



Reciprocating Machinery Analysis with an FFT Analyser

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Introduction

This application note describes the instrumentation considerations for the use of an FFT analyser with a variable trigger delay, such as the B & K models 2031 and 2033 analysers, for frequency analysis on reciprocating machinery. The use of the analyser's trigger system extend the benefits of FFT analysis to repetitive non-stationary signals.

The note explains how to set the analyser controls to perform this analysis. As the technique covers such a wide variety of applications in terms of variety of machinery the interpretation of results in terms of specific machines is not covered.

FFT based frequency analysers analyse signals in blocks of a length which depends on the frequency range selected. For stationary data, the timing of the analysis is not critical, but unfortunately the signals from reciprocating machines are highly non-stationary. Triggered analysis allows selection of the position in time of the block for analysis in relation to some trigger event. Triggered analysis can also be used to analyse transient phenomena, but this note explains how it also gives the possibility of analysis of the non-stationary but repetitive signals produced by reciprocating machinery.

If a trigger signal on a once per cycle basis is available from a machine, from the viewpoint of the analyser an apparently stationary signal can be obtained corresponding to some part of the machine's cycle (Fig 1). The technique may be used with any signal which repeats in a cyclic fashion, such as reciprocating engines and compressors, process machinery, printing presses and so on, if a suitable trigger signal is available.

It is necessary that the analyser used have a finely variable trigger delay and this is provided on both the models 2031 and 2033, as well as the usual automatic triggering of the averaging process which is necessary for the technique. The 2033 has

a considerably wider range of trigger delay than the 2031.

The advantages of the technique can be seen in the analysis of a part of the operating cycle of a reciprocating engine. Naturally a selected

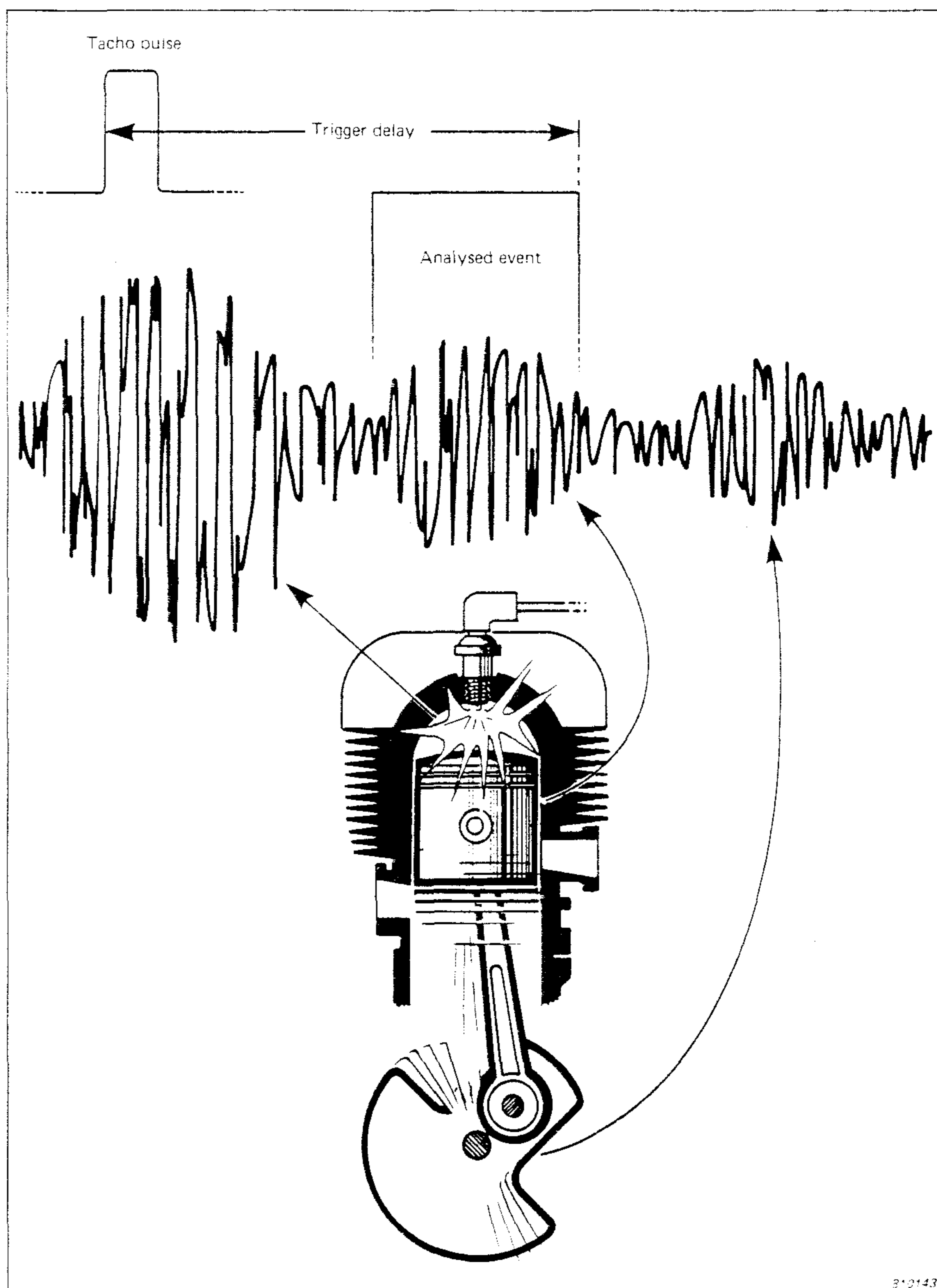


Fig.1. Analysis of an event at a selected time

part of the cycle can be isolated from the others for study, but another advantage of the method is an improvement in signal to noise ratio. Suppose that it is wished to measure changes in vibration level on one of the cylinders of a six cylinder engine, and that the level of vibration at the measurement point used is comparable from all the cylinders. If only a part, say one quarter, of the process associated with this cylinder is of interest, this is about 1 / 24 of the signal available. The other 23 / 24 of the

signal is noise, so a corresponding signal to noise improvement can be obtained over a simple average spectrum for the machine. If, as quite commonly happens, only a relatively weak signal is available from the phenomenon it is wished to analyse, an even greater improvement would be obtained. In a practical situation, with several dB variance on the average spectrum from the machine, it would be virtually impossible to determine from the simple averaged spectrum if a change in level

of an isolated event had occurred.

The note is divided into sections concerned with individual points about the technique. The first sections deal with preliminary considerations - instruments, trigger signals and machinery related considerations. This is followed by the procedure for analyzer set up and the final sections deal with specific details which do not apply to all measurements.

Instrumentation and Implementation

Instrumentation Setup

The instrumentation setup of Fig.2 is typical of that used. Signals for analysis can be derived from a number of transducers, such as accelerometers, microphones, force transducers and so on - the analyser only requires a voltage input. The trigger signals will be dealt with in the next section. While the analog tape recorder offers advantages in extending the range of the analysis, as will be described later, it also offers the great advantages that it provides a permanent record and that the signal can be acquired in the field with battery powered equipment, where noise and general physical conditions often make analysis difficult, and analysed wherever it is practicable.

The analyser can be manually controlled either for single spectra or a series of spectra, and these results recorded on a model 7400 digital tape cassette recorder. The process may also be carried out under control of a programmable calculator or computer, which can then be used for generating useful data presentations, as will be described later.

Trigger Signals

The trigger signal can be derived from any part of the machinery which gives a once per cycle signal at a known time, as the time delay can be readily calculated. If no signal is inherently available suitable pickups include the probes types MM 0002 (magnetic), MM 0004 (ca-

pacitive) and MM 0012 (infra red photo-electric reflective). The latter is simple to use in temporary situations and connects directly to the type 2976 Phase Indicator (old type number 5767), and a minor modification (B & K No. WH 0898) to bring out an internal signal provides a signal suitable for triggering an analyser or recording on tape for later use.

Machinery Considerations

A trigger pulse must be provided from the machine for the analyses. Note that the trigger must be once per cycle, so in a four stroke engine the trigger must be taken at 1/2 engine speed, for example from the camshaft or injection pump. The available timing information is often

in the form of crankshaft angles and r.p.m. and must be converted into delay time and cycle time.

In practice tachometers are not very accurate, and a convenient way of measuring the speed is to measure the cycle time directly off the analyser time domain display from the trigger pulse.

For comparison purposes both the load and speed of the machine should be the same, or some compensation technique developed. Speed variations will cause the relative analysis time to change and may cause phenomena to overlap by differing amounts, and so not be comparable.

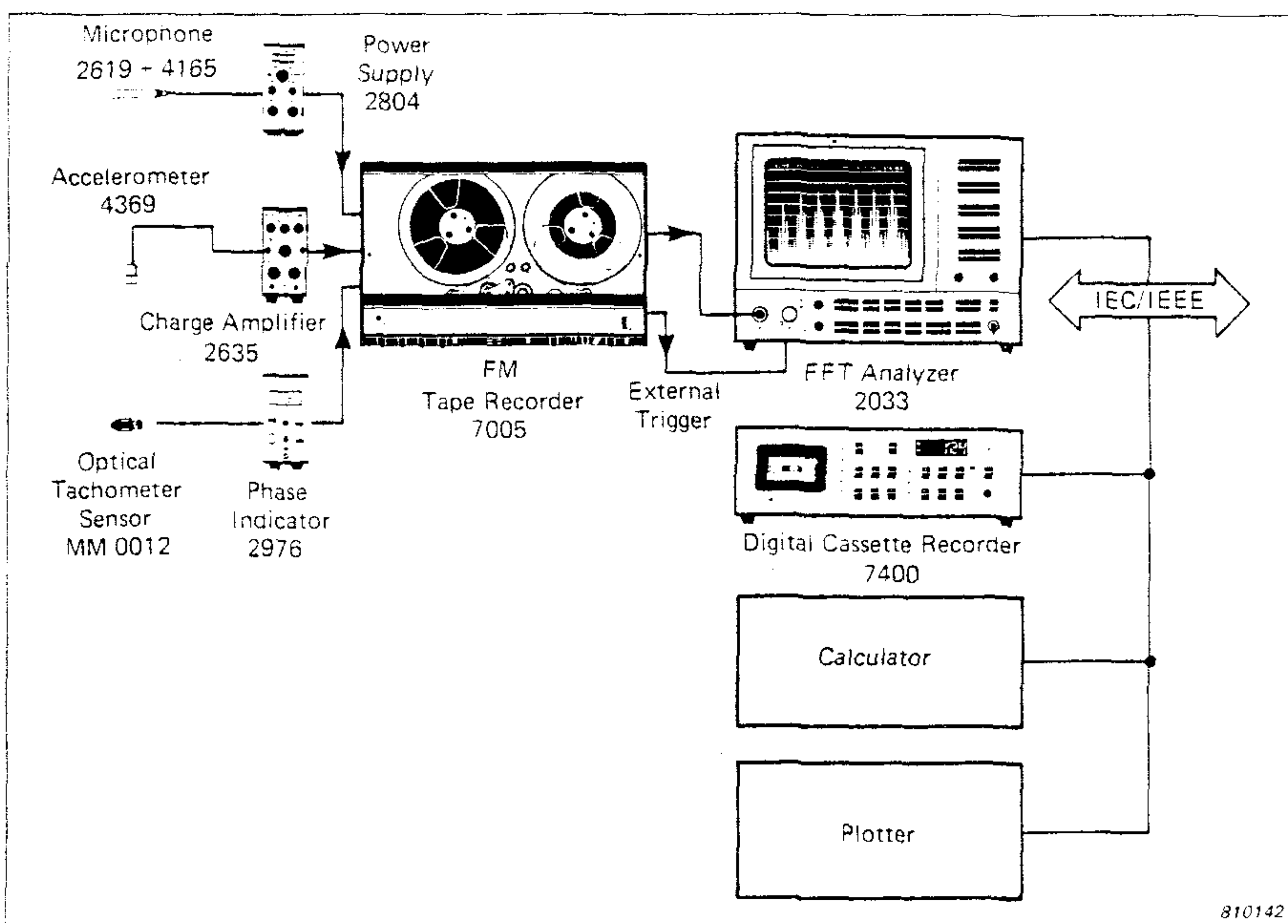


Fig.2. Instrumentation used

Selection Of Analyser Control Settings

The technique is naturally constrained to some extent as to the range of parameters possible. It is a fundamental rule of frequency analysis that the analysis cannot take place at an instant in time, but only over a length of time. It is not possible to arbitrarily select this length of data for analysis, that is the time resolution, as it is related by fundamental limitations to the frequency resolution. The basic requirement in setting the analyser controls is to select the time resolution and full scale frequency to cover the required event, and to obtain the appropriate "K-samples after trigger" (2033) or "Records after trigger" (2031) setting to obtain the analysis centred on a particular time. The way in which each of the data values obtained is located in time and frequency is shown in Fig.3. Examples of the calculation involved for some practical situations are given at the end of this section.

The first choice to be made is the frequency range/analysis time resolution combination for the analyser.

The analysis is normally carried out with a Hanning weighting selected. This gives an effective analysis time or time resolution of 0.4 of the FFT block length, as the data is not given an even weighting along its length. The values of time resolution, actual block length, frequency resolution and full scale frequency available on the 2033 and 2031 are given in Table 1. They are connected by the following relationships:

$$\text{Time resolution} = 0.4 \times T$$

$$\begin{aligned} T &= \text{FFT block length} \\ &= 1 / \text{Frequency resolution} \end{aligned}$$

For baseband:

$$\begin{aligned} \text{Frequency resolution} \\ &= \text{Full scale frequency} / 400 \end{aligned}$$

For zoom:

$$\begin{aligned} \text{Frequency resolution} \\ &= \text{Frequency span} / 4000 \end{aligned}$$

Either the frequency range, and thus frequency resolution, or else the analysis time resolution can be decided on first, but it must be checked

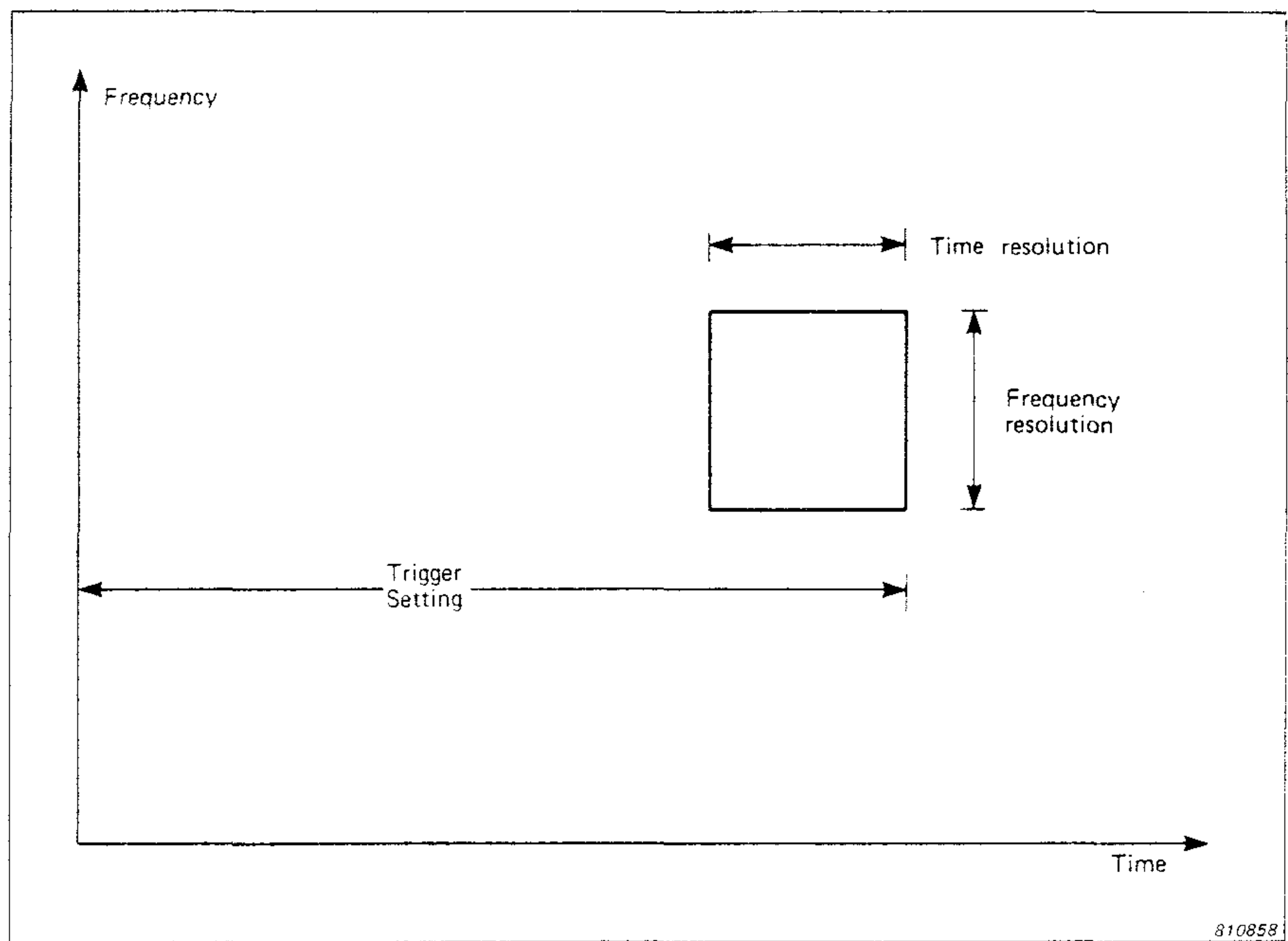


Fig.3. Time and frequency resolution

to see if it is feasible in terms of the requirements for the other parameter. The choice of time resolution might be given by the requirement to cover a certain part of the machine's operating cycle, for example valve opening or piston slap. The accuracy of the time resolution is not normally critical because of the smoothing effects of the Hanning window and whatever is the nearest analysis range suffices, although in principle an external clock on the analyser can give any required value for the resolution.

The trigger control settings of the analyser give the time between the trigger and the end of the data record, as shown in Figs.1 and 3, and are calibrated in units of the basis FFT block size of K-samples. One K-sample is 1024 samples and covers a time T as above. Thus the trigger settings for a given time delay, t in seconds from the trigger to the centre of the analysis are, for the 2033 on baseband:

$$D = t f_{\max} / 400 + 9,5$$

and on zoom:

$$D = t f_{\max} / 400 + 5,0$$

and for the 2031 :

$$D = t f_{\max} / 400 + 0,5$$

$$t = \text{required time delay}$$

f_{\max} = analyser full scale frequency

D = trigger setting on analyser screen.

In the 2031 D may vary from 0 to 9.9 and in the 2033 from 0 to 64.0. This can give a negative value for t, and this is in fact quite possible, because of the memory in the analysers, particularly the 2033 with its 10 K memory. The values of T can be calculated as above, or are as given in Table 1.

Typical procedures

In practice baseband analysis with some full scale frequency and time resolution is usually required, and one of the two following simple procedures can usually be followed. The first procedure obtains an analysis at a selected time with a given time resolution and the second covers the cycle of a machine running at some r.p.m. with a given number of spectra. Other situations are quite feasible, for example the use of zoom, analysis of a part of a cycle and so on. Note that if either procedure gives an analysis full scale frequency setting higher than that required, the extra analysis results are simply discarded, and if more frequency resolution than required is provided analysis lines can be averaged together.

Analysis at a given time

a) Pick an analyser time resolution from Table 1 shorter than or

Time Resolution	Time Record Length	Frequency Resolution	Full Scale Frequency	
160 sec.	400 sec.	2.5 mHz	1 Hz	(note 1)
80 sec.	200 sec.	5 mHz	2 Hz	(note 1)
32 sec.	80 sec.	12.5 mHz	5 Hz	(note 1)
16 sec.	40 sec.	25 mHz	10 Hz	
8 sec.	20 sec.	50 mHz	20 Hz	
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32 ms.	80 ms.	12.5 Hz	5 kHz	
16 ms.	40 ms.	25 Hz	10 kHz	
8 ms.	20 ms.	50 Hz	20 kHz	
3.2 ms.	8 ms.	125 Hz	50 kHz	(note 2)
1.6 ms.	4 ms.	250 Hz	100 kHz	(note 2)
0.8 ms.	2 ms.	500 Hz	200 kHz	(note 2)

note 1: Using zoom analysis (model 2033 only)

note 2: Using tape recorder speed change. Note that the upper frequency may be limited to lower values – for example 14 kHz for FM recording and 60 kHz for direct recording

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Table 1. Time/frequency relationships for FFT analysers

equal to the time resolution required to get the required full scale frequency. If necessary the time resolution can be lengthened by averaging adjacent spectra as described in a later section.

- b) The selected full scale frequency and the required time delay give the trigger setting.

Example: Analysis to 10 kHz required with a time resolution of 8 ms at 324 ms after a trigger signal.

- a) Table 1 gives an analyser full scale frequency of 20 kHz to get the 8 ms resolution.
b) For the 2033 the K-samples after trigger setting is

$$[(324 \text{ ms} \times 20 \text{ kHz})/400] + 9,5$$

$$= 25,7$$

Analysis of an Engine Cycle

- a) the r.p.m. or direct measurement gives the cycle time.
b) The required full scale frequency gives the time resolution.
c) The cycle time divided by the time resolution gives the minimum number of spectra. Double this to allow for picket fence effect. The resulting number can be increased by using a higher full scale frequency or decreased by averaging adjacent spectra, a technique which is described later in this note.
d) The timing information gives the initial trigger setting (round to the

nearest 0,1), and the cycle time gives the trigger setting range. An increment of 0,2 is normally used so this figure can be rounded to the nearest 0,2 and the last spectrum in the cycle can be discarded because it is the same as the first.

Example: Analysis to 20 kHz on a 4 stroke engine running with an 80 ms cycle (1500 r.p.m.) with a trigger at 12° BTDC, (before top dead centre) starting from TDC (top dead centre) and covering the whole cycle in at least 20 separate spectra.

- a) Cycle time is 80 ms
b) 20 kHz gives 8 ms resolution.
c) 80 ms divided by 8 ms gives only ten spectra. Use the tape recorder speed change to give a 50 kHz full scale and 3,2 ms resolution. This gives 25 separate spectra or 50 total, which is acceptable in terms of the 20 separate spectra required. Simply discard the results higher than 20 kHz i.e. all but the lower $20 \times 400/50 = 160$ lines.
d) Initial delay = $12/720 \times 80 \text{ ms}$ from 720° per cycle and 12° BTDC.
Initial analyzer setting = 9,7 from formula above for 2033.
Trigger range = $80 \text{ ms}/8 \text{ ms} - 0,2 = 9,8$
Final setting = $9,7 + 9,8 = 19,5$
Increment = 0,2

Extending The Analysis Range With The Aid Of A Tape Recorder

If a choice of the time resolution or the full scale frequency results in a requirement for a frequency range beyond the normal 20 kHz maximum, this can often be obtained by use of an analog tape recorder in the position in the measurement chain shown in Fig.A. The recording, including the tach pulse, is simply played back at a slower speed than that on which it was recorded, or indeed to extend the lower frequency range the opposite procedure can be followed. A factor of ten is obtained by this method, which is exactly equivalent to carrying out the analysis on a higher frequency range as is indicated in Table 1.

For example for a reciprocating engine with 200 ms cycle time an analysis covering only 2.9° can be obtained by slowing the tape down and using the 20 kHz range on the analyser. From Table 1 the time resolution is 0,8 ms, and $720 \times 0,8 / 200 = 2,9$. The analysis line spacing is 500 Hz up to either 14 kHz from DC using FM recording or up to 60 kHz from 40 Hz using direct recording.

Averaging Of Adjacent Spectra

If the choice of full scale frequency results in too short a time resolution, adjacent analyses can be averaged together to cover a longer time. This is done simply by setting the analyser to run for say an N spectra linear average with the trigger set to the beginning of the desired analysis time, letting the analysis run up to N, incrementing the trigger setting, pressing "averaging proceed" to acquire an additional N spectra and so on. The increment for the trigger should be 0,1, 0,2, 0,3 or 0,4. The reasons for this will be discussed shortly.

Time Resolution and Picket Fence Effect

If a series of spectra are used to cover a section of a machine's operating cycle, the choice of increment in the trigger settings between these spectra is limited. As the effective time resolution of a Hanning window is 0,4 of the record length the maximum increment is 0,4, which gives an error of 0,75 dB in terms of data missed by the analysis. For 0,1 and 0,2 increment there is zero error and 0,08 dB for 0,3.

However, if a very short event occurs, as is typical of reciprocating machines, it can fall between two spectra. With the settings above it will all be accounted for in the energy sense but it may be half in one spectrum and half in the next. This is similar to the picket fence effect in the time domain and gives a misleadingly low reading on two adjacent spectra. It is much reduced by using overlapping analyses and gives an error of 3,7 dB for 0,4 trigger increment, 2,0 dB for 0,3, 0,9 dB for 0,2 and 0,2 dB for 0,1. Thus for a smooth transition between analyses and low picket fence error a trigger increment of 0,2 or 0,1 should be used. 0,2 is normally suitable.

Data Presentation

The spectra produced can simply be presented in terms of a single spectra for a particular trigger setting, but a good pictorial presentation is to plot a series of spectra covering a whole or part cycle of the machine as a three dimensional plot. An example is given in Fig.4, which shows a vibration signal from the cylinder head of a marine diesel engine. It was produced on a digital plotter connected to an HP 9825 calculator and a B & K Type 2033 FFT analyser. This combination can run

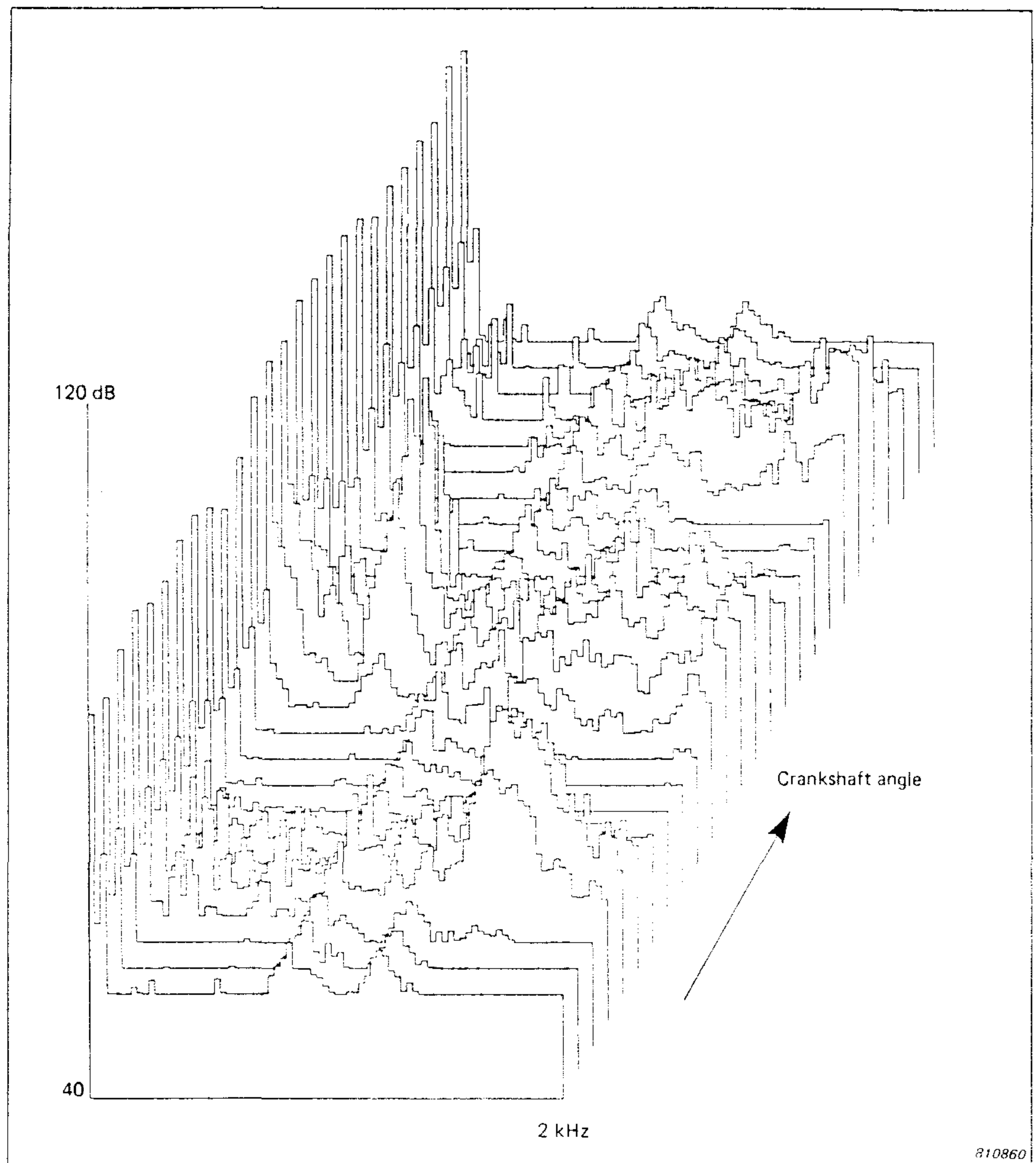


Fig.4. Analysis of marine diesel engine

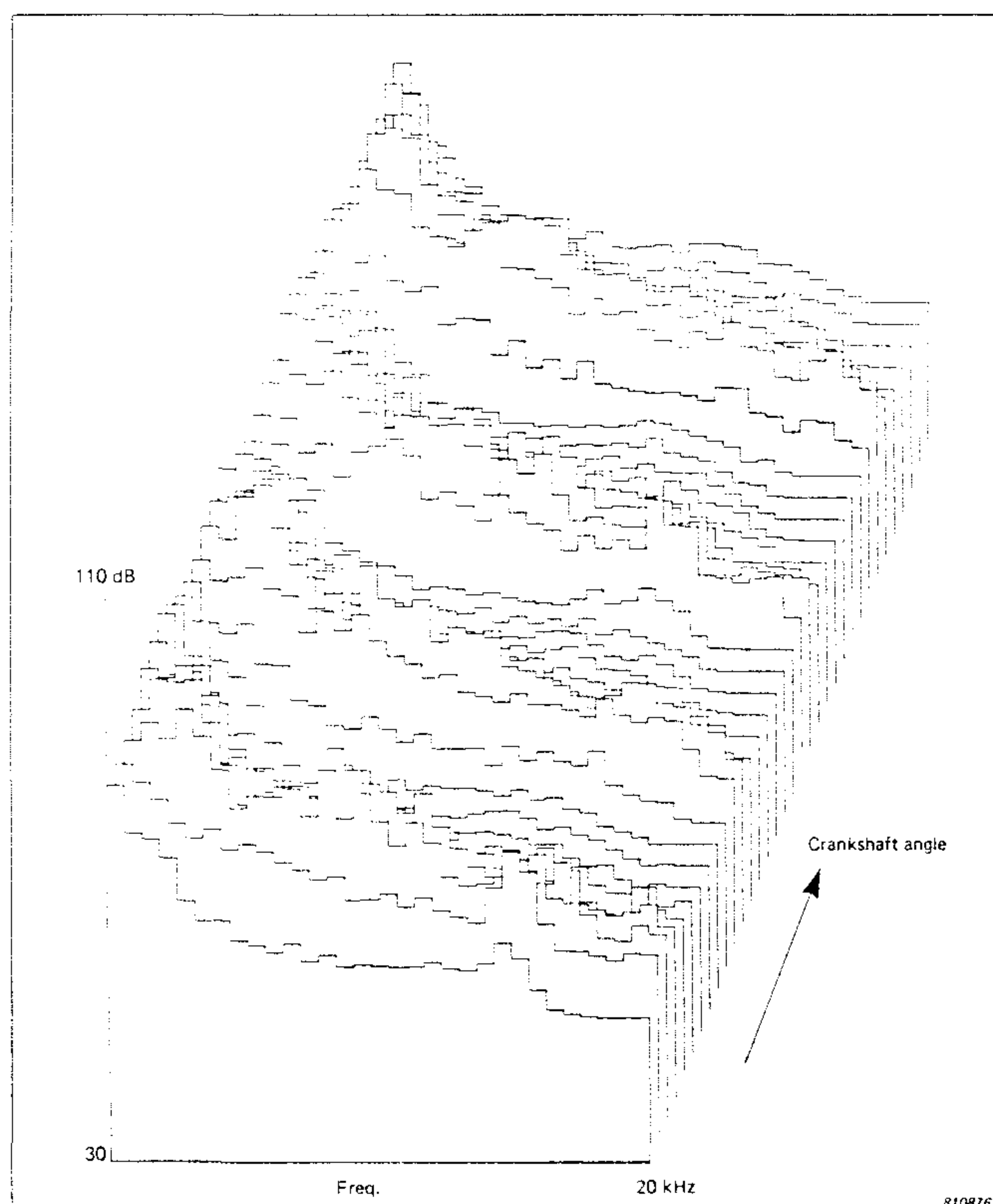


Fig.5.(a) Automotive diesel engine on a linear frequency scale

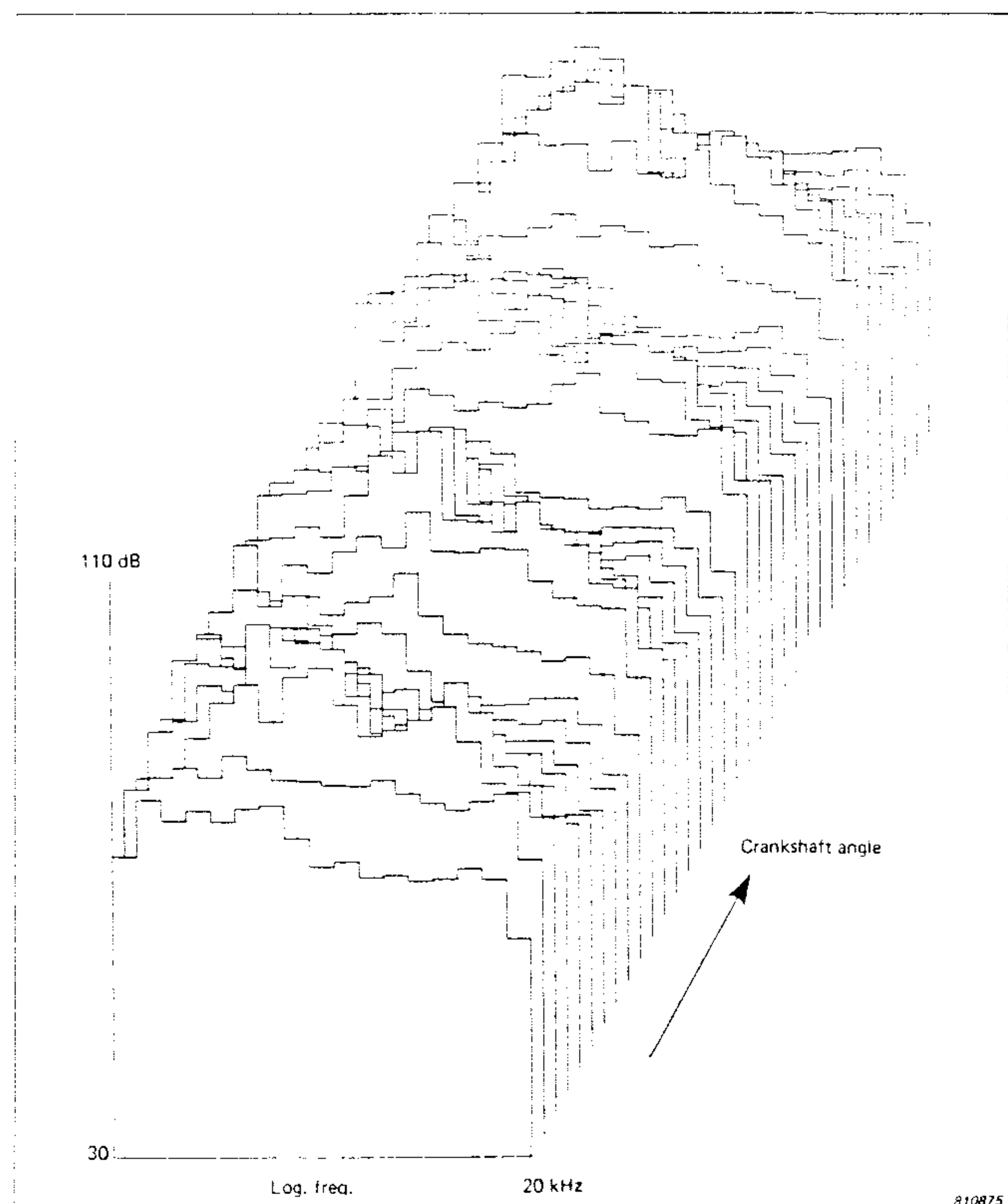


Fig.5.(b) Automotive diesel engine on a logarithmic frequency scale

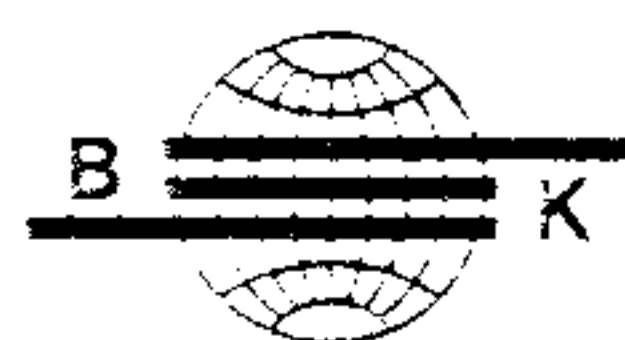
through the entire procedure for analysis automatically.

The signal produced by many types of machine tends to be impulsive in nature and therefore somewhat broadband, particularly at the higher frequencies. It is thus reasonable to average several lines together in order to actually reduce the frequency resolution, and this is actually useful in that it reduces the

amount of data involved without significant loss of information. This is shown in Fig.5(a) for an automotive diesel engine.

The next logical step from this is to use conversion to a logarithmic scale, such as 1/3 octave, by averaging adjacent bands. The machine's structural resonances tend to have a relatively constant percentage bandwidth so their absolute

bandwidth is higher at higher frequencies, as for example in Fig.4. A logarithmic frequency scale thus reduces the data in a manner more suited to its expected form. An example of this is shown in Fig.5(b) for the same engine. None of these data reduction techniques apply only to three dimensional plots, but can also be used on single spectra.



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