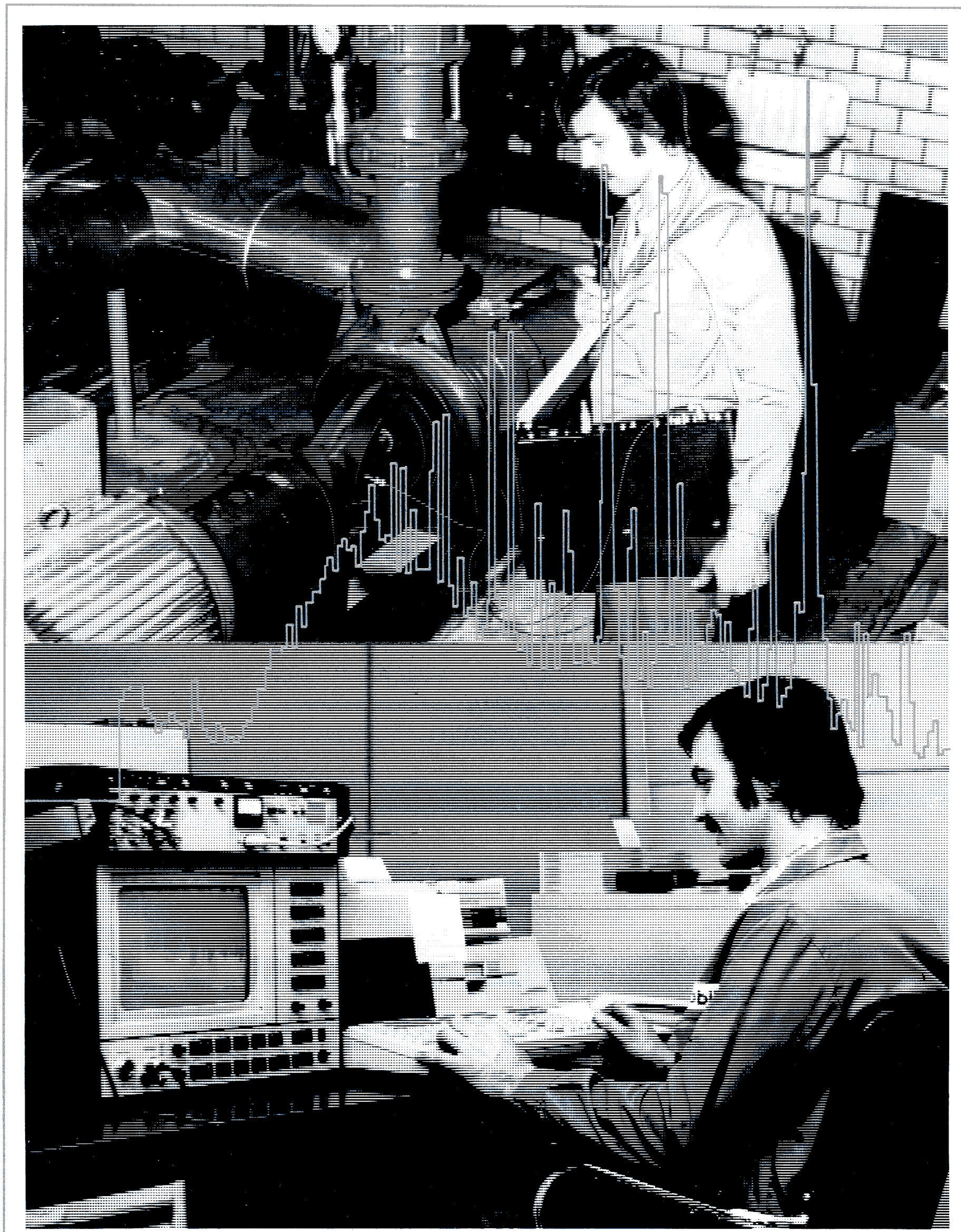
Vibration measurements in predictive maintenance



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Vibration measurements in predictive maintenance

by *Christian Claessens,*
Mobil Plastics Europe Inc.

Introduction

In July 1980, the first production unit at the Mobil plant of Latour was started up.

Starting a new plant entails the establishment of a maintenance department with its workshops, laboratories and stores. But above all, it entails decisions about stategy, organization and maintenance methods. We shall try to give a brief account of our experiences over the last two and a half years, the alternatives chosen, the techniques employed and the results obtained.

Periodic or predictive preventive maintenance?

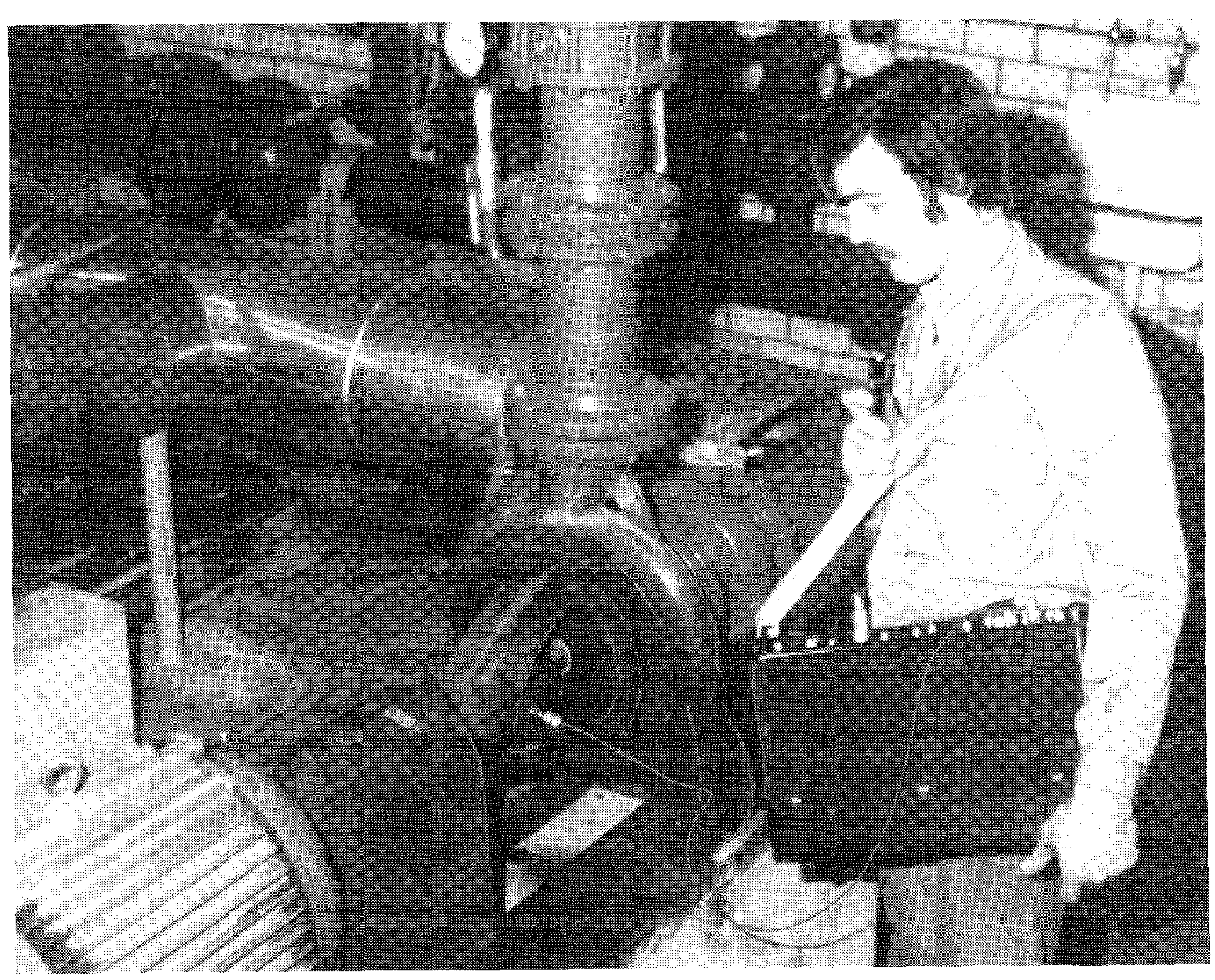
Nowadays the concept of preventive maintenance is widely recognised. In the process industry where the equipment is generally expensive and big, preventive maintenance proved economically sounder than run-to-break maintenance. An added benefit is a much safer operation.

Historically, periodic preventive maintenance was the first preventive type of maintenance to arise. It is based upon statistical background, that has been questioned quite a lot in recent years. It is based on the concept that the failure rate increases after a given number of running hours and that the period with low failure rate is constant for a type of equipment.

However, it is obvious that this troublefree operation period before maintenance if really needed varies greatly according to load conditions, production tolerancies, assembling conditions...

If a good reliability is requested between overhauls, this period must be shorter than the shortest time between failure. Thus, a large number of unnecessary overhauls will be carried out on machines that could have been kept in operation for a much longer time.

Furthermore, these overhauls are expensive in terms of spare parts, labour and downtime production losses. Even more serious is the fact that increasing overhaul frequency



also increases the number of human errors during dismantling, reassembling and starting-up.

Obviously the ideal method would be to perform preventive maintenance at irregular intervals, depending of the actual condition of the machine. This is the aim of predictive maintenance.

The main difficulties of this method are clear:

a) the actual condition of the machine must be known at any time

b) any change of condition, or fault development, must flash a warning with enough lead time.

Lead time is necessary to:

1. enable a scheduled shut-down which must not significantly disturb production
2. inform and prepare the maintenance crew
3. prepare or store the necessary spare parts and tools.

The condition monitoring of the machine is therefore the key in such a maintenance system. The monitoring must be technically well suited to the equipment and organized with the greatest possible care. It should be performed with enough personnel and good quality equipment.

Predictive maintenance is the method we are using on the five production lines of our plant. Only some machines, with a large amount of fast wearing parts are maintained on a periodic base.

Getting the monitoring program started

Machine condition monitoring is based on the periodic, and sometimes continuous, measurement of one or several parameters. The evolution of these is considered to be representative of the actual condition of the machine.

This implies the analysis of the trends, starting from a reference measurement, taken when the machine was considered to be in perfect working condition.

The choice of the parameter to be monitored and the measurement technique have therefore a tremendous impact on the efficiency of the predictive maintenance.

The sensitivity must be good enough to allow measurements within a reasonable time inverval, particularly if periodic monitoring is used.

Taking into account the variety of machines and the number of parameters that can be chosen, it is generally not possible to limit oneself to a single type of measurement on all the equipments.

Monitor parameter	Machines monitored	Number of measurement points	Measuring equipment	Periodicity
Vibration measurements	All rotating machinery	800	— 1 portable meter — 1 analogue analyzer — 1 FFT analyzer — 1 tape recorder — 1 computer + peripherals	6 weeks (4 weeks during the 2nd phase)
Shockwave measurements	All antifriction bearings (rolls and nips)	800	— 1 SPM* analyzer — 50 permanent transducers with grouped wiring	6 weeks (4 weeks during the 2nd phase)
Oil analysis	— Oil heating circuits — Gearboxes — Hydraulic circuits	200	— Partially contracted to Mobil Oil — Equipment for filtration membrane — Microscope — Kit for water determination	3 months
Water analysis	— Cooling circuits [closed] — Cooling circuits [open] — Hot water heating circuits	15	— Titration equipment — Portable pH-meter	1 week
Thermography	— Accessible high-voltage installations — Low-voltage distribution — DC drive circuits — Relay panels	About 150 installations	— Contracted to a consultant	6 months

* SPM: Shock Pulse Meter

Table 1. Monitoring programme

Parameter	Phase 1			Projected, "Classical" method			Phase 2 (with desk-computer)		
	Periodicity	Number of measurement points	Average time per month (in minutes)	Periodicity	Number of measurement points	Average time per month (in minutes)	Periodicity	Number of measurement points	Average time per month (in minutes)
Vibrations (spectral analysis)	6 weeks	400	4000	6 weeks	800	8000	4 weeks	800	3200
Shockwave measurements	6 weeks	750	1500	6 weeks	800	1000	4 weeks	800	2400
Analysis of oil	3 months	120	200	3 months	200	330	3 months	200	667
Analysis of water	1 week	13	780	1 week	15	900	1 week	15	900
Analyse and classification of data			3600			6020			2313
Diagnostic and decision-making			1000			1900			1000
Total time			11080			18750			10480
Number of hours per month			185			313			175
Number of operators			one			two			one
Time required from engineer			10%			20%			10%

These times do **not include:**
— **Training of personnel**
Physical placement of the measurement points (bolts, tappets, measurement points tagging, sampling points, etc.)

Table 2. Personal resources required

For the case of our plant, we have briefly described the monitoring program in table 1.

On reading this table, it will be realised that the task requires quite a lot of investment in instruments, but also a lot of manpower. Not only is it necessary to perform the measurements but to file all data and follow up their evolution. Any discrepancy must trigger a sequence of events:

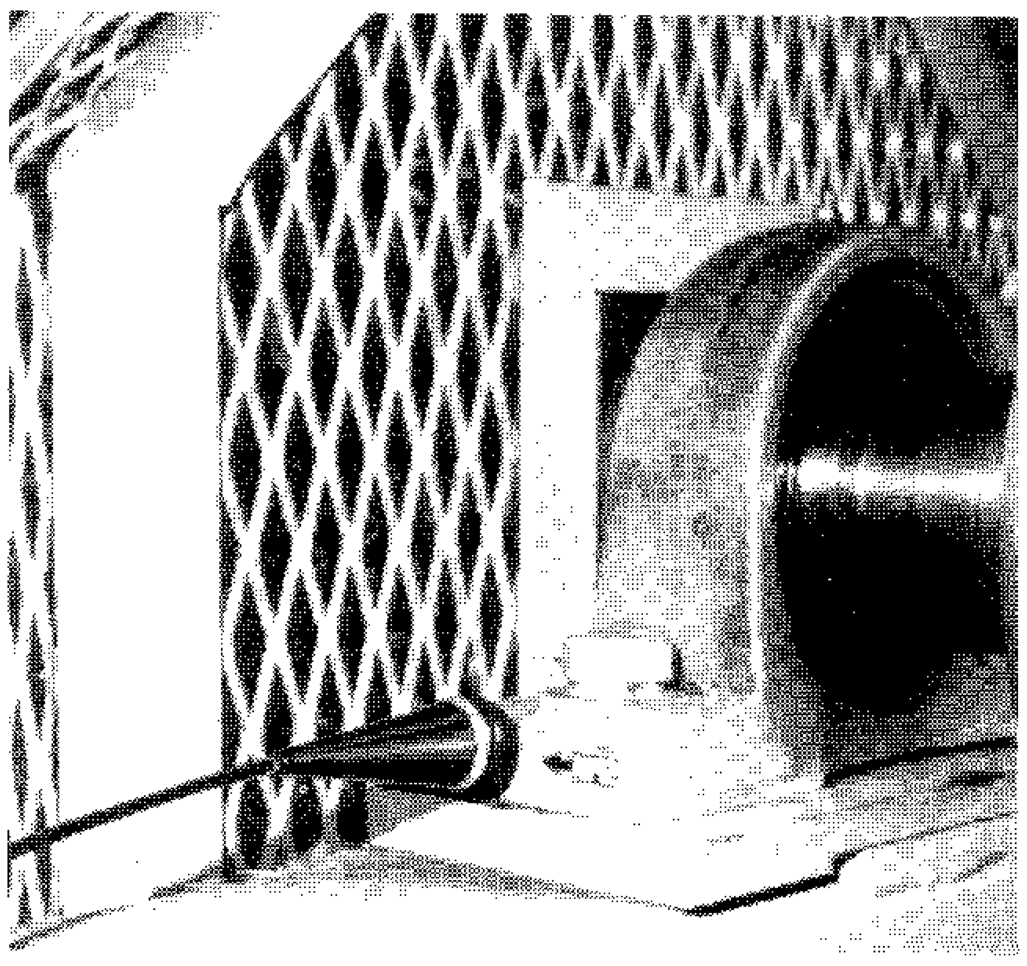
1. Decreasing the time interval of the measurements on the measuring point where the discrepancy was detected.
2. Additional measurements are taken in an attempt to produce a diagnose.
3. Planning of an overhaul during a scheduled shut-down.

When the number of measuring point exceeds about one hundred, the question arises whether or not to use a computer to handle the results. In the early beginning, our program was completely "manual". The results of this first phase, together with the increase in data volume due to plant extensions, led us to consider the use of a desk-computer.

To explain the problem more clearly, table 2 shows the work load related to the monitoring program.

The columns entitled "Phase 1" show the work load at the beginning of 1982; the columns under "Projected" show the workload for an increase in the number of measurement points without the aid of a desk-computer; the columns under "Phase 2" show the "desk-computer" solution which has actually been installed.

It is immediately evident that the use of a desk-computer enables a spectacular reduction in the time dedicated to vibration measurements and in particular to the spectral analysis.



Thus we were able to double the number of measurement points, reduce the interval between measurements (from 6 to 4 weeks) without an increase in personnel.

Furthermore the effectiveness of the system was found to be vastly improved. In fact:

1. The operators were relieved of a particularly boring job; the monthly analysis and the visual comparison of the spectra developed into a routine and led to a loss of attention. A machine may run for years without problems; this represents a considerable quantity of data which have no interest, and only serve to make the task more boring.

   Thus if a modification appeared in the form of the spectrum, the probability that it would go unnoticed was increased. This also led the operator to no longer perform the spectral analysis and to be content with an overall level measurement (r.m.s. velocity for example). The automatic comparison of a spectral analysis with a memorised reference measurement enables the operator to dedicate his time to more interesting and more useful tasks (diagnostics for example). The overall result is a greater motivation and a greater interest in the work being done.

2. Data gathering using a tape recorder can be conferred to non-specialised operators.

   This implies pre-set equipment, an easy procedure, as well as well-prepared measurement points with clear identification. The method of operation must be simple and clearly defined.

   The great advantage of such a procedure is that it permits data to be gathered by the maintenance team on watch for example at night or at week-ends, with a minimum of supervision.

3. The automatic analysis of the data greatly reduces the errors of estimation, reading, scale and subjective impression.

Instrumentation and methods for measuring vibrations

In the first phase, the monitoring program included an analogue analyzer with filters and automatic sweep system. This system allows a spectral analysis to be obtained on a graphic level recorder.

Furthermore, a certain number of simple machines (fans, small pumps) were only monitored by overall level measurement (r.m.s. velocity, and on some the crest factor) by means of a small vibration meter.

The majority of the SPM measurements were performed using a hand-held probe, without a measurement stud.

We have progressively: —

1. Increased the number of machines on which a complete spectral analysis is performed.
2. Mounted fixed measurement studs on all the bearings monitored by the SPM analyzer.
3. Mounted transducers permanently and have regrouped the wiring together for SPM measurements at points where access to the bearings is difficult or dangerous for the operator.

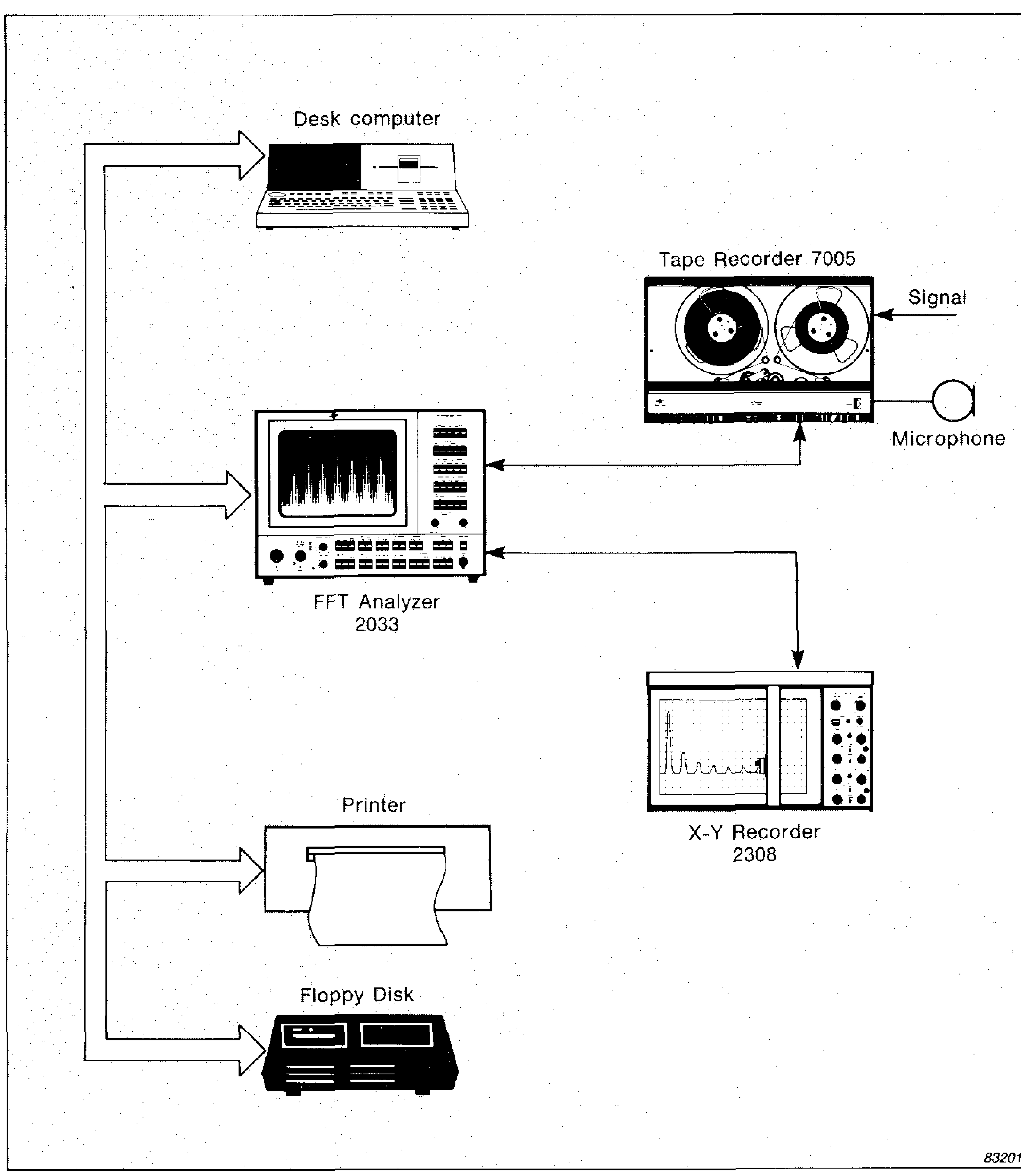


Fig. 1. Measurement system (phase 2)

Finally, during recent months, we have started a second phase where the measurements are assisted by a desk-computer.

Measurement system in the second phase

Our measurement system is built essentially around the Brüel & Kjær FFT analyzer Type 2033 and a Hewlett-Packard Calculator Type 9826 (see Fig.1).

The software employed is Brüel & Kjær module WH 1226 which we have slightly modified to meet our specific needs. It should be noted that programs to deal with the other measurements (SPM, analysis of oil and of water) are being prepared.

It is most important that these programs can be operated by non-specialised personnel. The programs are therefore built up with a "menu" (interactive language.)

We have two programs dedicated to monitoring and a series of programs which enable the diagnostic possibilities of the FFT analyzer to be fully exploited.

The calculator completely controls the analyzer via the IEEE interface.

The dedicated monitoring programs enable;

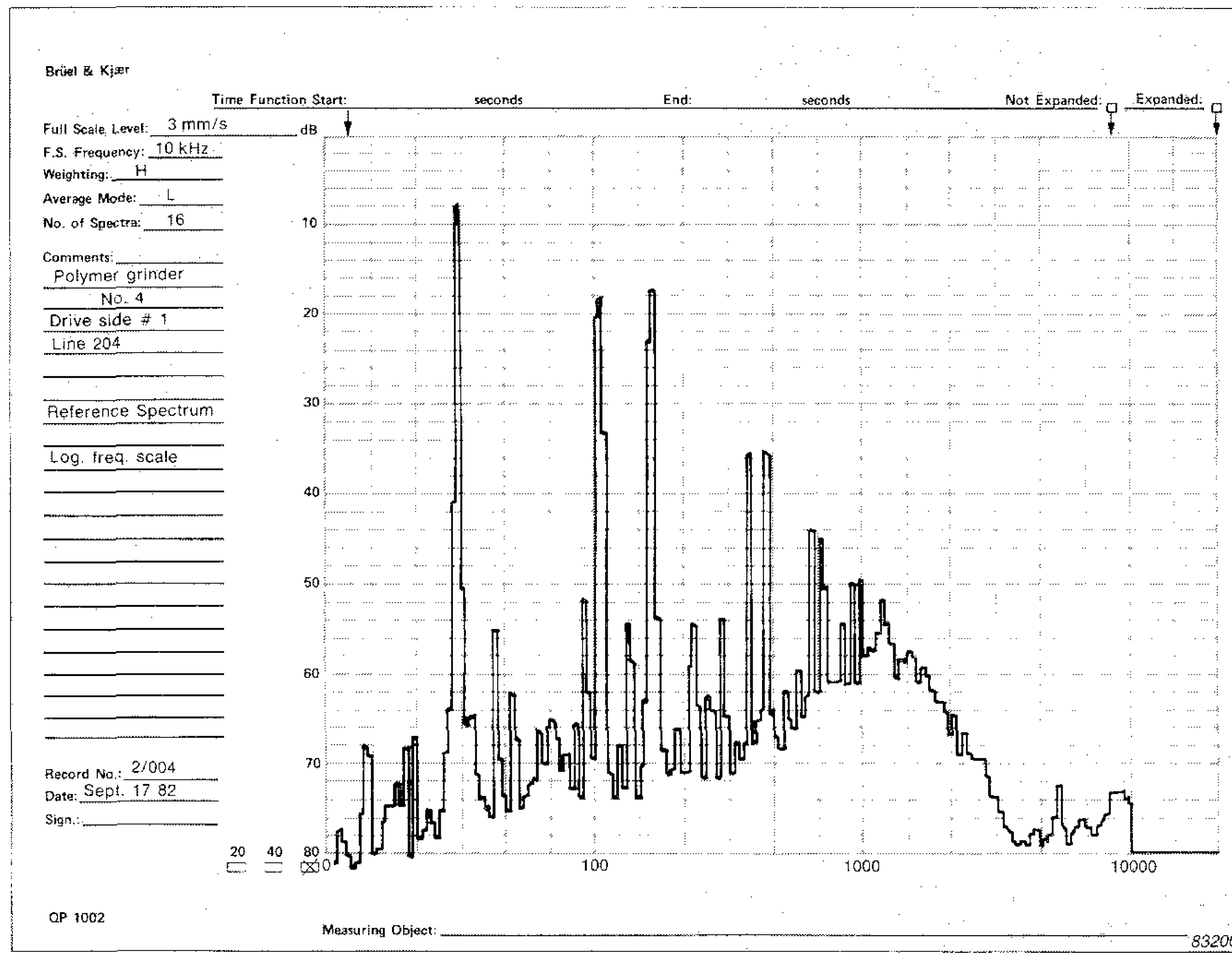


Fig. 2. Reference spectrum after conversion to filters of constant percentage bandwidth

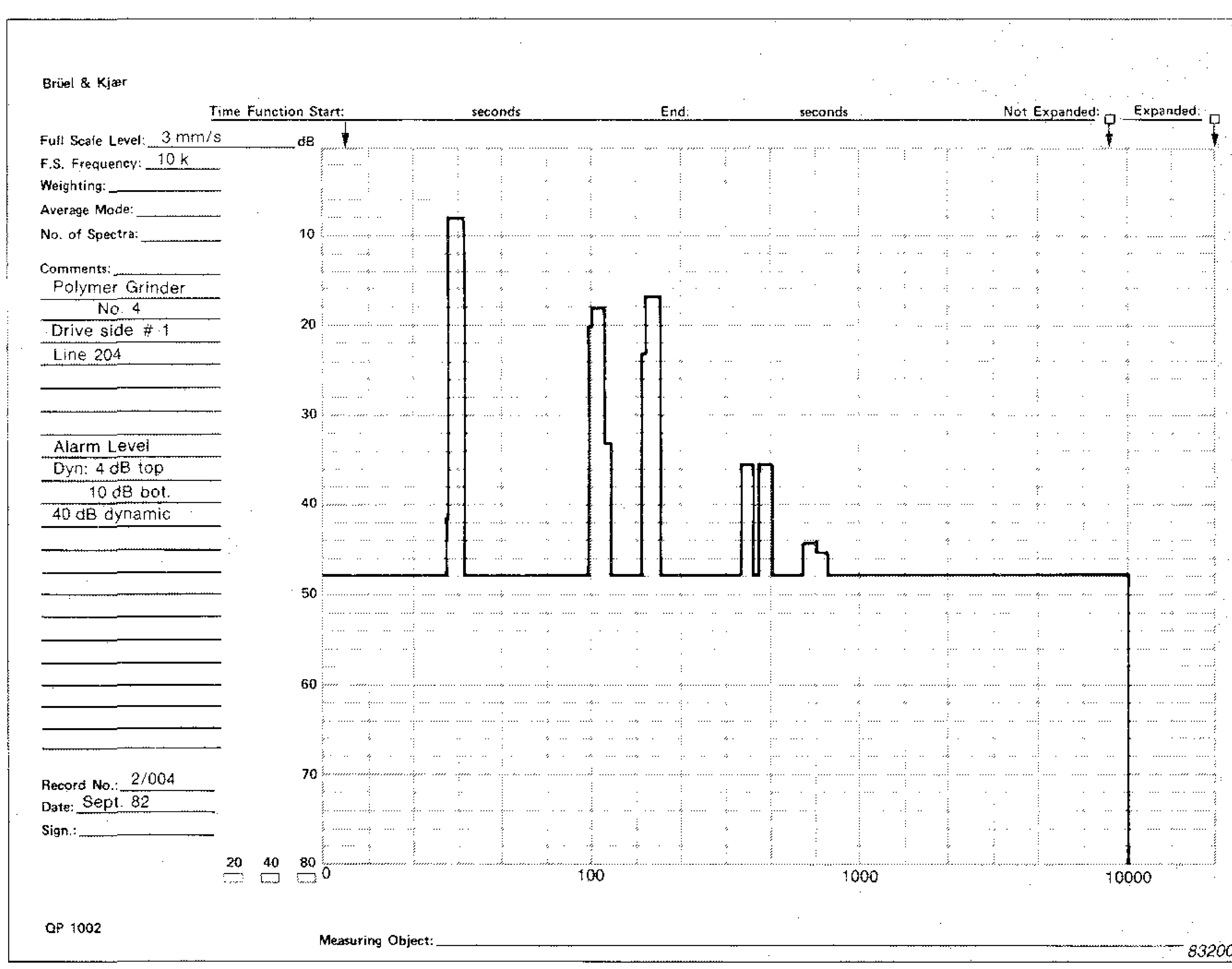


Fig. 3. Alarm levels calculated from the spectrum of Fig.2.
Dynamic range: 40 dB
Limit at maximum amplitude: 4 dB
Limit at minimum amplitude: 10 dB

a) The definition of a reference spectrum which can then be stored on disc. To avoid having to store several constant bandwidth spectra (in order to cover all the spectrum with a sufficient resolution), the calculator converts spectra to constant percentage bandwidth. Three spectra, linearly averaged, having respectively bandwidths of 100, 1000 and 10 000 Hz, are converted to a spectrum with a logarithmic frequency scale. The resolution of this spectrum can be varied, with a maximum of 60 bands/decade. If machines with variable operating speeds are monitored, it may be of interest to reduce the resolution slightly (e.g. 15 bands/decade). This spectrum serves as a reference base for all further measurements. It should be noted that for machines with variable speeds and/or variable loads, it may be necessary to establish several references depending on the operating conditions.

b) The performance of the routine monitoring. The measurements are recorded on magnetic tape (one minute's recording at each measurement point) and accompanied by a commentary made by the operator into a microphone. It should be noted that separate charge amplifiers are employed although in the near future a tape recorder with built-in amplifiers will be used. This will practically reduce the control manipulations to a simple start/stop operation.

When a certain number of measurements have been performed, the tape recorder is connected to the analyzer and the reference of the first measurement is recalled from the mass storage.

The calculator then generates a "mask" by taking a band on both sides of each spectral line with a value of 2 to 6 dB greater than the amplitude of the line.

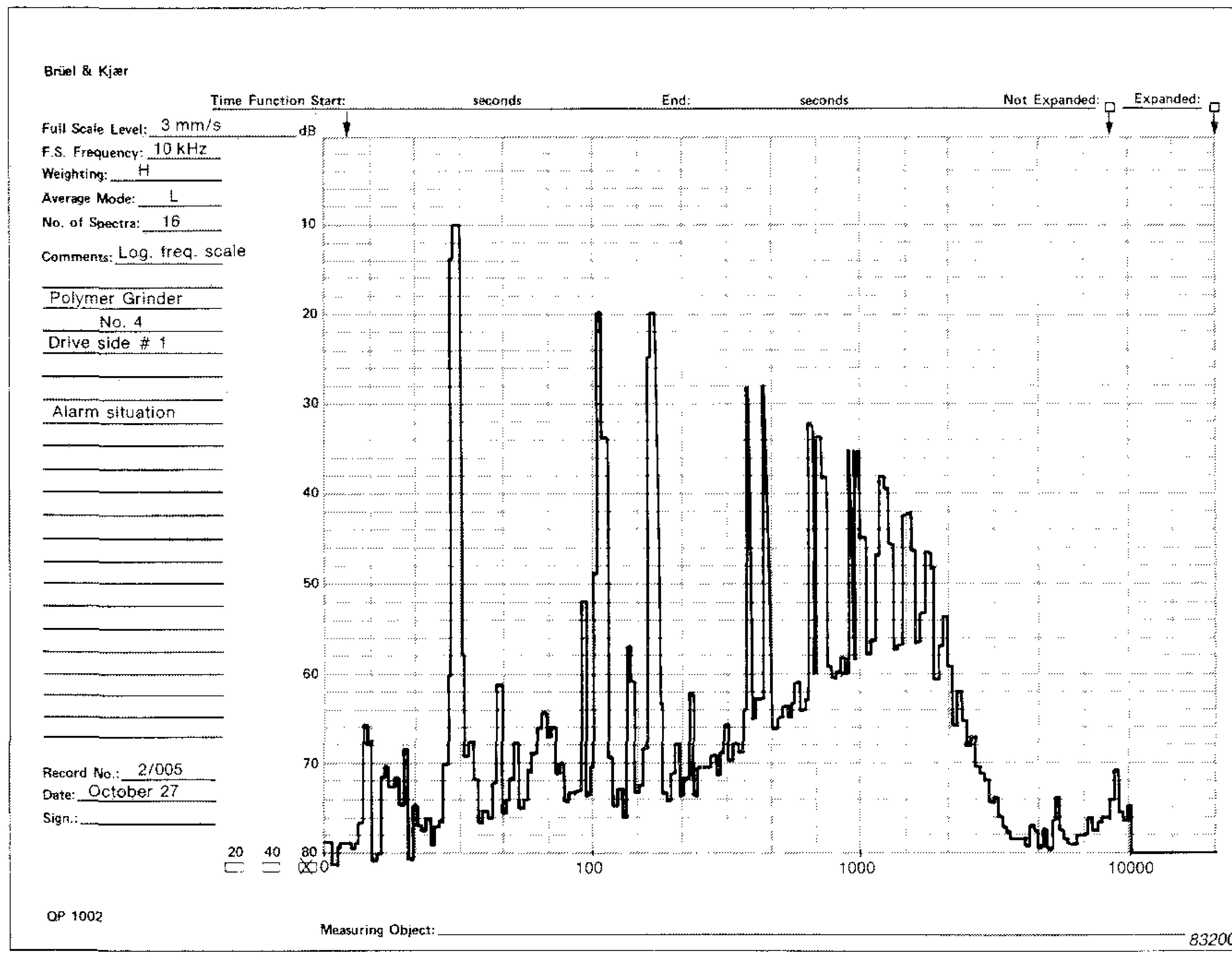


Fig. 4. New spectrum. Compared to Fig.2, there is an increase in amplitudes between 170 Hz and 2000 Hz

If the new measurement "fits" into the mask, that is, if no spectral line is greater than the mask, then no alarm message is produced. If on the contrary, a spectral line exceeds the mask level, then an error message is produced, (Figs.2 to 5).

Methods of analysis and diagnosis

When an anomaly is registered, either from the frequency analysis or from the SPM measurements, the next problem is to produce a diagnosis and to estimate the probable operation time before breakdown.

Other measures of monitoring can also supply complementary information or verification. For example an anomaly in a gear, detected by frequency analysis can be confirmed by the increase in the amount of debris in the oil or by a change in the debris' grain size.

Moreover, we use true diagnostic methods:

— Stroboscopic analysis: particularly useful in the analysis of belt drive transmissions and particularly timing belt drives.

MOBIL PLASTICS EUROPE
Maintenance Department
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Surveillance de routine des machines tournantes
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Reference vient du fichier: 1

Identification: MOTEUR PRINCIPAL MDO

Nouvelle mesure:

Identification: 18 SEPTEMBRE 1982

Comparaison des spectres

PAS DE CHANGEMENT SIGNIFICATIF DETECTE

Reference vient du fichier: 3

Identification: MOTEUR PRINC.ETL2

Nouvelle mesure:

Identification: 18/9/82 SPEC

Compensation de vitesse

La reference memorisee est 17.50Hz

La nouvelle frequence est: 20.25Hz

COMPENSATION: 2CH

Comparaison de spectres

FREQUENCY (Hz)	INCREMENT (dB)	INPUT LEVEL (dB)	REF. LEVEL (dB)
171	35.1	95.1	60.0
185	8.8	66.0	57.2

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Fig. 5. Generated messages
1. File 1: no evolution
2. File 3: alarm message with increases at 171 Hz and 185 Hz (corresponding to Fig.4)

— counting of SPM impulses: in the case of bearings rotating at very low speed, the amplitude of the pulses is not always indicative of the bearing condition. We prefer to use a counter over a one minute interval, or a graphical recording of the impulses as a function of time. The "blackening" of the paper is the criterion by which the state of the bearing is assessed (Fig.6).

— examination of the relative phase of the unbalance, by means of a balancing phasemeter and a photoelectric cell. This enables information to be gathered concerning the state of the internal components of a roll (corrosion, deposits, looseness) for instance.

— sideband analysis at the meshing frequencies of the gears. The meshing frequencies act as amplitude and/or frequency modulated carriers at the rotational frequencies of the various pinions or their harmonics. This is possible:

- either directly by using the zoom function of the analyzer and small programs to find the side bands (Fig.7).

- or via a "cepstrum" calculation. This is defined as the power spectrum of the logarithm of a power spectrum. It thus emphasises those spectral lines reoccurring periodically in the spectrum that is, the harmonics and the sidebands.

  This analytical tool is useful when confronted with a spectrum in which the sidebands of several meshing frequencies overlap and direct analysis is difficult (Fig.8 to 10). The calculation of "cepstrum" is part of the library of diagnostic programs.

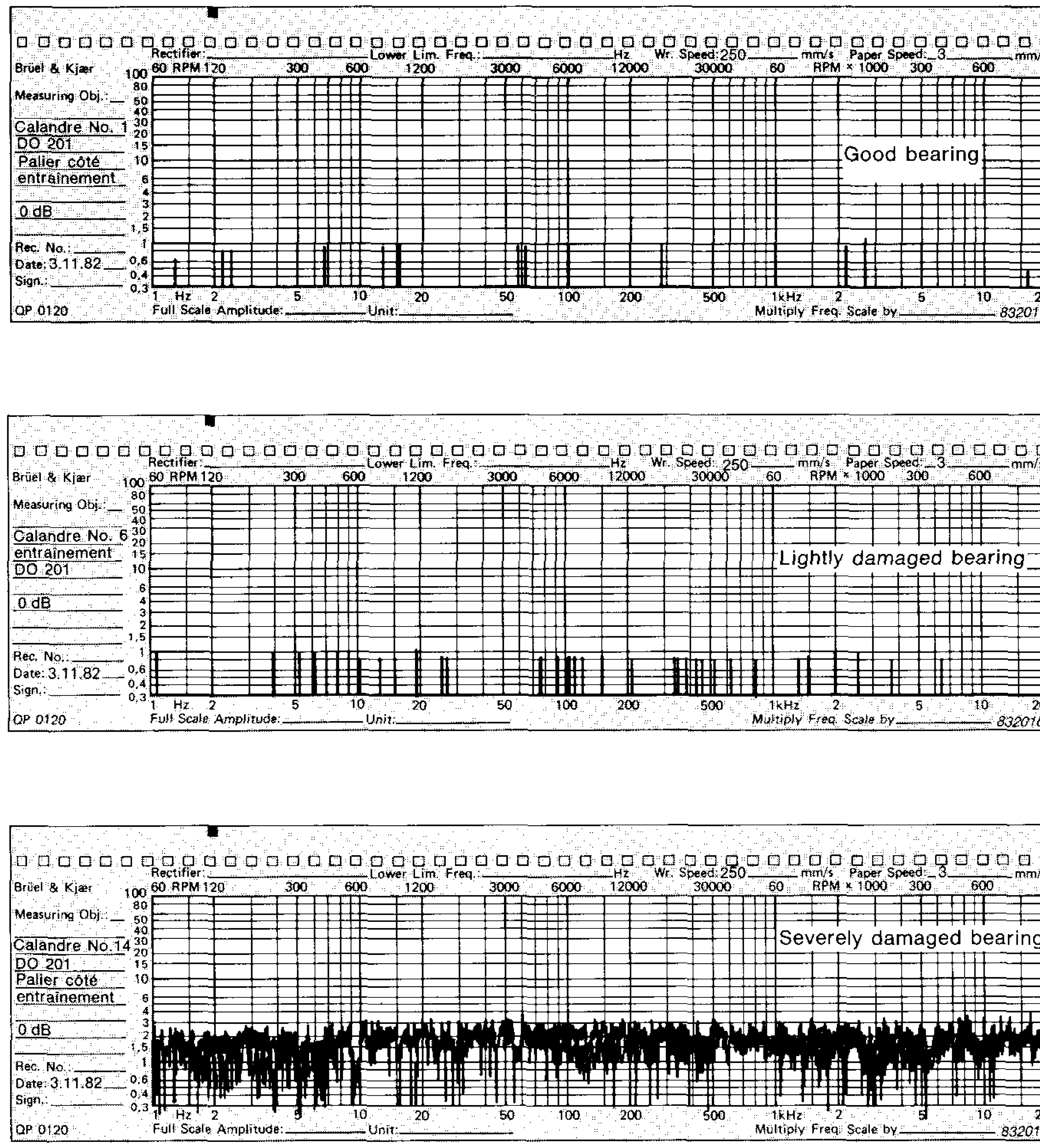

Fig. 6. SPM measurements on bearings at low frequencies

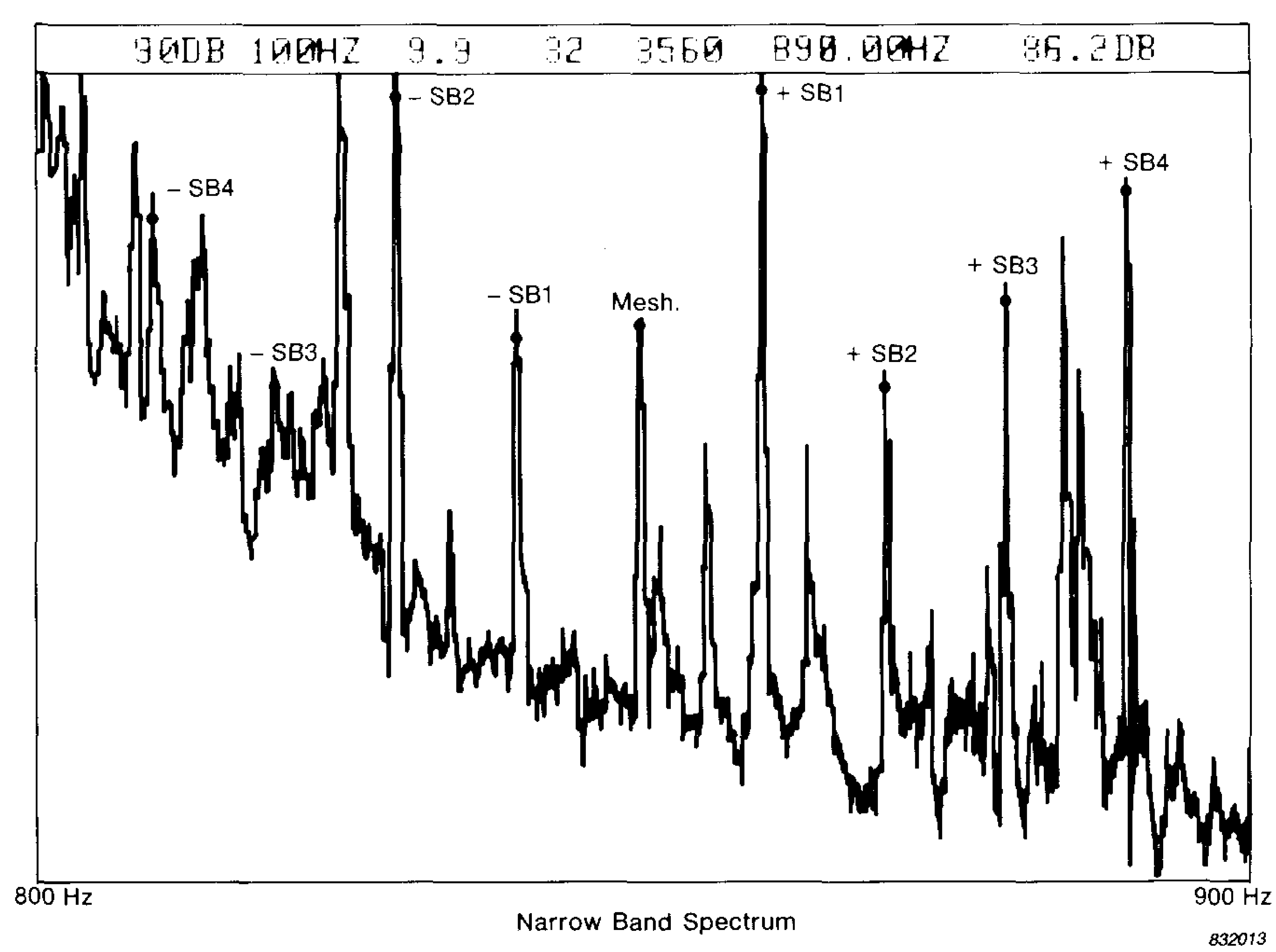

Fig. 7. Zoom of 100Hz about the meshing frequency of 850Hz showing the sidebands

Results obtained

The results of a predictive maintenance program are not easy to evaluate.

The success or failure of the program can be measured by the equipment up-time and the maintenance costs.

We have tried to evaluate the benefits obtained in an 18 month period from January 1981 to July 1982 concerning 28 documented cases (Table 3).

We have calculated:

1. The saving achieved in direct maintenance costs; that is, the difference between the cost of repairs made as a result of a scheduled shut-down (following the detection of a fault) and the costs which would have arisen had the fault been allowed to develop until a breakdown occurred.

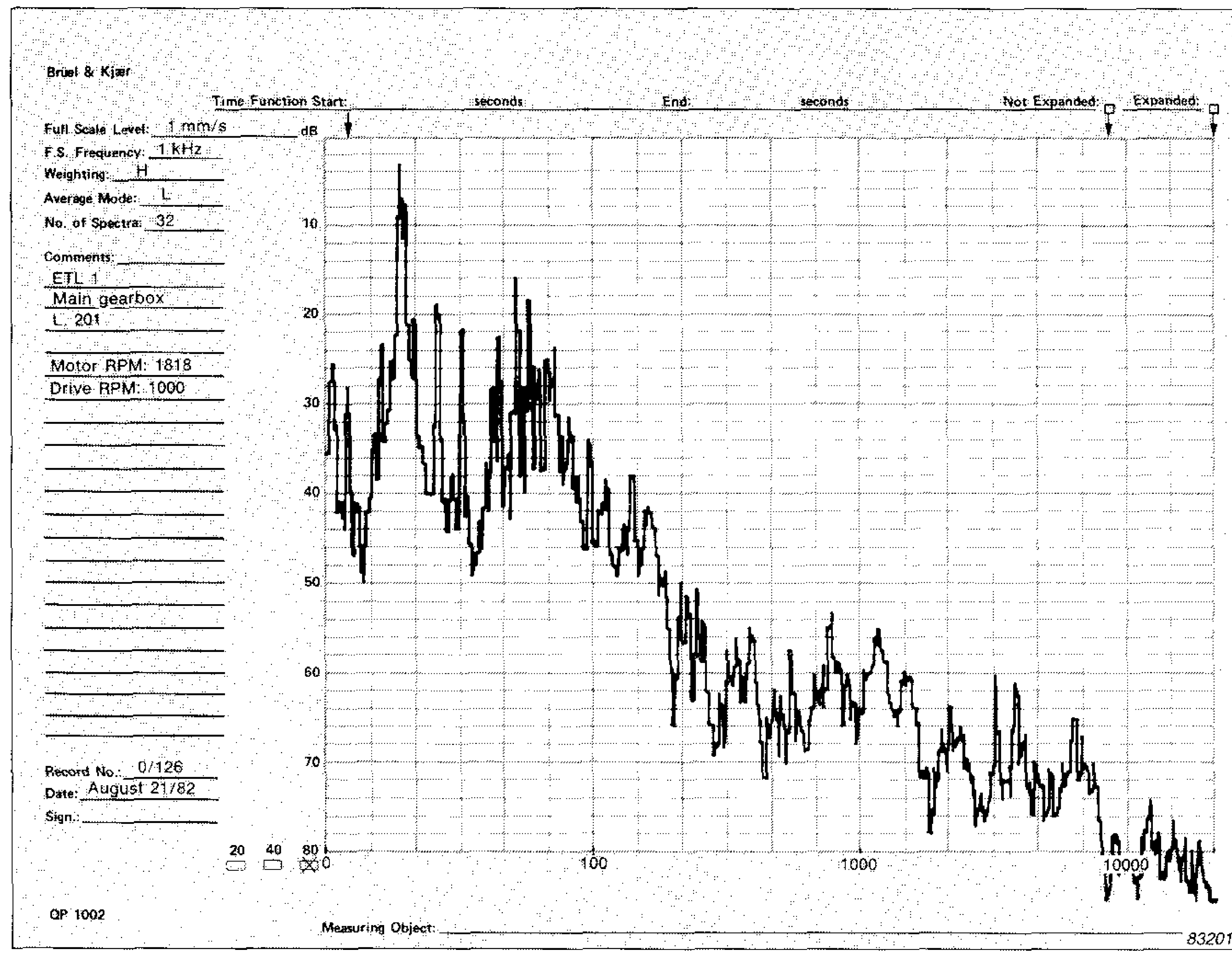

Fig. 8. Spectrum of a gear containing numerous harmonics and sidebands about the meshing frequency

Number	Machine	Component	Fault	Estimated savings (Belgian Francs)	Avoided stoppages (hours)
1	201	Slitting roll	Bearing and shaft end damaged	220.000	16
2	201	MDO 1	4 bearings damaged (faulty mounting)	400.000	30
3	202	Cooling pump	Motor's pillow block and coupling	35.000	8
4	201	DC motor extruder	Brushes and brush holders faulty	500.000	120
5	211	Coating roll	Mounting fault in pillow block	350.000	12
6	202	MDO 2	Shaft's universal joint defective	50.000	8
7	auxil.	Circulation pump nr. 1	Mounting not bolted properly to foundation	40.000	4
8	201	TDO-fan nr. 9	Cracks on mover	75.000	6
9	211	Cooling roll nr. 2	Defect pillow block	175.000	30
10	201	Pump, transfer line	Defect pillow block	55.000	8
11	201	Blower of air-knife	Unbalance in rotor	86.000	12
12	202	Gauge helper	Defect in motor's coupling	20.000	6
13	211	Transmission of treater E	Gear (bad pre-tension of the bearings)	60.000	8
14	202	MDO 3 — Angle piece gearbox	Bearing ruined on the primary shaft	39.000	3
15	201	Main gear — treater W	Worn attack pinion due to bad mounting	43.000	5
16	211	Cooling roll nr. 1	Defect bearing	175.000	12
17	211	Roll at exit of oven nr. 2	Defect bearing	32.000	4
18	211	Cooling roll nr. 3	Pillow block support crack	85.000	12
19	202	Winder W	Damaged shaft end	131.000	3
20	201	Aerial transfer 3 & 5	Worn bearings	34.000	3
21	202	Treater E	Poor alignment of pullies	25.000	2
22	202	Folder transmission at oven exit	Dry gear, defective seal	60.000	13
23	211	Schmitt coupling TCI	Needle bearing defective	60.000	6
24	203	Thermal fluid pump nr. 9	Bearing worn	25.000	3
25	201	Oven's circulation ventilator	Unbalance due to deposits on the rotor	35.000	4
26	203	Presser transmission	Misalignment of pullies	32.000	2
27	202	Gauge gear	Dry gear, packing leak	60.000	3
28	203	Main extruder	Motor misalignment	133.000	10
			TOTAL	3.035.000	253

Table 3. Documented cases from January 1981 to July 1982

2. The saving achieved in production time due to the fact that the repair was made at scheduled shut-down (e.g. a change in production) and its effect was reduced relative to the repair time required after a breakdown.

Overall then, considerable savings were made compared to run-to-break maintenance.

The saving obtained by comparison with a periodic preventive maintenance is more difficult to estimate as it is difficult to set a figure on the efficiency of this approach.

Conclusions

Predictive preventive maintenance has proved to be a viable alternative to periodic preventive maintenance. It has produced considerable gains in machine up-time as well as substantial savings in spare parts and in labour costs.

Although vibration measurements are the basic tools for machine monitoring, they should be used simultaneously with other techniques (analysis of oil, thermography, efficiency tests).

Furthermore, if a high degree of efficiency is required from these measurements, then it is not enough to perform non-filtered measurements of vibration level, but as much as possible, to perform a spectral analysis.

When the number of measurement points reaches a hundred (and this number is rapidly reached if predictive maintenance is employed), the only viable solution is to employ a computer to help in the measurements and data reduction.

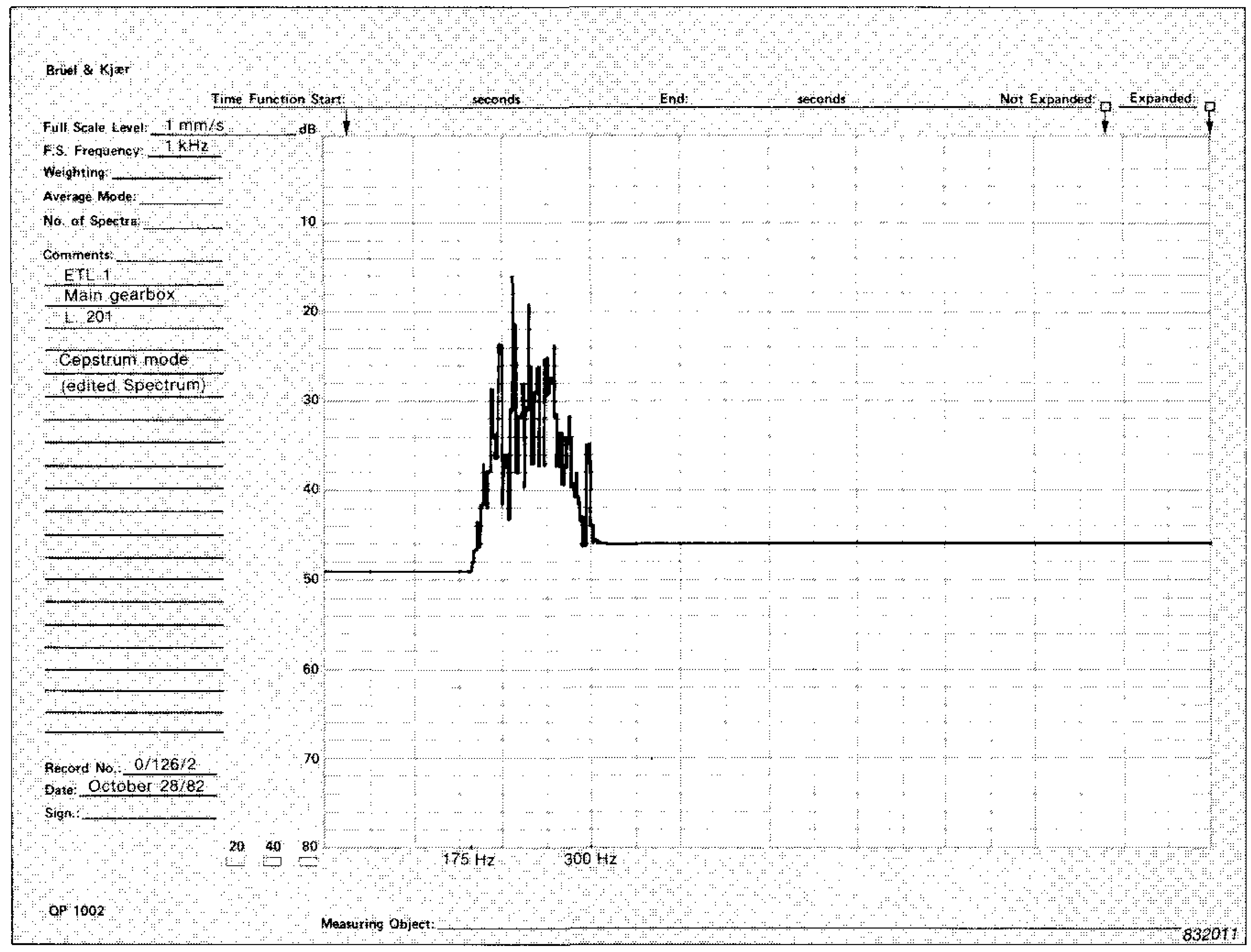

Fig. 9. "Edited" spectrum before the calculation of cepstrum, so as to eliminate harmonics far from the meshing frequency

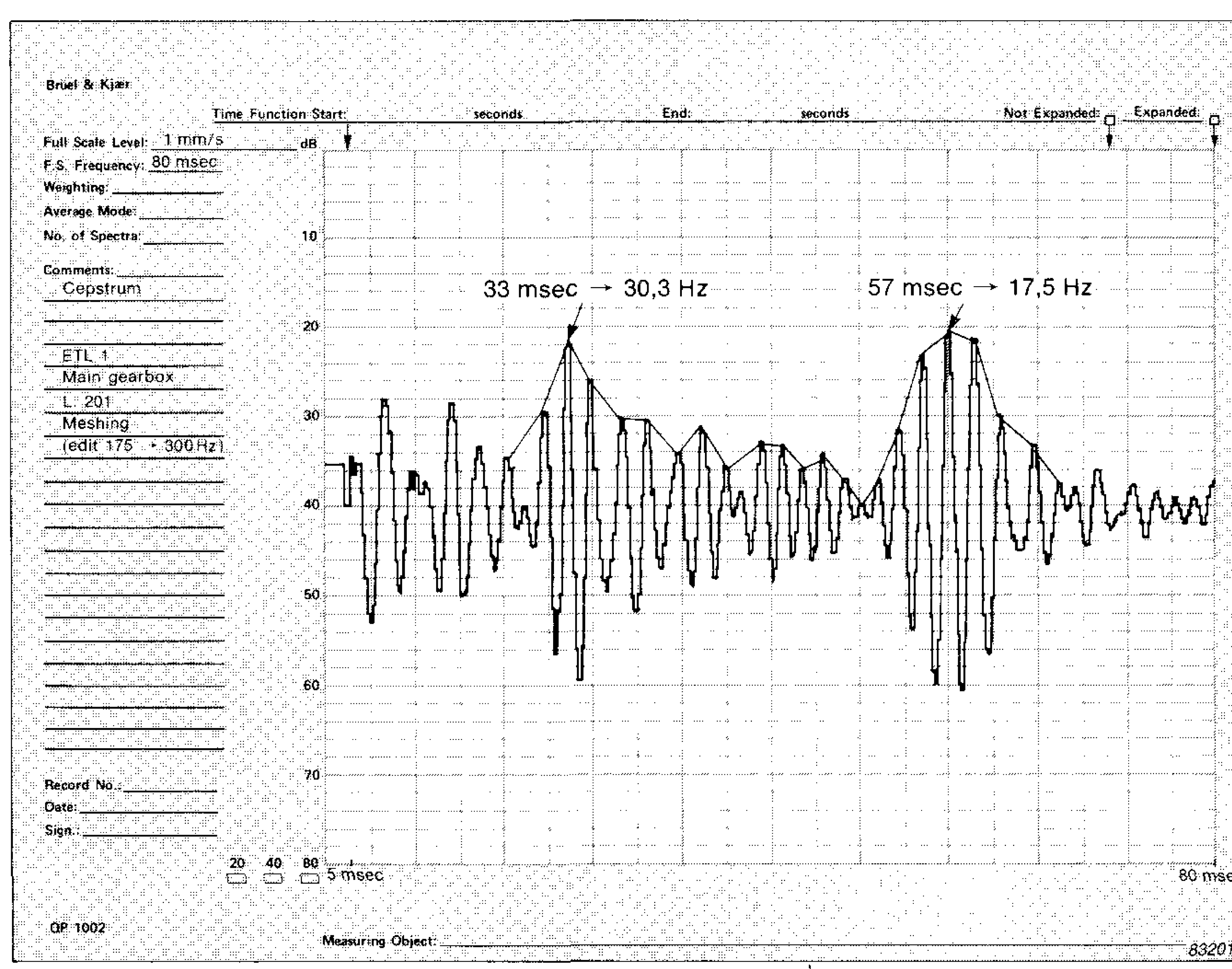

Fig. 10. Cepstrum calculated from Fig.9. The two lines at 33 msec. and 57 msec. correspond to the rotation speeds of the pinions

Brüel & Kjær

WORLD HEADQUARTERS: DK-2850 Nærum · Denmark · Telephone: +45 2 80 05 00 · Telex: 37316 bruka dk · Fax: +45 2 80 14 05

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