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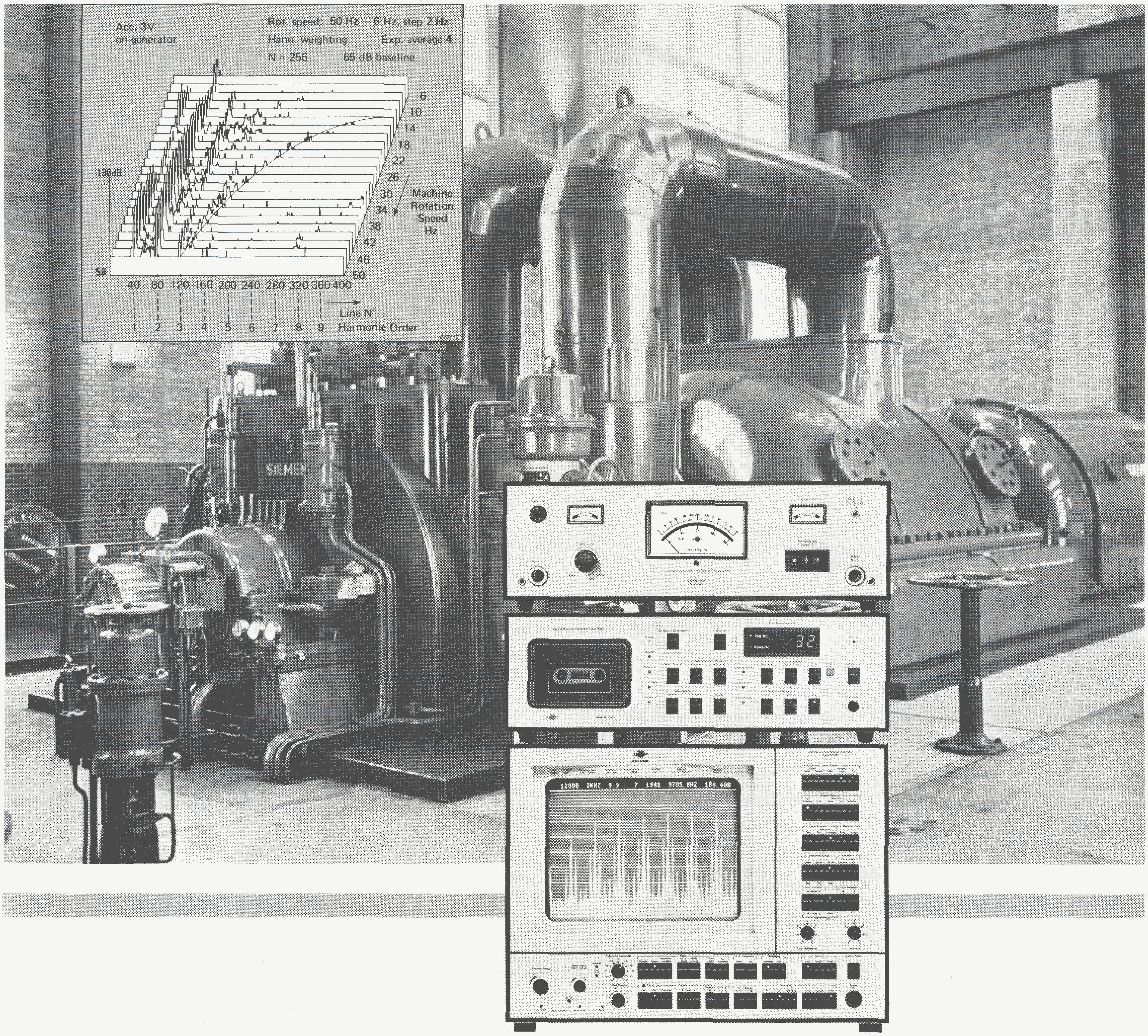

Order Analysis Using Zoom FFT

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by *Henrik Herlufsen*, Brüel & Kjær

Introduction

In the analysis of vibration signals from rotating machines with varying speed, order analysis using an FFT analyzer can be a useful tool, particularly when analysing the vibrations during a run-up or a run-down of a machine. Of particular interest in that case is the analysis of structural resonances excited by the fundamental or the harmonics of the rotational frequencies in the mechanical system. Determination of the critical speeds, where the normal modes of the rotating shaft are excited, is very important on large machines such as turbines and generators (turbogenerators).

Use of an FFT analyzer in the normal internal sampling mode (i.e. non-tracking) and plotting of the spectrum at certain fixed steps in rotation speed of the machine gives *the so-called Campbell diagram.* This is a 3-D waterfall type of plot, where vibration levels as a function of frequency are plotted against rotation speed of the machine (plotted vertically). This means that the harmonic components appear on radial lines through the point (0 Hz, 0 speed) while structural resonances appear on vertical straight lines (constant frequency lines). This plot can thus be very useful. The smearing of the components, which appears because the time window used for the individual spectra represents a certain sweep in the speed, is however a disadvantage. The power of the components becomes spread over several lines. In particular, high frequency components in the spectrum, such as toothmesh frequencies, might be smeared so much that details in sideband structures are lost in the analysis. This is the main reason why order analysis is used instead.

In general one can say that order analysis, by use of an FFT analyzer, is an analysis by which the harmonic pattern of the vibration signal from a rotating machine is stabilized in certain lines independent of speed variations. This means that all the power of a certain harmonic is concentrated in one line and the smearing that would result in nor*mal analysis is avoided.*

A fundamental requirement of the FFT analyzer is that it has an external sampling facility, but provided this is available an order analysis can be performed. In the baseband mode (i.e. calculation of all the lines available according to the sampling rate), however, speed variations will cause the so-called antialiasing filter to limit the analysis range of the analyzer. This will be explained later. By changing manually the antialiasing filter during the run-up or run-down, a fast and real-time order analysis can be performed, but only the lowest lines give correct analysis (how many lines depends on the step in cut-off frequency from one filter to the next).

The zoom facility in the High Resolution Signal Analyzer Type 2033 provides a solution to this problem as it permits alias-free order analysis over a wide range of speed. Order analysis of the fundamental and lower harmonics is possible, without distortion from the antialiasing filter, over a speed variation of 1 to 15 (for example from 400 r.p.m. to 6000 r.p.m.). High resolution order analysis around some higher frequency components can be performed without distortion from the filter over a reduced speed variation and can, as will be shown later, be very useful.

The intention of this Application Note is, firstly, to explain the principle of order analysis (tracking) by use of an FFT analyzer with zoom facility and, secondly, to give an example of the application of this analysis as performed on a large turbogenerator system in a power generating plant.

Principle and Instrumentation

A typical instrument set-up is shown in Fig.1. The basic idea in order analysis is to pick up a pulse train synchronous with the rotational frequency of the machine and use this as a reference to generate the internal clock in the analyzer. The rotation frequency is, as shown, detected by a tachometer probe, such as the Magnetic Pick-up Type MM 0002 or the Photoelectric Probe Type MM 0012. The analyzer is provided with a multiple of this frequency which becomes the synchronizing frequency for the analog-to-digital converter, i.e. the external sampling rate. The frequency multiplication (with factor N) is carried out by the Tracking Frequency Multiplier Type 1901, see Fig.1.

This means that the analyzer will sample the signal a certain number of times for each rotation of the machine instead of at a fixed sampling rate. This principle is illustrated in Fig.2. A sweep of the fundamental component of some hypothetical signal is shown in Fig.2(a) (sweep rate heavily exaggerated). In the normal internal sampling mode the content in the time memory of the analyzer and calculated spectrum will be as shown in Fig.2(b). The sampling frequency $f_s = 2{,}56 \times f_{max.}$, where $f_{max.}$ is the selected full scale frequency of the analyzer. This is a normal Fourier analysis.

With external sampling, however, the component will be sampled a fixed number of times for each period. With a multiplication factor N = 8 we will get 8 samples per period of the fundamental, as shown in Fig.2(c). The analyzer will interpret this fundamental sweeping frequency as a fixed frequency and it will show up in one spectrum line, without any smearing. With a 1K (K = 1024) time memory (giving a 400 line spectrum) it will show up in line number 1024/N = 1024/8 = 128, because the sampling frequency corresponds to line 1024. A detailed discussion of the FFT principle will be found in Ref. 1. Likewise the harmonics will show up at multiples of this line number.

Fig.3 shows the analysis of the first 4 harmonics of a 50 Hz to 45 Hz sweep of a distorted sine-

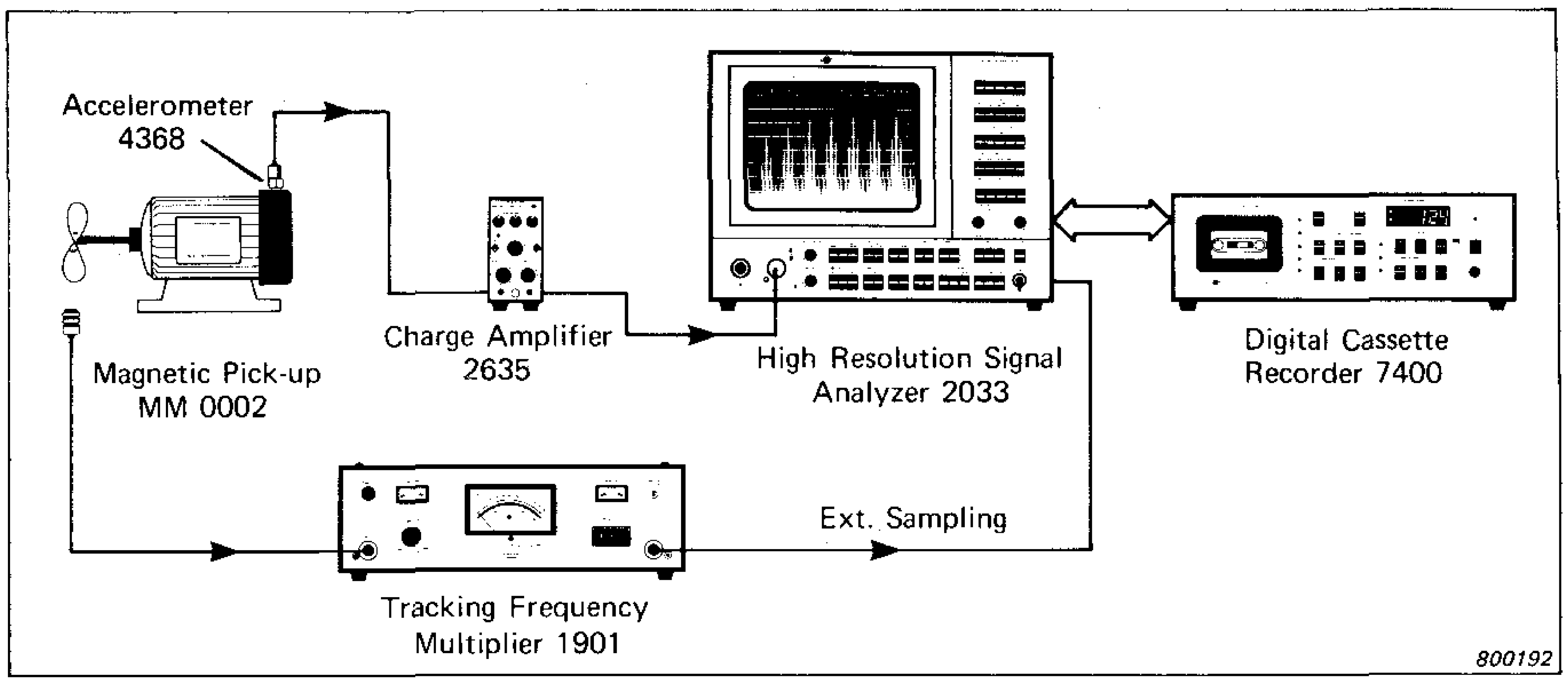


Fig.1. Instrumental set-up for order analysis

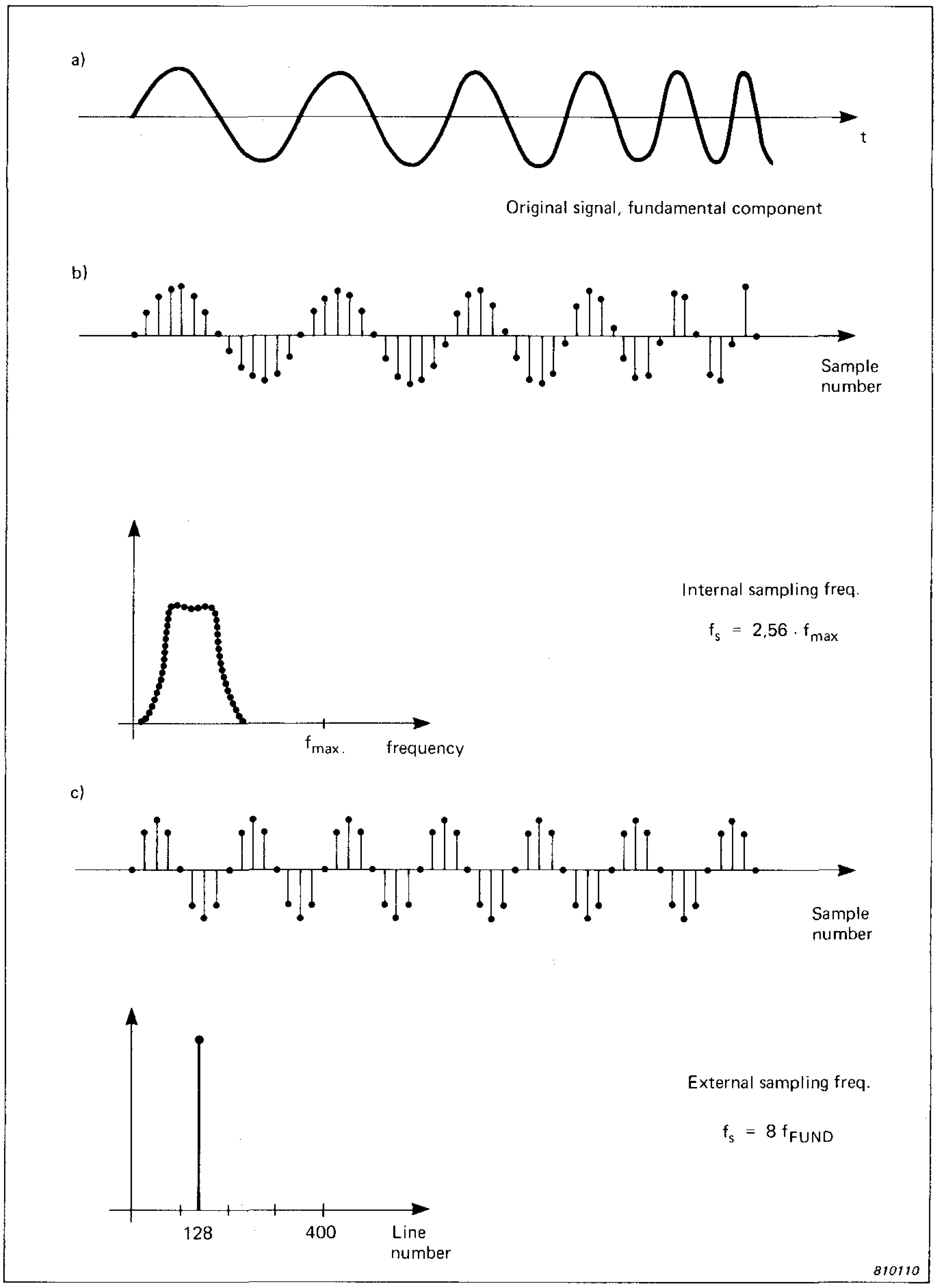
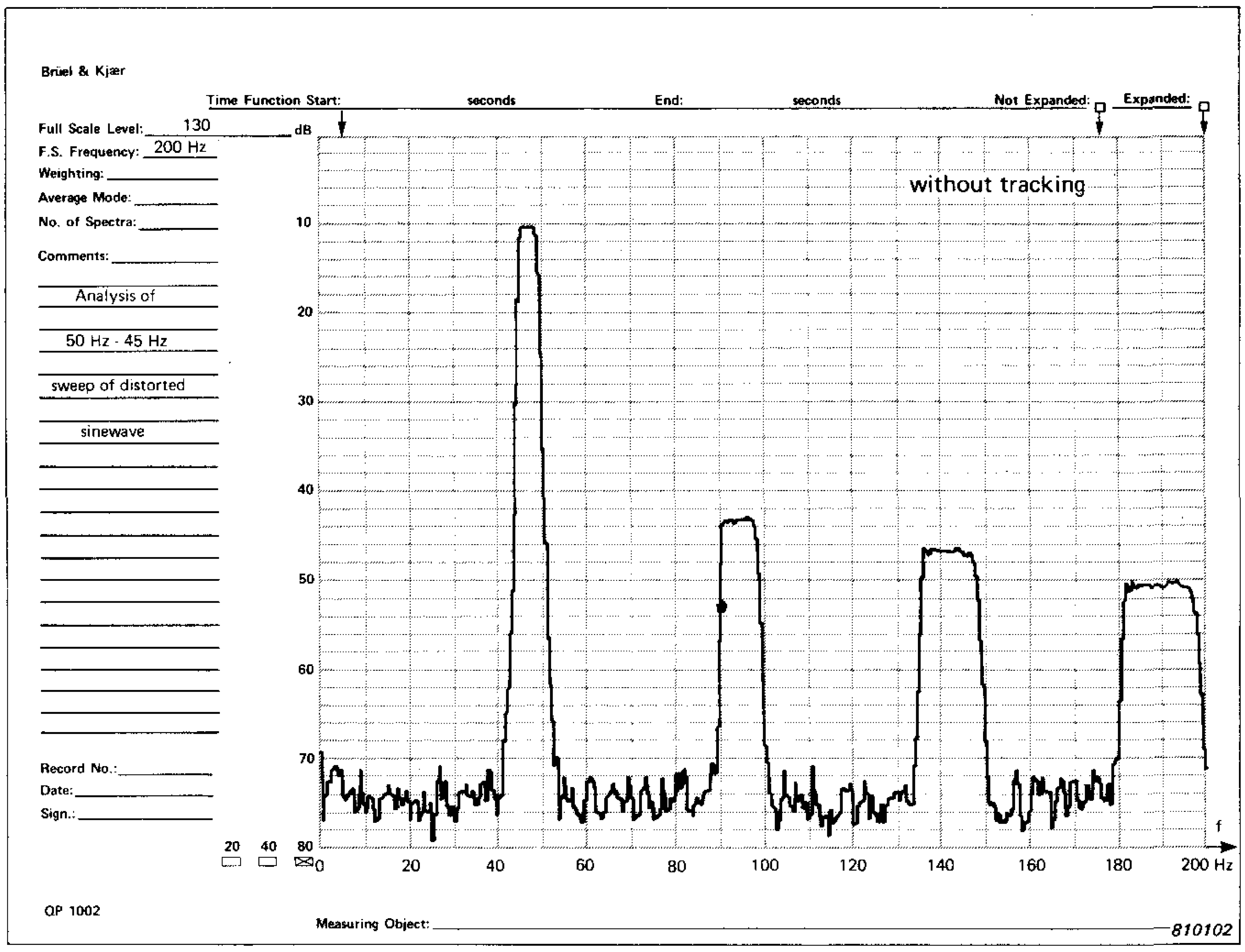


Fig.2. Principle in order analysis
a) original signal, fundamental component
b) samples and calculated spectrum with internal sampling frequency $f_s = 2{,}56\, f_{max}$
c) samples and calculated spectrum with external sampling frequency $f_s = 8\, f_{FUND}$

wave a) with internal sampling and b) with external sampling (tracking). With tracking, all the power of the individual harmonics is concentrated in a particular line. Thus the fundamental in Fig.3(a) is smeared over more than 6 lines and the fundamental at line 80 in Fig.3(b) is seen to be 8 dB higher. At the 4. harmonic the smearing is 4 times wider and the component is 8 + 6 = 14 dB higher with tracking than without tracking. In this example a 400 line baseband analysis and a multiplication factor of 12,8 was used, placing the fundamental in line number 1024/12,8 = 80.

In any sampling process, i. e. converting a continuous time signal to a discrete signal, aliasing of frequencies has to be considered. After the sampling process it is impossible to distinguish between low frequencies and frequencies above half the sampling frequency $f_s/2$, called the Nyquist frequency f_N. This is the principle behind the use of the stroboscope for example. High frequencies become aliased down to low frequencies which the eye can follow and interpret. In order to avoid this ambiguity it is necessary to lowpass filter the analog signal before sampling. This is done by an antialiasing filter whose cut-off frequency can be changed in discrete steps. To get a correct spectrum the filter should be chosen relative to the sampling frequency, as shown in Fig.4(a). In the normal baseband mode (non-zoomed) 400 lines are calculated up the cut-off frequency. The aliasing, having the effect of folding the spectrum around f_N, is indicated by the dotted lines. Change of the rotation speed of the machine, i. e. change of the sampling frequency, will, however, cause the filter to reduce the analysis range and dynamic range, as shown in Fig.4(b) and (c). In (b) the speed of the machine has been increased relative to that in (a) and it is seen that the filter cut-off has entered the 400 line analysis range. In (c) the speed has been decreased relative to (a) and the components with frequencies above f_N, which come through the filter, are folded back into the analysis giving wrong results.

In the baseband mode one is thus restricted to very limited speed variations in order to retain a correct 400-line order spectrum.



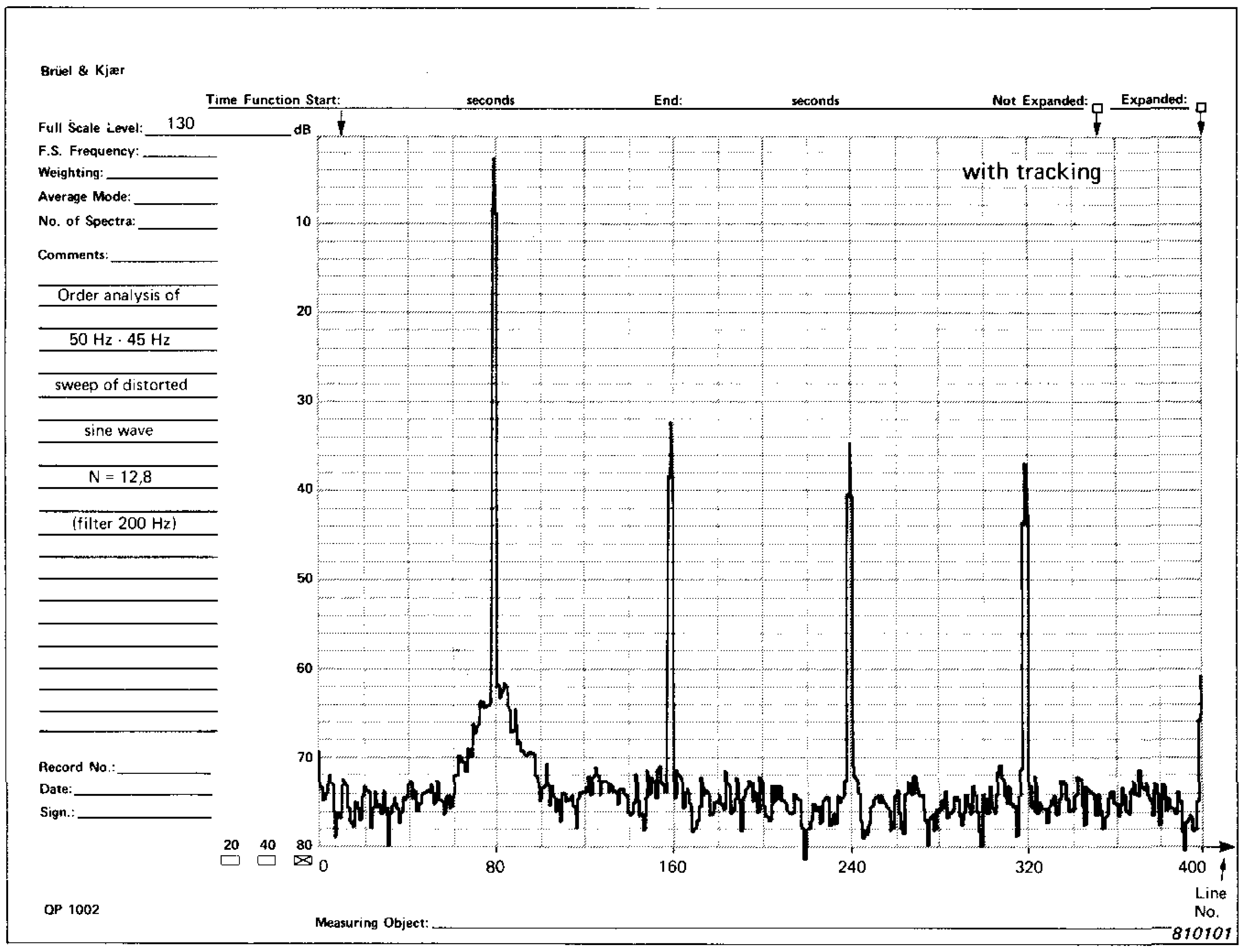


Fig.3. Analysis of first 4 harmonics of a 50 Hz to 45 Hz sweep of a distorted sinewave
a) with internal sampling
b) with external sampling

By use of zoom, however, this problem can be solved. Zoom is an analysis of only a part of the total baseband range. The High Resolution Signal Analyzer Type 2033 is in fact a 4000-line analyzer calculating and displaying only 400 lines at a time. For a detailed discussion of zoom FFT see Ref. 2. Zooming at the lower 40 lines in the spectrum in Fig.4(a), for example, will give a 400 line analysis, as shown in Fig.4(d). From this situation the rotation speed obviously can be increased a factor of ten before distortion in the 400 line spectrum from the filter occurs (as in (b)). Furthermore, the speed can be decreased a factor of 1,5 before aliased components enter the zoom analysis range (as in (c)).

An order analysis of the fundamental and its harmonics (i.e. lower 400 lines) is thus possible without changing the filter while the speed is changing a factor of 15. In practice this means that the important part of a run-up or run-down of the machine can be covered. The lower speed limit might here be set by the Tracking Frequency Multiplier Type 1901 which cannot accept less than 5 Hz (300 r.p.m.) at the input.

For a zoom analysis around some *higher harmonic (e.g. a toothmesh* frequency) as in Fig.4(e) the allowable speed range for correct analysis will be reduced and it might be necessary to change the filter during the run-up or run-down in order to cover the whole speed range of interest.

Thus before performing an order analysis two parameters have to be determined: 1) The cut-off frequency of the antialiasing filter and 2) The frequency multiplication factor N. The cut-off frequency has to be equal or higher than the frequency, at full rotation speed, of the highest harmonic of interest. That antialiasing filter with the lowest cut-off frequency fulfilling this requirement should be chosen. The frequency multiplication factor N determines the line numbers in which the harmonics will appear on the analyzer. In the zoom mode, the High Resolution Signal Analyzer Type 2033 is using the 10 K time memory for calculation of selected 400 lines out of the 4000 lines (zoom factor 10). The sampling frequency thus corresponds to line 10240. From the desired arrangement of the fundamental and harmonics the multiplication factor N is now given by the relation: N × LINE No. OF FUNDAMENTAL = 10240.

The analysis is performed in the zoom mode, requiring the 10 K time record, and is not in real-time. The calculation time in the zoom mode is one second. Therefore it is only applicable to large machines which speed up and slow down very slowly, so that real-time analysis is not necessary and the amplitude variations (amplitude smear-

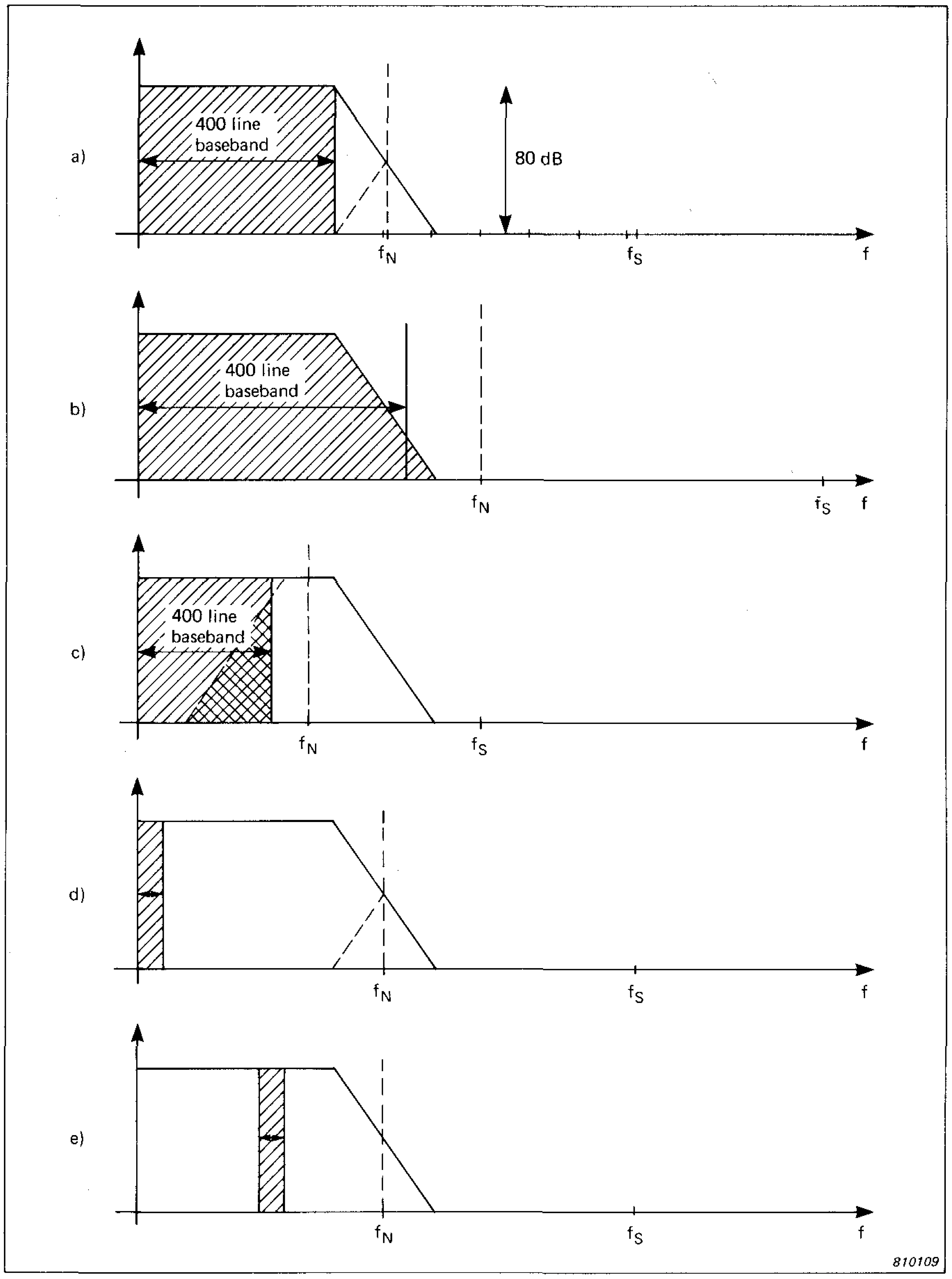


Fig.4. Analysis ranges with external sampling f_s in different situation
a) Baseband analysis with correct f_s
b) Baseband analysis with too high f_s
c) Baseband analysis with too low f_s
d) + e) zoom analysis, without distortion from filter or aliasing

ing) along the 10 K record is negligible even for relatively high Q resonances. In practice, the run through the speed range of interest should last more than, say, 5 minutes.

Practical Measurements

Run-down of a large turbogenerator:

The vibration signals (acceleration) at the bearings of the generator and the turbine were recorded at the same time as a tacho signal from a Photoelectric Tachometer Probe Type MM 0012 giving the rotation frequency of the shaft.

The run-down lasted nearly 15 minutes and was therefore suitable for order analysis (zoom tracking). Firstly, the lowest 10 harmonics of the vibration signal are analysed during the run-down. This is done by arranging for the fundamental to be in line 40 of the lowest 400 lines of a zoom analysis.

Choice of multiplication factor N and antialiasing filter is as follows:

In zoom mode the sampling frequency corresponds to line 10240, which means that

$$N = \frac{10240}{\text{LINE No. OF FUNDAMENTAL}}$$

$$\text{Thus } N = \frac{10240}{40} = \underline{256}$$

Max. rotation speed is 50 Hz, meaning that for the analysis of the first 10 harmonics the 500 Hz antialiasing filter should be chosen.

Aliasfree tracking would then be possible down to 3,2 Hz rotation speed without changing the filter, but the Tracking Frequency Multiplier Type 1901 limits the order analysis to a minimum of 5 Hz rotation speed. For each 2 Hz change in rotation speed the order spectrum was manually stored on the Digital Cassette Recorder Type 7400 (see Fig.1).

A 3-dimensional plot of the stored spectra of the vertical vibration signal at the generator bearings is shown in Fig.5. A baseline at 65 dB is inserted in order to get rid of the visually disturbing random noise and provide a reference level. The first 3 harmonics are significant in level and show characteristic resonances. For example, a resonance is seen in the fundamental between 16 — 18 Hz rotation speed which evidently is also excited by the second harmonic between 8 — 10 Hz rotation speed. The constant frequency components, presumably vibrations from other machines transmitted through the foundations, show up on hyperbolic curves in the rotation speed—harmonic order plane. The curves are given by: c × n = f, where c is speed, n is harmonic order and f is the frequency. Fig.6 shows some examples of constant frequency curves. The curve for the 150 Hz component is drawn in Fig.5. Notice the smearing of the constant frequency components. As an overall view of all the related components this plot is very useful. A more detailed analysis of the individual harmonics can be made by plotting the level of a particular line versus rotation speed on the X-Y Recorder Type 2308. Fig.7a) and b) show the fundamental and second harmonic versus rotation speed and actual frequency for the same signal. The X deflection is a DC voltage proportional to frequency from the Tracking Frequency Multiplier Type 1901. The resonances can now be seen in more detail. It is seen that the resonance between 16 and 18 Hz actually has its peak at 17,5 Hz and is excited by both the fundamental and second harmonic. The broad resonance shape around 29 Hz in the fundamental is also discernible in the second harmonic. The increased level at 45 Hz in the fundamental corresponds to a critical speed stated by the manufacturer to be at 45,8 Hz. This resonance is not seen in the second harmonic. In the 50 Hz — 100 Hz range of the second harmonic at least four resonance peaks are seen. Some of these might be com-

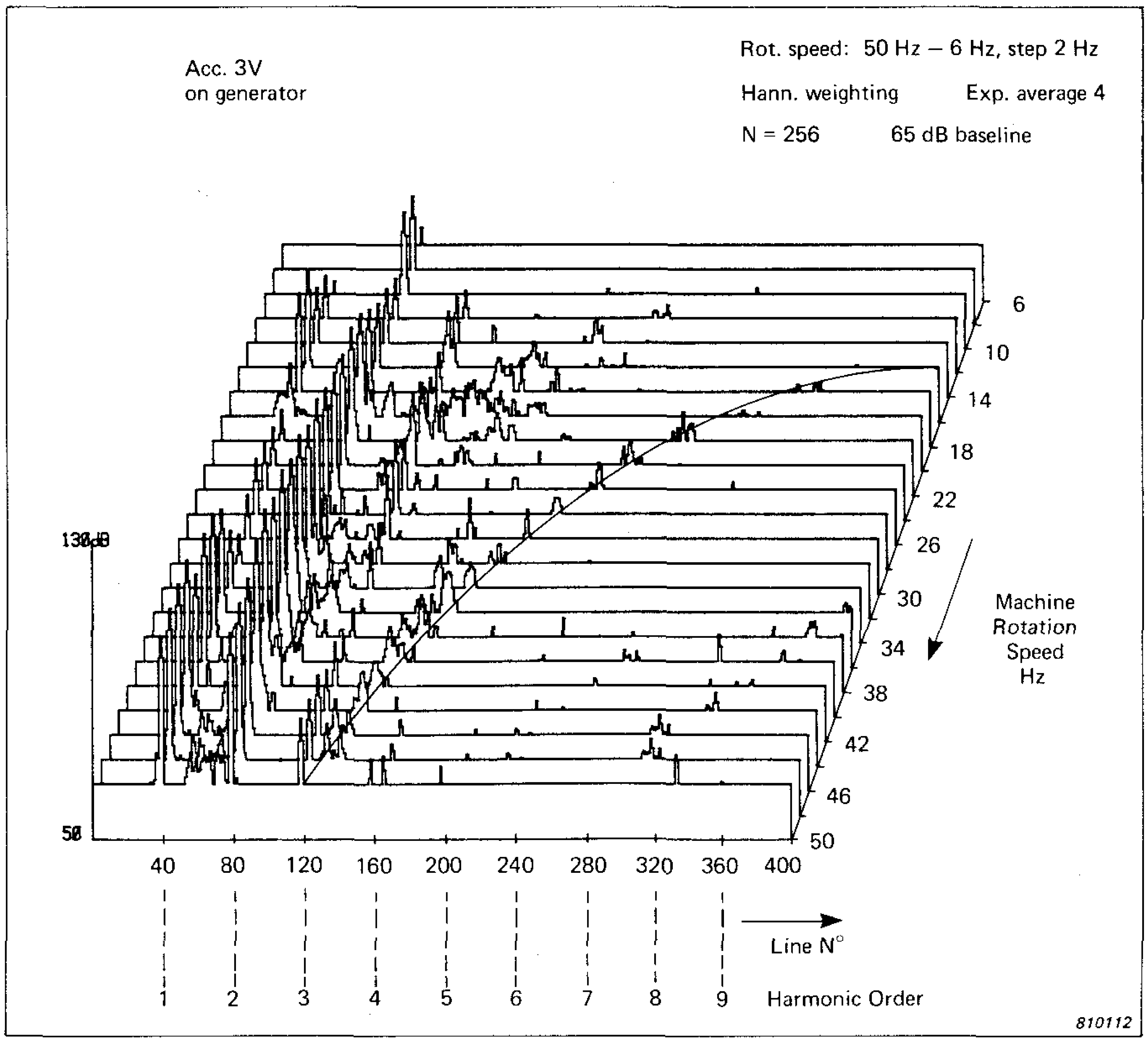


Fig.5. Order analysis of lower harmonics of generator vibration signal during rundown

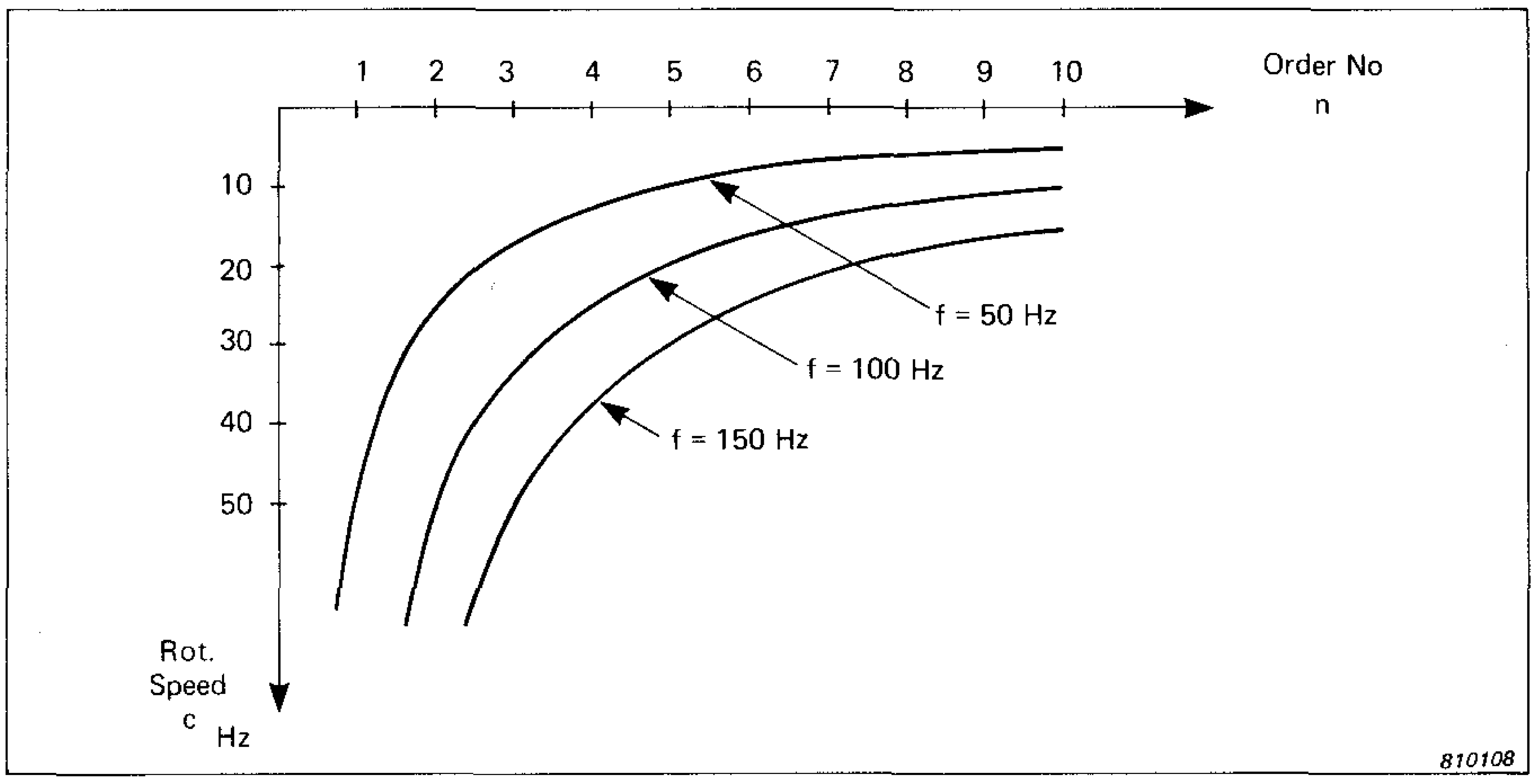


Fig.6. Constant frequency curves

binations of more than one resonance.

As mentioned, acceleration was measured in this example. Acceleration is the vibration parameter which puts emphasis on the high frequencies and is thus preferable if it is wanted to raise the higher harmonics relative to the dominating first harmonics. If, however, rather a measure of the energy in the vibration is wanted the velocity should be measured (by integration of acceleration), as the kinetic energy is proportional to velocity squared.

The first two harmonics in Fig.7a) and b) are shown on a linear frequency scale. Structural resonances are normally analyzed on a logarithmic frequency scale, as constant Q-factor (amplification ratio of resonant peaks) corresponds to constant percentage bandwidth. In this example, with analysis over only one decade, a logarithmic frequency scale is however not essential, but could have been chosen just as well.

As well as order analysis of the lower harmonics, order analysis of some higher frequency range can be of great interest. This is the case when, for example, gears, impellers, etc. which are mounted on the shaft give rise to high frequency components.

Fig.8 shows a zoomed order analysis centred on the 39th harmonic of the vibration signal of the turbine during run-down. The 39th harmonic is the toothmeshing frequency of a gear on the turbine shaft driving an oil pump. The multiplication factor N was set to 512 placing the fundamental in line 20. The 39th harmonic then appears in line 780.

The spectrum was stored on the digital cassette recorder for each 2 Hz change in rotation speed. The 3-dimensional plot in Fig.8 shows 200 lines of the 400 line zoomed spectrum for rotation speeds from 50 Hz to 24 Hz. The 39th harmonic is 1950 Hz at full speed and the 5 kHz filter was chosen. With this filter no aliased components will enter the analysis range before the rotation speed is below ~ 17 Hz. If analysis below that speed were required, the filter could be changed to 2 kHz at that speed, and the analysis would still be aliasfree.

Fig.7. a) Fundamental of generator vibration signal during rundown
b) 2. harmonic of generator vibration signal during rundown

It is seen that the dominant family of sidebands comes from modulation by the oil pump shaft rotation frequency. This shaft rotates at ~ 23,5 Hz at full speed. The lines showing the positions of this sideband family are drawn on the 3-D plot. Some modulation from the main shaft rotation frequency is seen as well as sidebands with a spacing of 20 lines. A baseline at 54 dB has been inserted. Flat weighting is used and this is why components appear as single lines. The flat (or rectangular) time weighting function has the advantage of giving a narrow filter bandwidth equal to the line spacing, while the smooth Hanning window gives a bandwidth of 1,5 times the line spacing. The flat weighting should, however, only be used when the time window contains an integer number of periods (see Ref. 1).

It is interesting to see that the toothmesh component excites resonances at rotation speeds of 38 Hz and 28 Hz. It is also seen how first the left sideband frequencies, then the toothmesh frequency, and finally the right sideband frequencies are excited during the run-down. This high resolution analysis can give useful information for diagnostic purposes.

In order to see the detailed behaviour of the toothmesh component during the run-down, line No. 780 was recorded versus rotation speed (and also calibrated in terms of actual frequency) on an X-Y Recorder Type 2308, as was done for the fundamental and second harmonic of Figs.7a) and b). The result is shown in Fig.9. The filter was here set to 2 kHz and analysis down to 8 Hz rotation speed performed.

Separating this component from the sidebands by means of an analog tracking filter would require less than 1% filter bandwidth, and to obtain the same signal to noise ratio would require a filter bandwidth as low as 0,13%.

Apart from the significant resonances already seen in Fig.8, the analysis in Fig.9 reveals several lower peaks in the toothmesh component.

The vibration signal at the generator bearing contained among other components a significant 37th harmonic and harmonics of this. A 3-dimensional plot of a 400 line zoomed order analysis around this 37th harmonic during run-down is shown in Fig.10. Multiplication factor N was 512, placing the 37th harmonic in line No. 740. This component was found to be caused by a fan with 37 blades in the generator cooling system. Some peaks are easily seen. No sideband structure is seen around this component, indicating that it is a rather pure blade-passing frequency without modulation. The fundamental in line 740 is plotted versus rotation speed in Fig.11a. Peaks showed up in the higher harmonics at nearly the same rotation speeds as in the fundamental. The second harmonic of the blade-passing frequency is shown in Fig.11b). This indicates that the increases are not due to structural resonances, but might be caused by increased turbulence in the blower at different speeds.

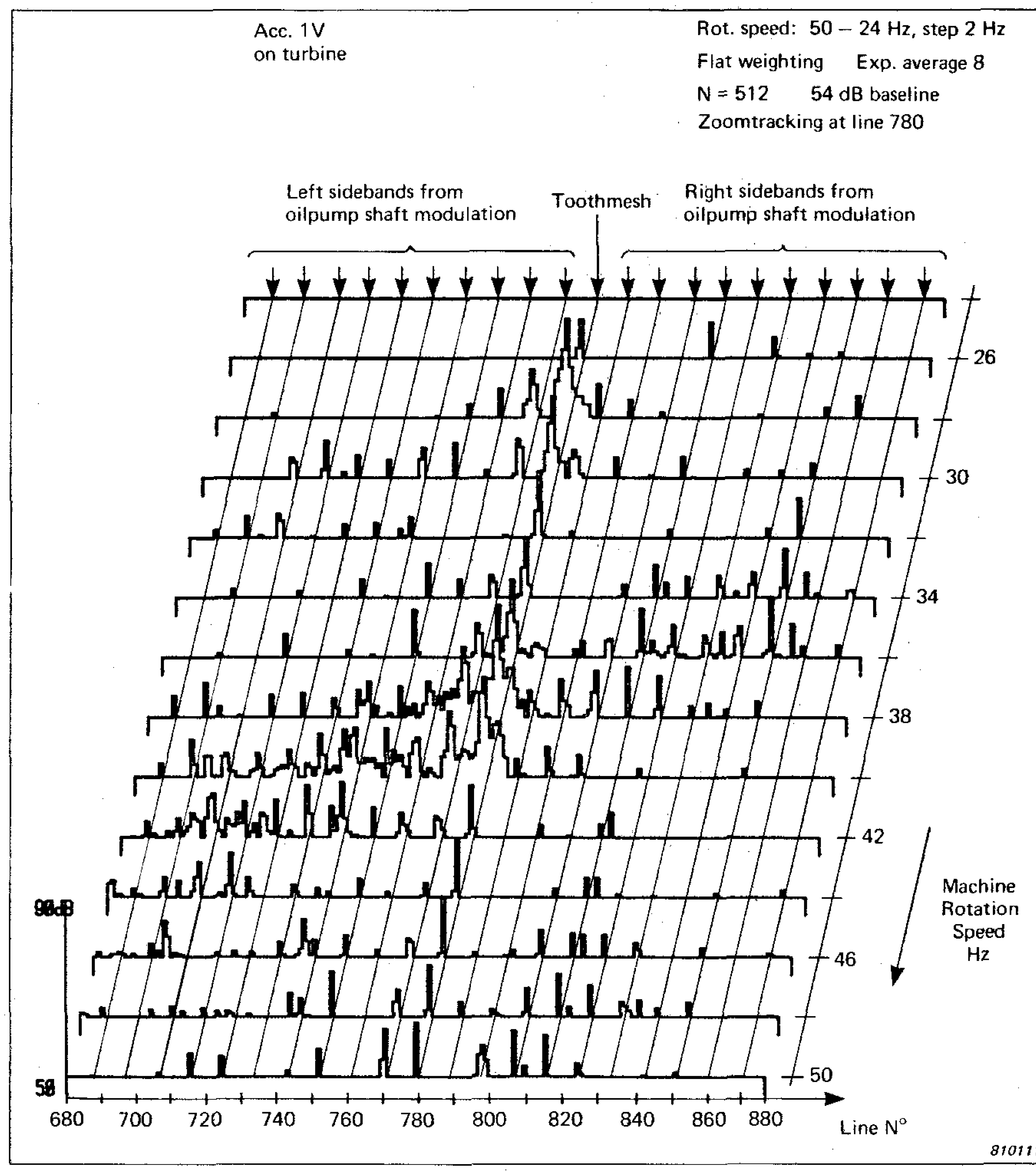


Fig.8. 200 line zoomed order analysis around toothmesh component

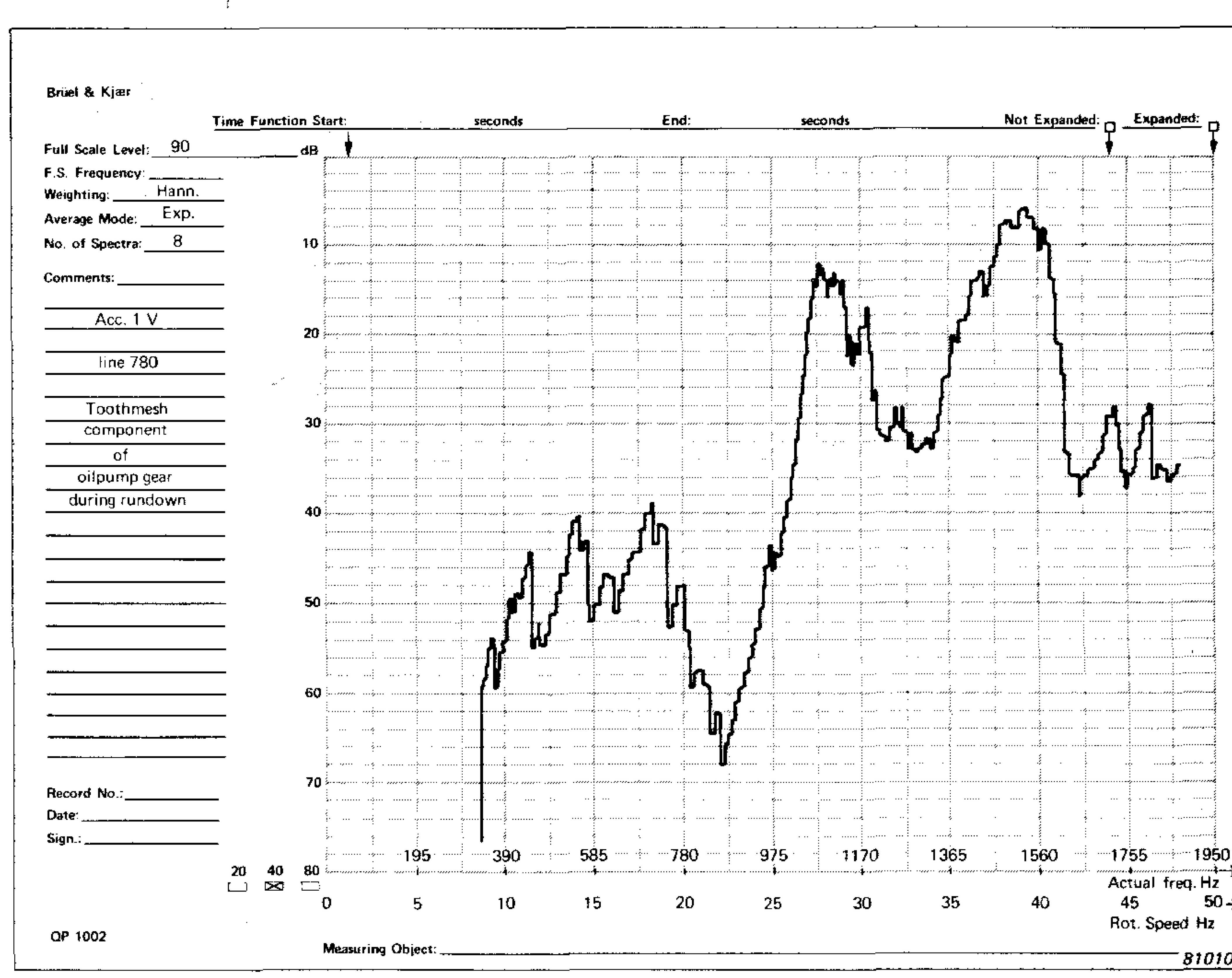


Fig.9. Toothmesh component of oil pump gear during rundown

Conclusion

By use of the external sampling facility and zoom mode in the High Resolution Signal Analyzer Type 2033 aliasfree order analysis (tracking) has become possible in the analysis of vibrations during run-ups or run-downs of machines.

The analysis is performed in the zoom mode, requiring the long time record, and is not in real time, which means that the method is only applicable to machines that speed up and slow down slowly. The run through the speed range of interest should last more than, say, 5 minutes. The limitation is set by the one second calculation time and the amplitude variation along the time record. The 10 K time record contains a certain speed range of the machine and it is an average amplitude in that range which is calculated. This is however only a limitation for very high Q resonances and caused no problems in the example showed in this note.

The great advantage of order analysis is that all the components of interest can be analysed simultaneously, and that all the power of the different harmonic or sideband components is concentrated in single lines, avoiding the smearing effect.

Apart from analysis of the lower harmonics, which of course are of main interest in determining resonances and critical speeds of large machines, zoomed order analysis around higher frequencies is possible. The high resolution analysis thus obtained gives the possibility of diagnosis which might have been impossible without use of tracking.

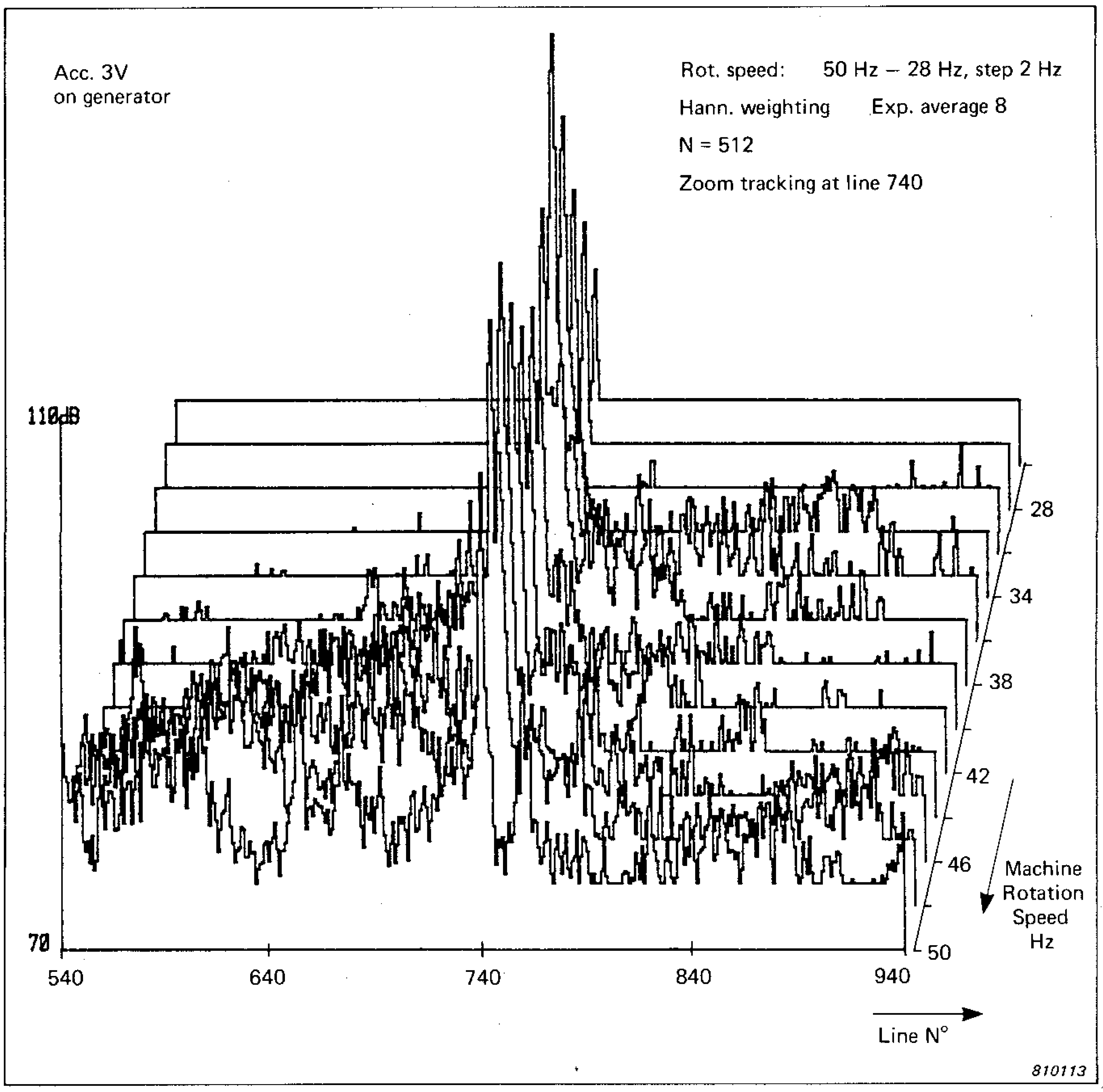


Fig.10. 400 line zoomed order analysis around the 37. harmonic (line 740) during rundown

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Ref. 1: N. Thrane: The discrete Fourier Transform and FFT Analyzers. B & K Technical Review No. 1-1979.

Ref. 2: N. Thrane: Zoom FFT. B & K Technical Review No. 2-1980.

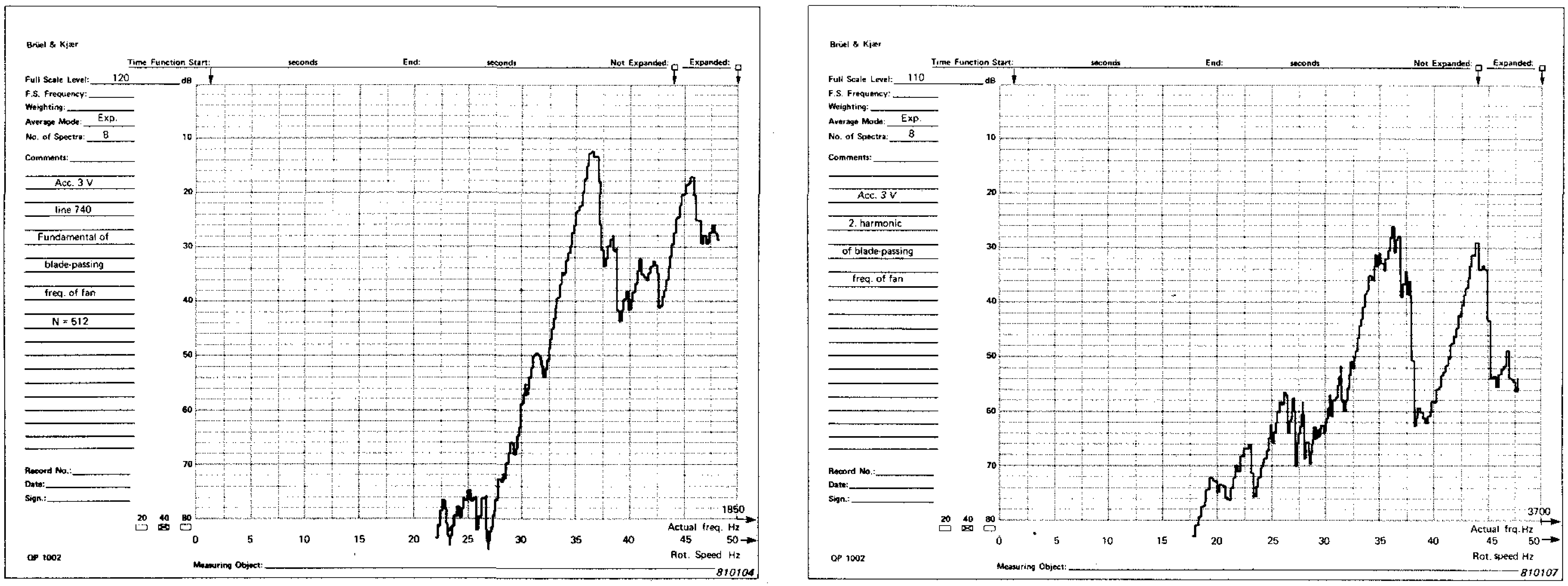

Fig.11. Fundamental a) and second harmonic b) of blade-passing frequency of fan during rundown

Bruel & Kjaer Instruments, Inc.
185 Forest Street, Marlborough, Massachusetts 01752 / (617) 481-7000 TWX 710/347-1187

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