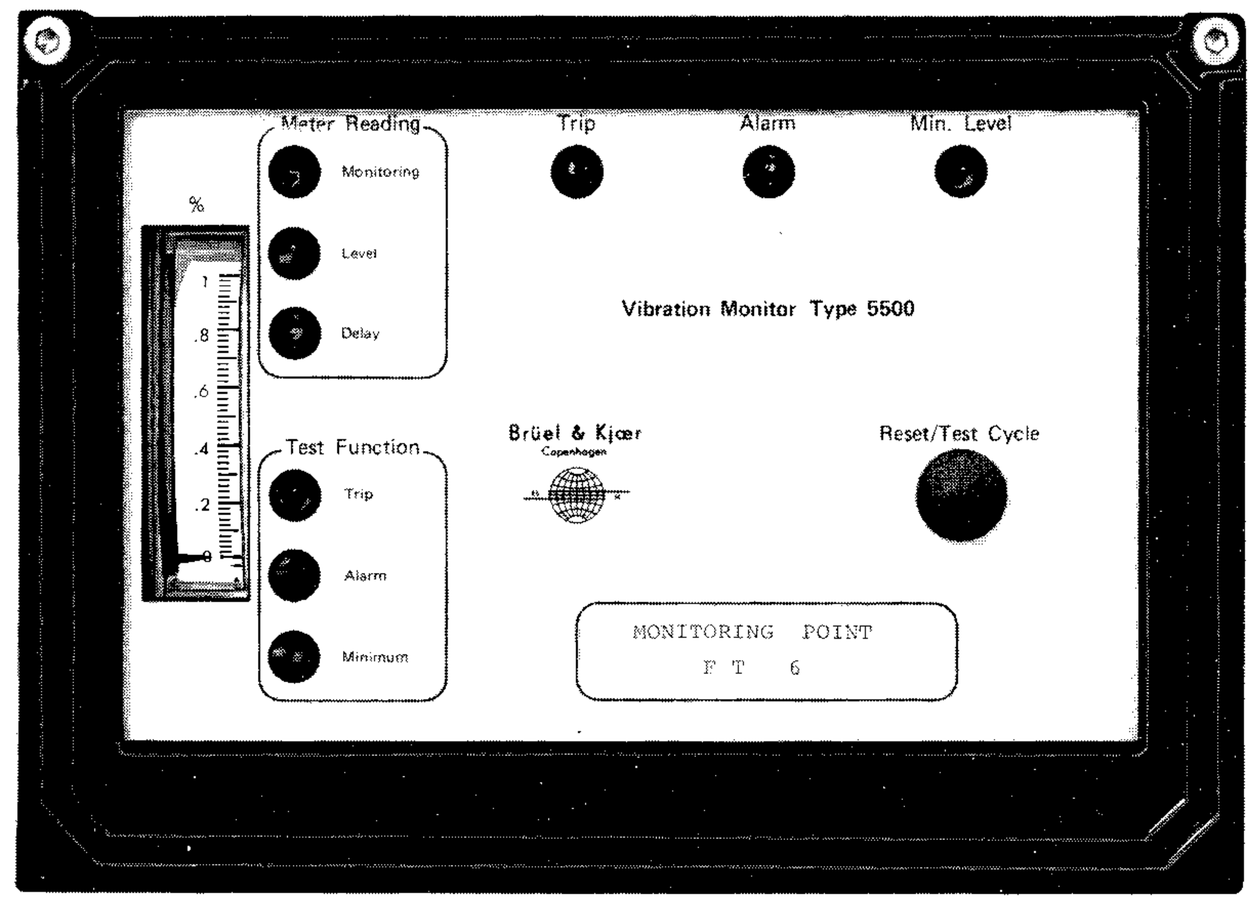
(i) It is possible to carry out statistical analysis and thus obtain more valid information about trends, likelihood of failure etc. (Stewart (14)).
(ii) Cepstra can be calculated by an FFT program, possibly written in a high-level language such as Fortran (18).

It should be mentioned that with a suitable input-output device such as a Digital Event Recorder, a mini-computer with external storage (tape, disk, or drum) can be used to perform spectrum analysis by programmed FFT methods, plus all the other data processing mentioned. The main disadvantages are that programming would normally have to be in assembler language, and that programmed FFT is slow compared with hardware (typically 1 s).

PERMANENT MONITORING

Most permanent monitoring systems monitor a single quantity such as band-limited RMS velocity in the same way as a simple portable meter, and most of the same considerations apply. The main difference lies in the extremely high reliability required, and for example special consideration must be paid to ruggedness of cables, avoidance of noise pickup etc. Care must also be taken that the monitor does not give false alarms as a result of electrical mains transients, external mechanical shocks and suchlike. This can be achieved by requiring that the monitored level is outside the set limit for the whole of a set time delay. It is also desirable for the operator in the event of an alarm to be able to check quickly that the monitor is adjusted and functioning correctly.

Fig. 12 Industrial Vibration Monitor



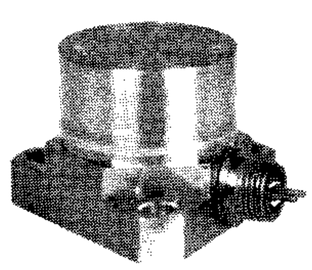


Fig. 12 shows a single channel monitor with many desirable features; a rugged waterproof housing, "Alarm", "Trip" and "Min. level" (indicates damage to pickup or cable) circuits each with time delay. All set levels and time delays can be adjusted (though not externally) and in fact the only external button initiates a checking sequence of the set levels and delays.

Continuous Spectrum Monitoring

For valuable complex machines which are crucial to the operation of a plant, it may be deemed justified to monitor the vibration spectrum continuously, thereby combining the advantages of both permanent monitoring and spectral analysis.

This can virtually only be done with a real-time analyzer, though in this case a 1/3-octave resolution may be considered adequate, if supplemented with a narrow band analysis facility for diagnosis of changes detected in the 1/3-octave spectrum.

Normally, to justify the use of an expensive real-time analyzer, it would have to be used for a number of monitoring points, perhaps several different machines. In this case it would be necessary to multiplex between the various input signals and apply different criteria for the evaluation of each spectrum, something which would almost inevitably require the use of a computer (mini or micro). Introduction of a computer makes the use of a narrow band real-time analyzer feasible (since simple spectrum comparison is unlikely to be satisfactory (19)), and introduces many interesting possibilities. One such possibility envisaged in the foreseeable future is an operation in timesharing mode between fixed and regular calculations on a number of permanently connected channels, and intermittent operator-controlled calculations of various types. These could consist of special calculations (eg. cepstra) on the connected channels, or simple spectrum checking of additional signals recorded intermittently from a number of other machines, and brought to the console on a tape recorder.

CONCLUDING REMARKS

The latter system may seem a little far-fetched, but it could very easily become an economical proposition if it can be proved that incipient failure can be predicted with a high degree of certainty. It is believed that the state of the art is rapidly nearing this point.

Perhaps one of the main inhibiting factors in the past has been the lack of certainty in this respect. Plant operators have understandably been reluctant to invest large sums of money in instruments to determine whether the techniques described herein will work on their machines, and on the other hand the instrument manufacturers have not had much access to operating plant.

It is hoped that this paper indicates how it is possible to build up instrument systems from fairly modest beginnings, as experience is accumulated and the need for more sophistication makes itself apparent. It is also hoped that it (and the references) will help to avoid pitfalls which lead to faulty conclusions and thus can do a great deal of harm.

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