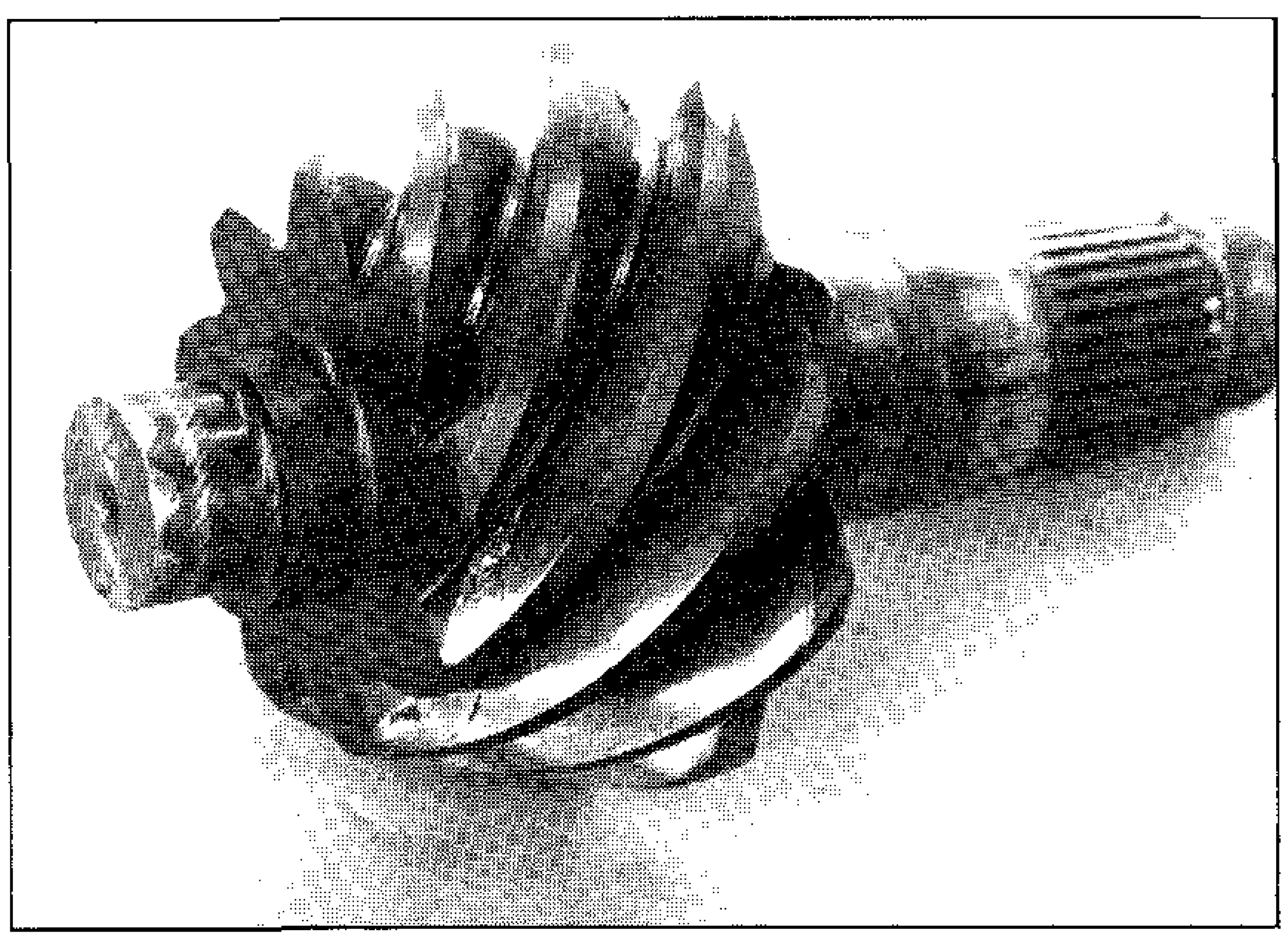
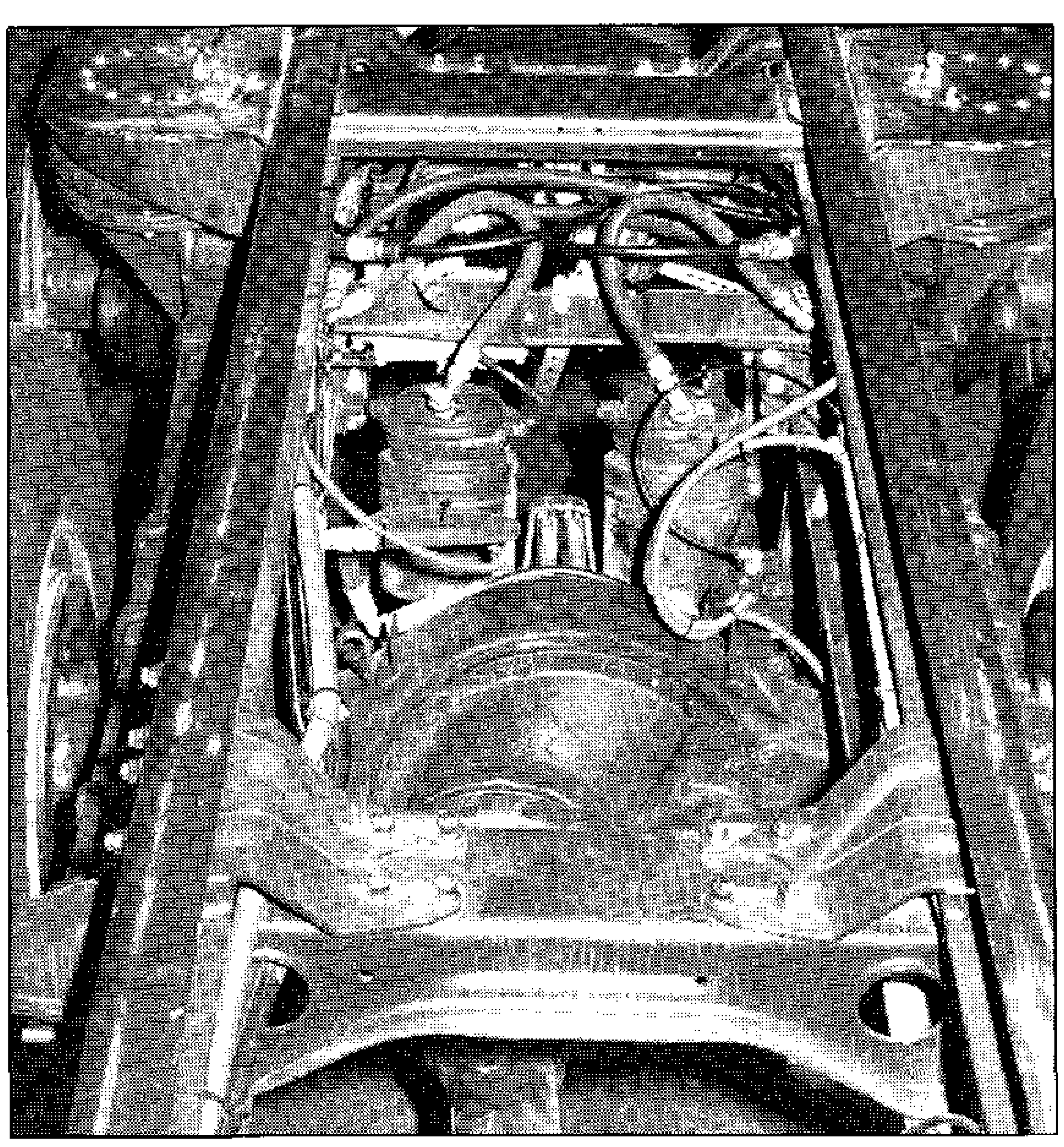
Application Notes

Early Detection of Gear Faults Using Vibration Analysis in a Manufacturer's Test Department

Better Axle Gears on RABA Trucks:-





Industrial users know the benefits of vibration measurement for machine condition monitoring:- breakdown avoidance and efficient maintenance planning. But manufacturers should also be aware of the benefits, for instance in production quality control (QC). In Hungary an important manufacturer has been using vibration measurement to study gear failure, to identify failure mechanisms and improve or establish production quality.
The early detection of faults just starting to occur, that has been achieved, is of interest to all users of vibration measurement or monitoring.

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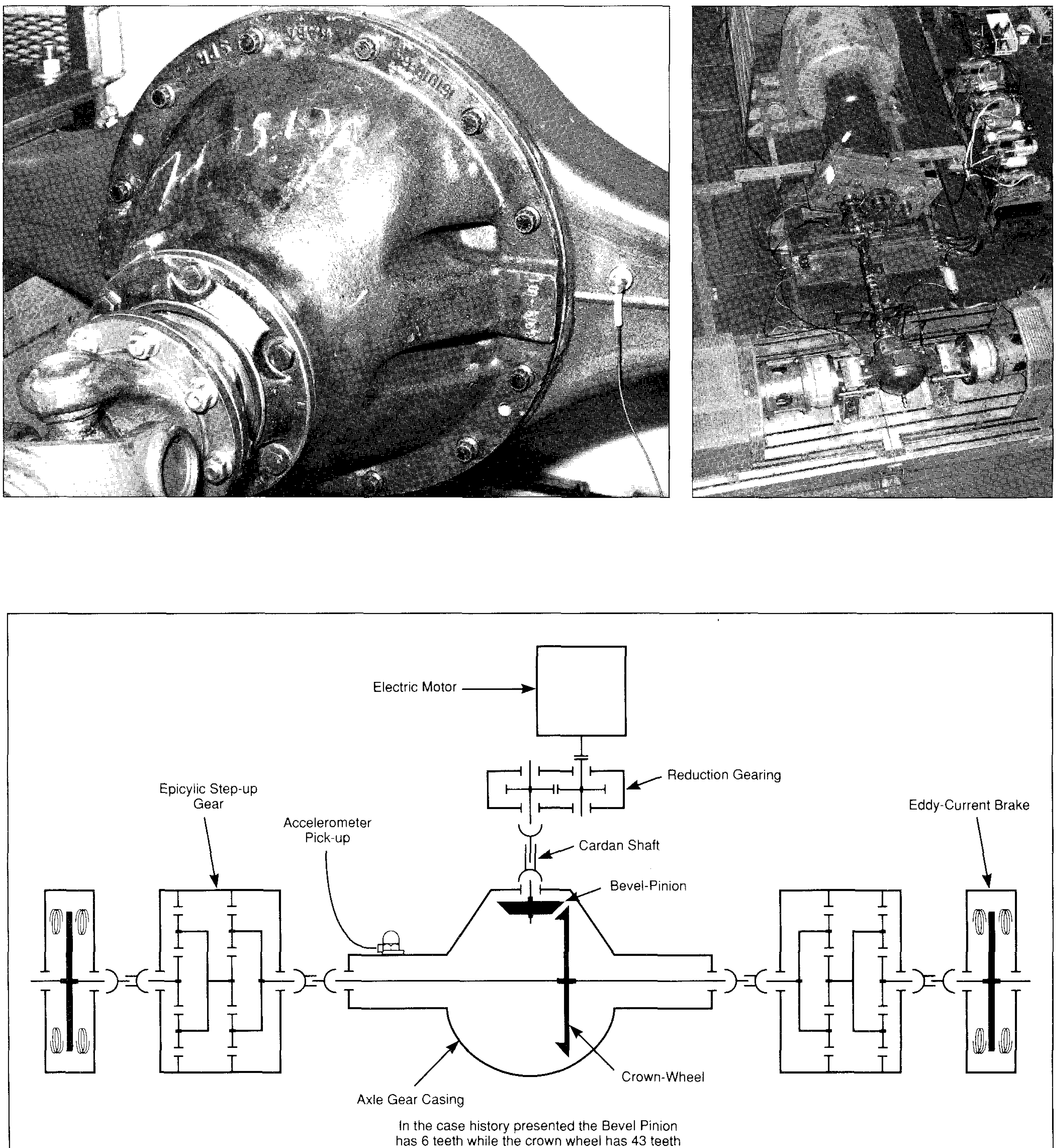

Fig. 1. Photographs of the test stand and schematic of the arrangement identifying the component parts

Early Detection of Gear Faults Using Vibration Analysis in a Manufacturer's Test Department

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Introduction

A study of gear vibration in heavy-truck rear-axle-units has been made in the test department at the RABA factory in Györ, Hungary. RABA is a major manufacturer in Hungary, with a workforce of some 16,000. They manufacture diesels, gears, axle-units, trucks and agricultural vehicles. They have many export markets outside eastern Europe, including the USA.

Reasons to Test

The test department has been involved in vibration testing of truck rear-axle-units in response to three different needs of the manufacturer— 1. testing after customer complaint (failure in service)—2. prototype testing—3. production-line batch-testing. The testing consists of running the units to breakdown, on a specially constructed test bed. The gear vibration is monitored during the tests, to identify failure occurring. This way it has been possible to halt the tests and study the failure mechanisms, before the faults progress beyond all possibility of recognition of the original failure.

Using Vibration

Faults, when they begin to occur, alter the frequency spectrum of the gear vibration. Particular faults are identified by recognizing the growth of distinctive sideband patterns in the spectrum. A program was instigated by the co-author in Hungary, to provide early warning of gear-wear and failure, by using this pattern recognition technique. The result was that the wear and failure mechanisms could be studied by the materials experts and gear design experts, who improve the design and production accordingly—An important example of how vibration measurement can aid manufacturers as well as end-users.

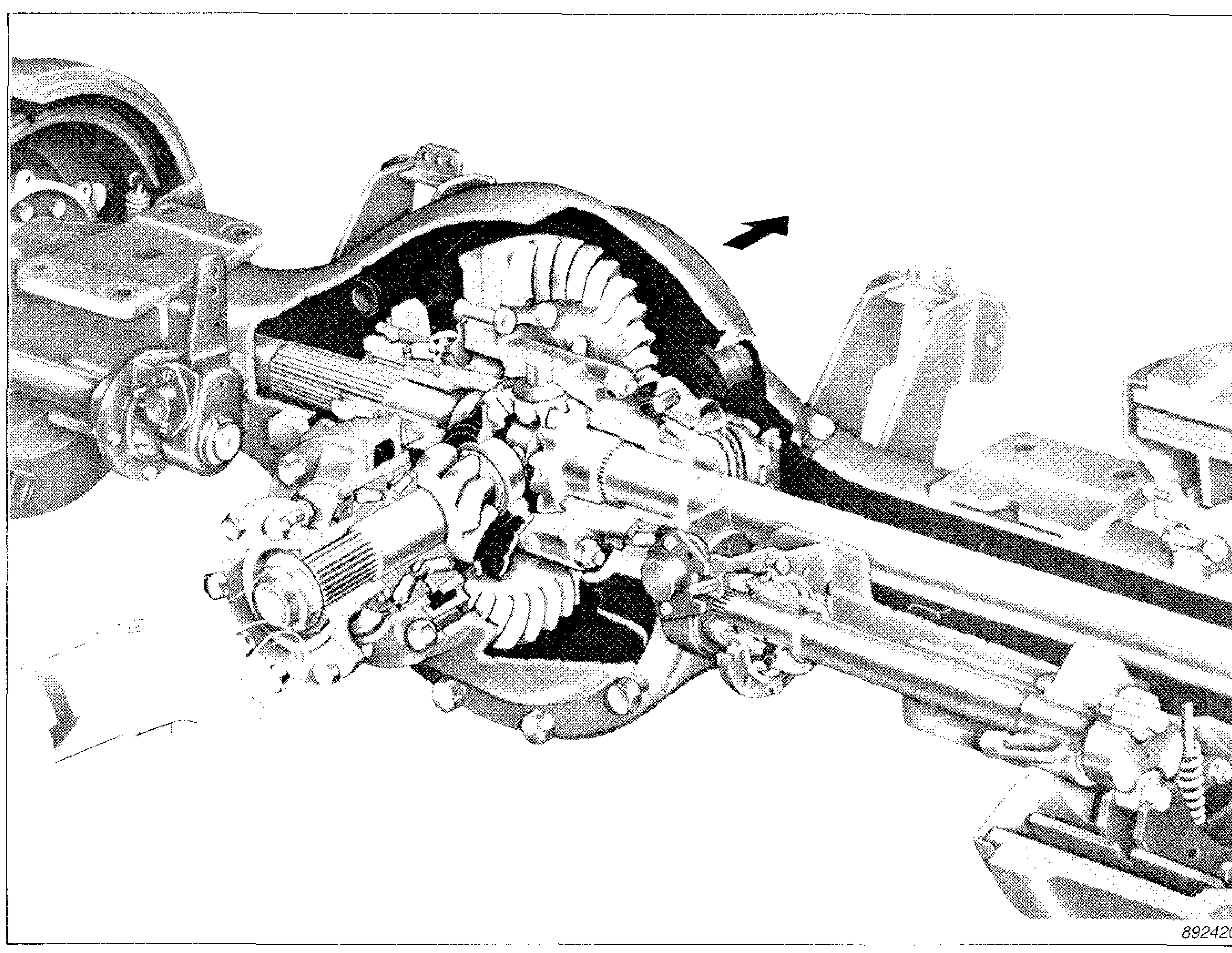


Fig. 2. Cut-away drawing showing the arrangement of gears in the axle

The Axle Gears are Driven to Breakdown

A special test stand is used to drive the axle gears at constant speed and high load. The arrangement can be seen in the photographs in Fig. 1, which also shows the schematic layout of the test stand, as used for all the tests.

The arrangement of the axle-gears can be seen in Fig. 2, the bevel-pinion gear is driven by the cardan shaft as when fitted in the trucks, and this gear drives the large crown-wheel which turns the rear-axle shafts. The centre compensating gears allow one of the shafts to move differentially with respect to the other. However, on the test stand the output shafts are braked with eddy-current brakes, and the torque is controlled to maintain equal load and thus equal shaft speed on both output shafts, so the differential-compensating gears do not turn. It is the bevel-pinion gear and the crown-wheel gear that are the objects of the testing, and it is the vibration from these gears that is monitored. The epicylic gears are used simply to step up the speed of the output shafts, to the operational speed of the eddy-current brakes.

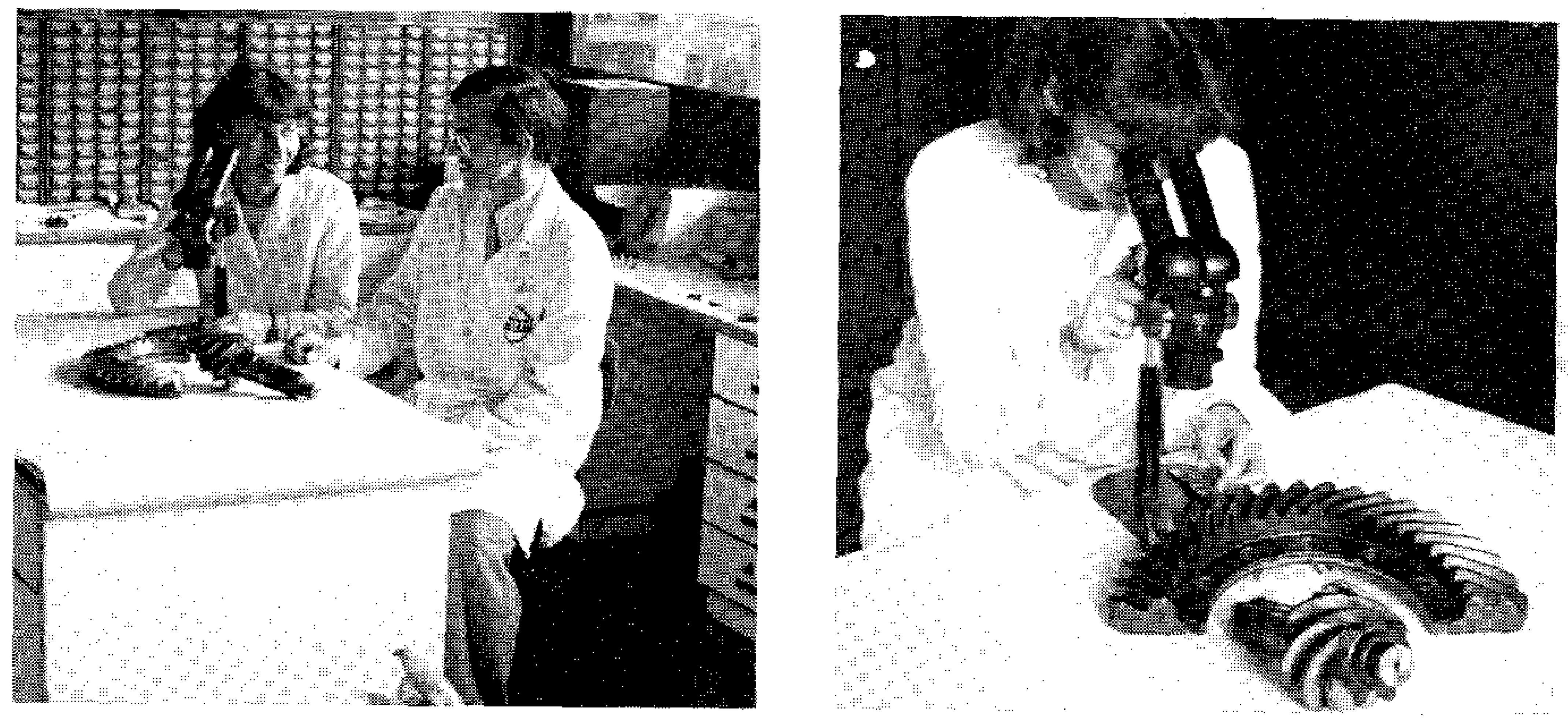
Making Measurements

A single accelerometer is used to measure the gear vibration and the mounting of this can be seen from the close-up photograph of the axle in Fig. 1. The mounting position was selected carefully after trial-and-error mounting of accelerometers in various locations on the axle. The position chosen allows all the expected toothmesh frequencies[1], especially those from the bevel-pinion and the crown-wheel, to be measured quite satisfactorily with the single accelerometer.

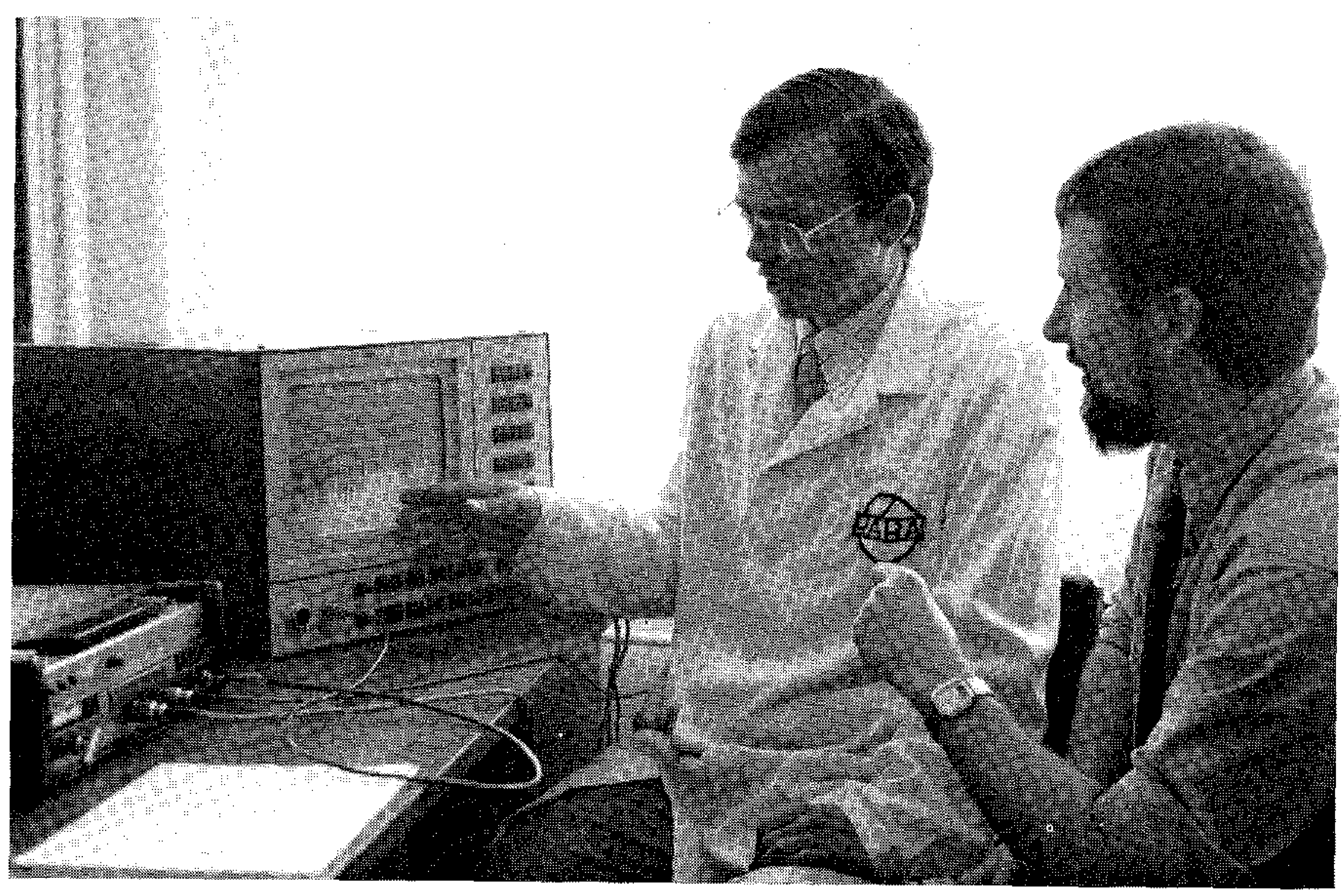
The toothmesh frequency in the axle gear is quite low, so a large number of harmonics can be included in a spectrum of, say 2 kHz. This is ideal for recording on an analogue tape recorder with a bandwidth of, typically, 10 to 20 kHz. Important information can sometimes be derived at the higher harmonics of toothmesh frequency, and the spectrum at these frequencies should be examined.

The gears are driven to breakdown, i.e. until failure occurs, while the vibration spectrum is monitored on a Brüel & Kjær Type 2033 analyzer. In the current arrangement a technician watches the spectrum develop as faults produce established pattern changes. The tests may be stopped to visually examine the fault development, and then restarted.

1 The toothmesh frequency of a gear pair is a frequency component in the vibration spectrum at a frequency equal to the rotational speed of one of the gear shafts times the number of teeth on that gear wheel.



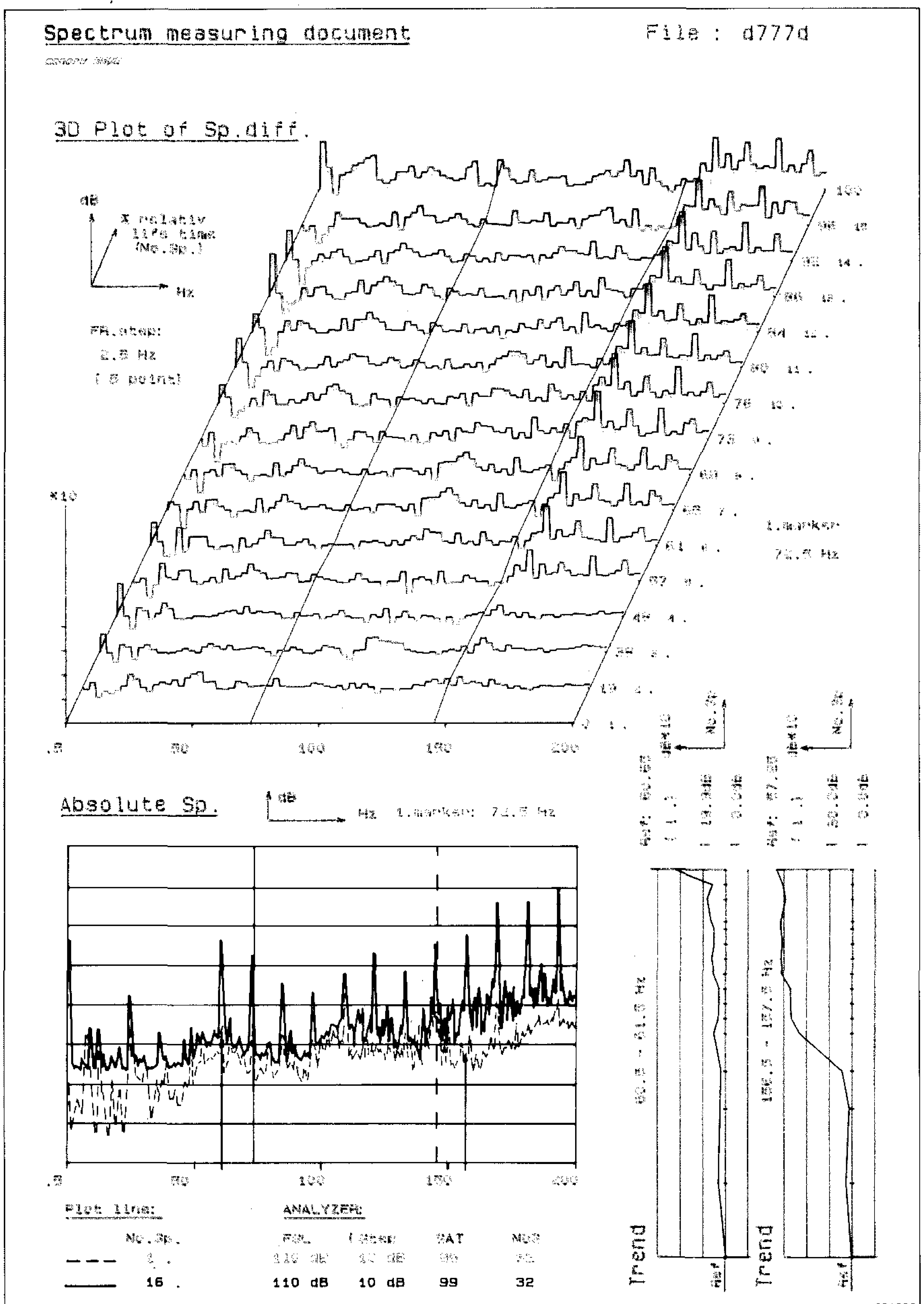
Specimens of gear failure are delivered to the materials analysis laboratory.



The authors discuss the gearbox vibration spectra displayed on the Type 2033 analyzer.

All the tests have vibration measurements stored on magnetic tape and Laszlo uses the 2033 to generate all the baseband and zoom spectra as required. He has created an interface system and documentation system on an IBM Personal Computer and all spectra are stored and managed in a database on this computer. Also included are facilities for harmonic and sideband cursors, plus a number of other features including the ability to Trend on vibration amplitude across a narrow frequency band and flexible plotting capabilities.

Fig. 3. Aspects of the work in Hungary



A typical plot produced on Laszlo's system as part of the test documentation. It shows a 3D plot of 16 spectral records (difference spectra with the first record as the reference spectrum), the actual spectra for the 1st and 16th records and, finally, trend plots of vibration amplitude growth across two narrow frequency intervals.

The Development of The Test Program

Need to Prevent Damage

The gears are driven to breakdown also for the purpose of endurance testing. The load that is applied simulates the climbing of a maximally loaded vehicle on a slope of a certain gradient. Before vibration monitoring was introduced, unexpected failure of the gears would often cause sudden seizures. Aside from possible damage to the test bed, the gears in many cases were in such a state of destruction that it was impossible to decide what the primary failure must have been. The tests could be stopped for regular visual checks, but this was not reliable enough to prevent damage.

The vibration monitoring began with an investigation of the vibration spectra to identify the changes caused by failures occurring. The vibration was recorded on a Brüel & Kjær tape recorder at regular intervals during each test. This taped vibration was subsequently analyzed on the Type 2033 to compare spectrum information with the notes from the tests and establish how faults could be identified in the vibration signal. It was found that the growth of sidebands, spaced by the rotational speeds of either the crown-wheel or bevel-pinion (depending on which gear-wheel the fault occurred), indicated the fault development. The sidebands were always centred around one of the toothmesh harmonics, and would occur in the spectrum within the range of the first 3 or 4 crown/pinion toothmesh harmonics, see Fig. 4.

Identifying the Sidebands

By creating simple masks of transparent material with lines at the sideband-spacing and the toothmesh frequency harmonics, the next stage was to take the Type 2033 to the test stand and monitor the faults occurring on the analyzer-screen. The test technician placed the masks over the analyzer-screen, aligned the toothmesh harmonics on the mask and the screen, and then watched for growth in the spectrum on the lines marked with the sideband-spacing. Every time any sideband or toothmesh component increased on the 2033 screen (by a dB value predetermined for the gear type), the technician made a tape recording, as well as recording at regular intervals. The test engineer would then decide whether to stop the test for an inspection or not. This trial system was operated highly successfully

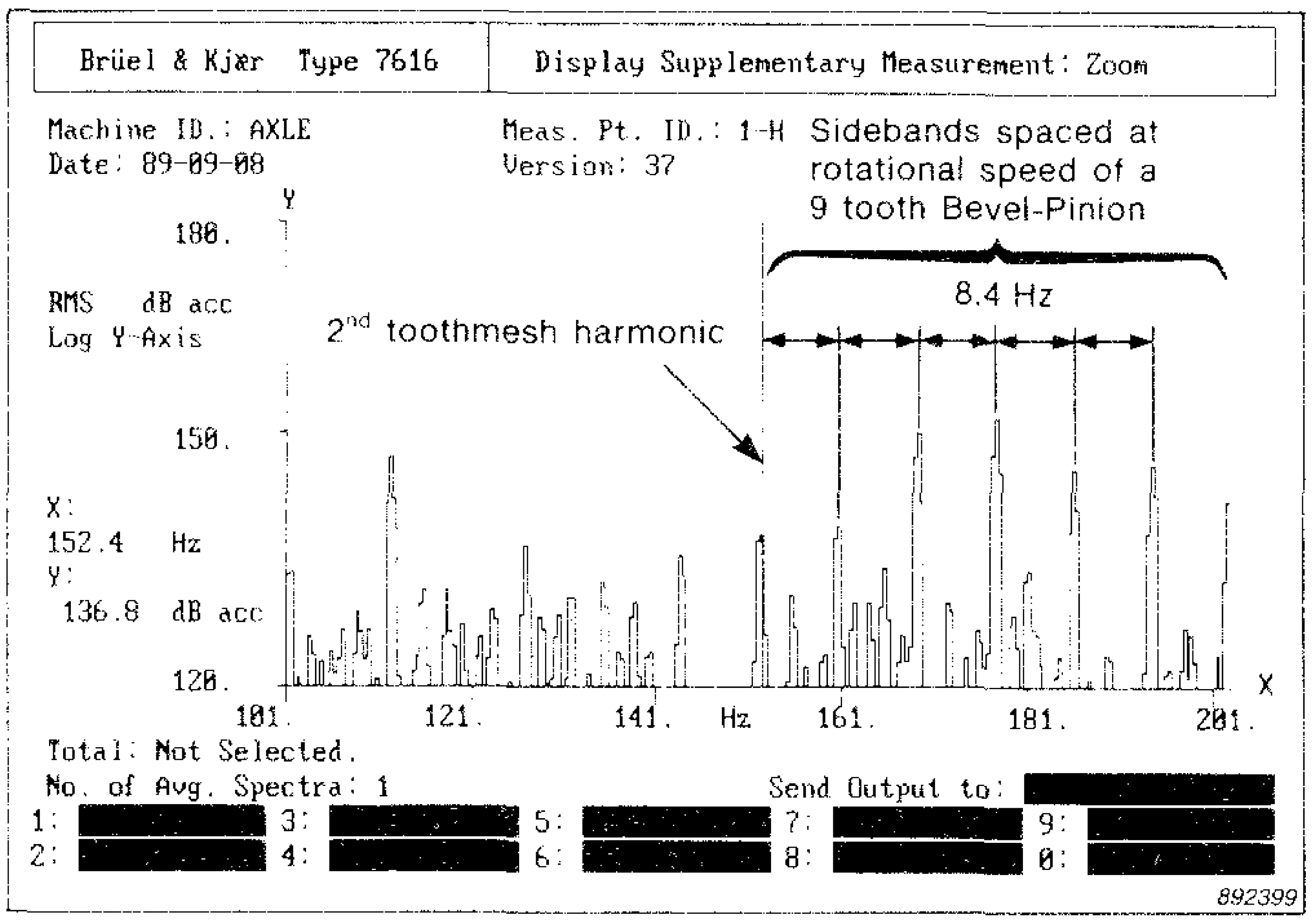


Fig. 4. Growing sidebands of bevel-pinion rotational frequency indicate a fault on a 9 tooth bevel-pinion

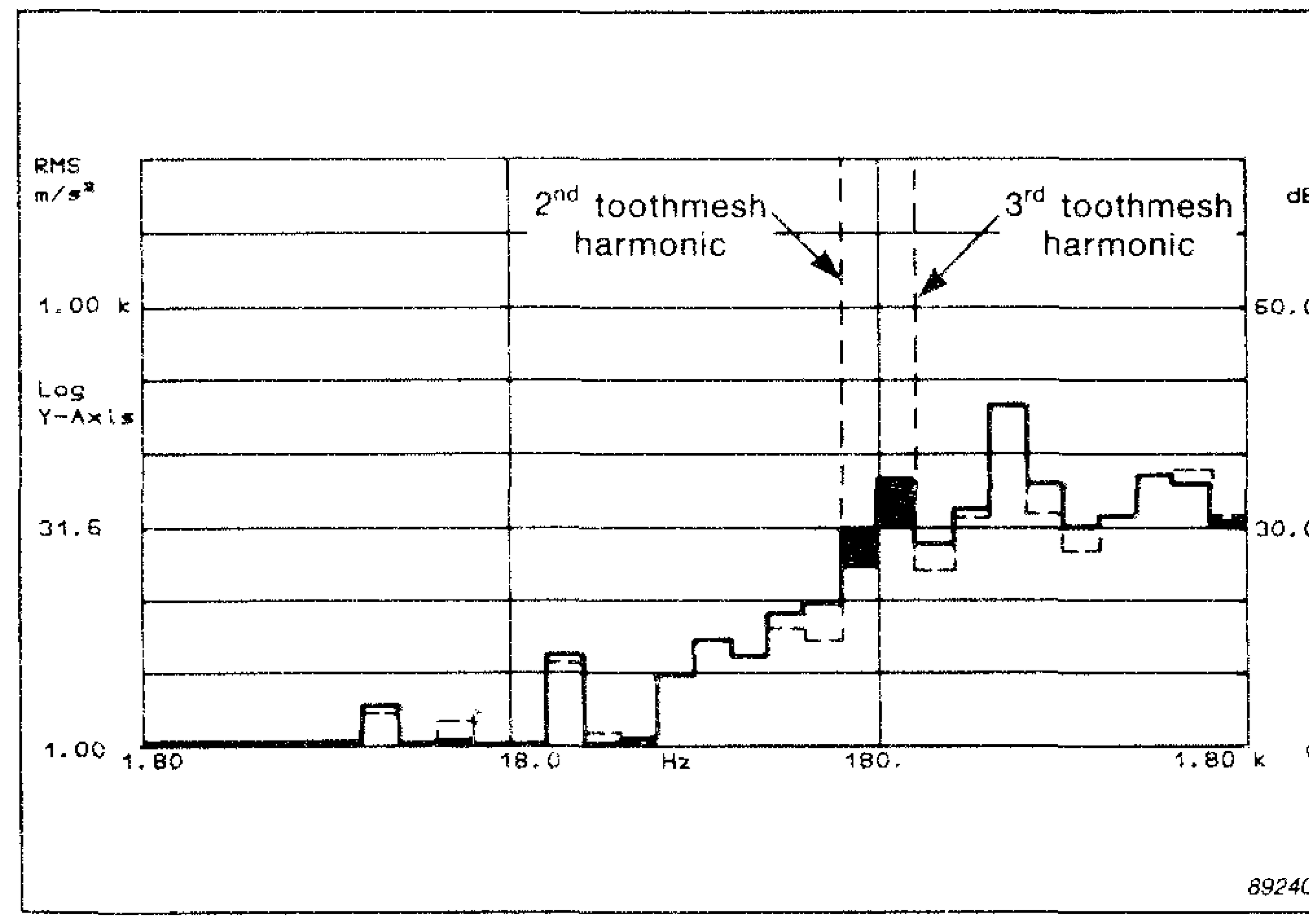


Fig. 5. Spectrum Comparison plot showing how the region (shown shaded), between the 2nd and 3rd toothmesh harmonics, rises as tooth pitting starts to occur (the solid curve is the sixth spectral record and the dotted curve is the fourth)

from late 1987. As a result the test department is developing a computerised system, to perform the same tasks as the technician, but extended to make simultaneous measurements on more than one test bed.

Case History of a Complex Defect

The case history presented here is representative of many of the tests where failure was detected in the process of occurring, but before breakage or seizure of the gears. It is the vibration record of a complex defect, i.e. the failure was firstly the pitting, followed by the crack and fracture of the bevel-pinion. Fig. 3 includes a 3D plot of spectrum difference of 16 measured spectra, measured at equal intervals during the test. This plot is part of the test documentation from RABA. The other plots used (Fig. 4 to Fig. 7) are produced using a Brüel & Kjær Type 2515 Analyzer and Type 7616 Application Software, from a copy tape of the original recordings.

The Pitting Appears in the Spectrum

The evidence of pitting appears in the spectrum in the region between the 2nd and 3rd toothmesh harmonics, appearing first at the 5th spectral record. Fig. 5 shows a spectrum-comparison-plot of the 4th and 6th spectral records. This plot extends to 2 kHz and shows that frequencies above the 3rd toothmesh harmonic show no significant change.

The test was stopped after the 5th spectral record and the pitting on one of the teeth visually examined. This was repeated after the 10th record, where the pitting was observed to be much more widespread. Baseband, zoom and cepstra taken at the 5th and 10th records are shown in Fig. 6. These plots clearly illustrate the growing sidebands.

The 10th record corresponds to 75 % of the life of this particular gear set, which was actually run to destruction, when 2 teeth on the bevel-pinion cracked after the 16th record. This is seen in Fig. 7, which shows a rapid increase in the vibration spectrum of this record with sidebands coming up in amplitude also between the lower toothmesh harmonics, (Fig. 7 shows baseband, zoom, cepstrum and zoom cepstrum of the 16th record). As before, the growing sidebands of pinion-speed are clear, but the zoom cepstrum also indicates wear on the crown-wheel with the appearance of a sideband at crown-wheel-speed. (The opportunity to verify the crown-wheel wear was missed, as the test was allowed to continue).

Total Breakdown

Of the total life of this gear under test, the pinion fractured 0,7% of its lifetime after the 16th spectral record was taken. This particular test took place fairly early on in the development of the test program, and the warning apparent from the spectrum analyzer was not heeded before the fracture occurred.

Finally.....What Does it Mean?

The tests have resulted in a purely empirical method of monitoring the failure of gears of the type described. There are no mathematical calculations to show why the sidebands grow **exactly** where they do. This has not been necessary since over many tests the results have been consistent. Note that tests where also made on axle-units with different numbers of teeth on the pinion and crown, than the particular unit on which the case history has been presented.

How Would The Spectrum Be Expected To Look?

Having said that it has not been calculated exactly where the sidebands will appear, the sideband patterns can be "understood" from frequency analysis theory:

The tooth faults are periodic with the gear shaft rotational speed which must then reflect as a fundamental component in the modulation spectrum. The modulation is quite complex, but the resulting toothmesh signal can be represented in the time domain as the product of a phase modulated "carrier" signal and a signal describing the "envelope" of the amplitude variation. Interested readers are referred to the references given at the end of this Application Note for in depth discussion of this, including useful explanatory diagrams for which there is not space enough in this Application Note.

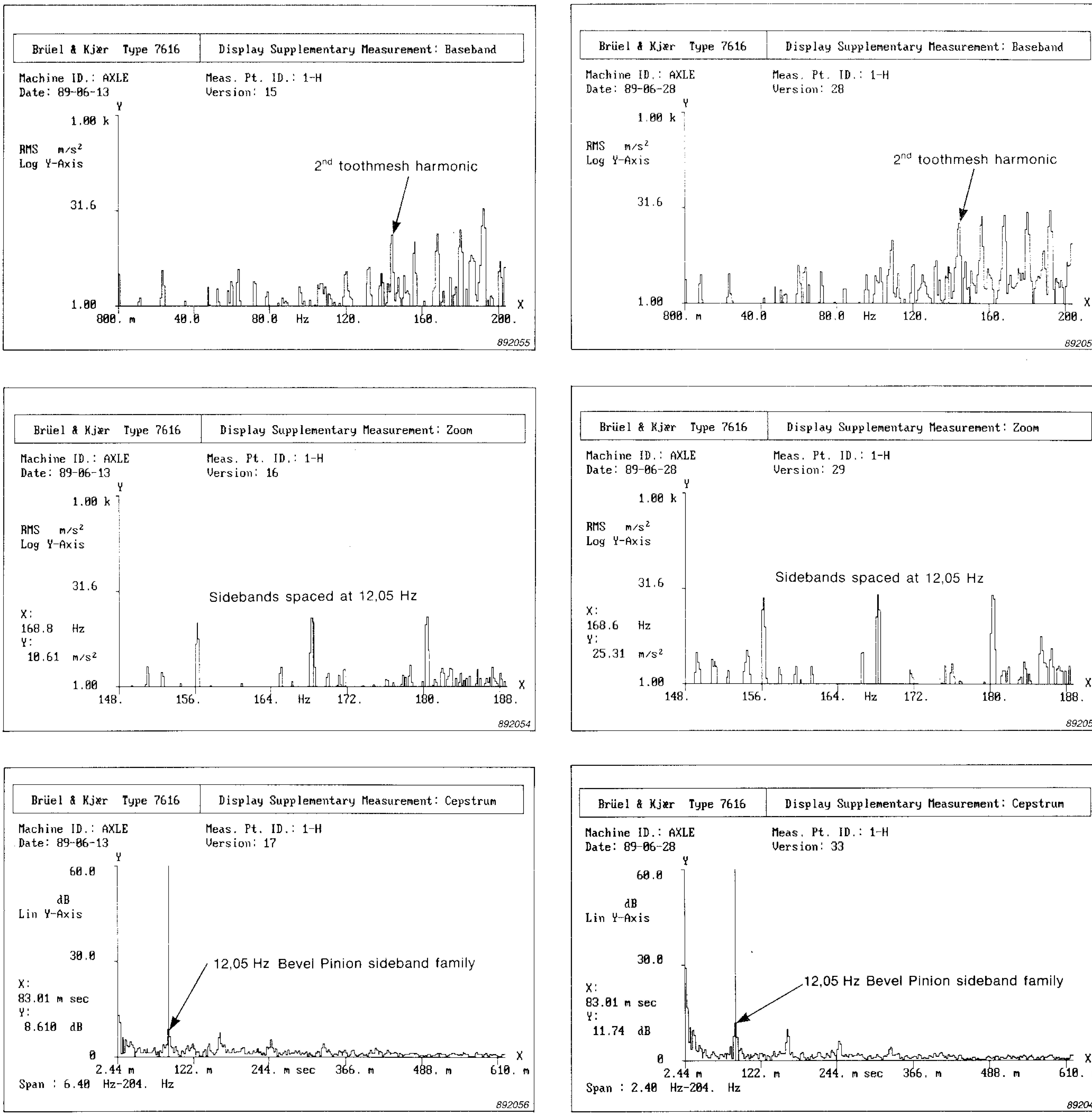


Fig. 6. Baseband, zoom and cepstra taken at the 5th and 10th records in the columns to left and right respectively, showing the growing sidebands as pitting spreads from one to more teeth on the 6 tooth bevel-pinion

Multiplication in the time domain, according to the Convolution Theorem, transforms to a convolution in the frequency domain. The resultant spectrum of the modulated toothmesh signal is thus described by the convolution of the "carrier" spectrum with the "envelope" spectrum. This explains why the sidebands are always centred around the toothmesh harmonics. The fact that sidebands appear (and can disappear) in different locations, can readily be appreciated if you are familiar with frequency/phase modulation and amplitude modulation, (see the references). It is thus impossible to predict the sidebands exactly, without prior knowledge of the faults, and a mathematical description of the forces generated by these faults. However, it is possible to predict all the locations where the sidebands can appear, and so look for them there. This is exactly what has been done at RABA.

Other Faults

Finally, the story of one other particular test is quite appropriate. In this particular test the technician noticed "sidebands" growing but not where the masks placed on the analyzer screen indicated they should grow. By moving a mask he ascertained that the "sidebands" were indeed spaced at the rotational speed of the bevel-pinion, but they were not centred around a toothmesh harmonic. The investigation of this test led to the discovery of an incorrectly fitted bearing on the bevel-pinion shaft.

The explanation of why the "side-

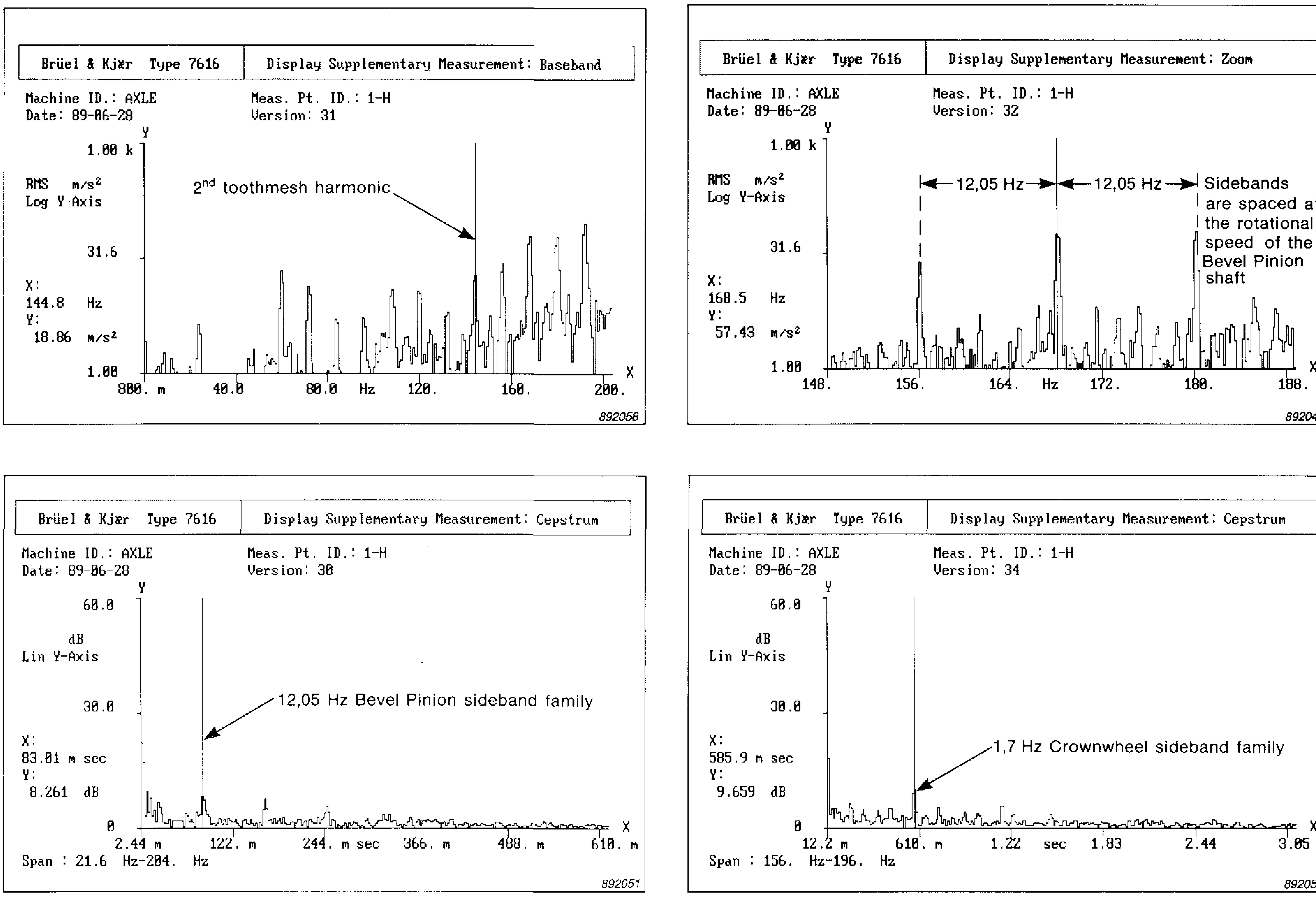


Fig. 7. Baseband, zoom, cepstrum and zoom cepstrum of the 16th record, when a tooth cracked on the bevel-pinion

bands" were not centred on a toothmesh frequency is simply that the bearing fault has nothing to do with the toothmesh signal. Just as components from other gears and shafts on the test stand **add** into the spectrum, to give the total measured spectrum, the vibration components from the bearing fault also are added into the total spectrum.

Conclusion

It can be confidently stated that the vibration monitoring has been entirely successful in controlling the gear tests: The monitoring of the vibration spectrum always indicates when a test should be stopped, to allow examination of the failure mechanisms in the gear material. As such it is an invaluable aid to the Test Department and RABA. This should encourage the wider application of vibration monitoring in industry, as the quality control (QC) market finds that good vibration monitoring, with modern signal analysis, has great potential. Brüel & Kjær has all the transducer and signal analysis requirements for vibration monitoring and an expanding range of permanent monitoring software. Just as important, they have an enviable reputation for unequalled quality.

Acknowledgement

The authors would like to acknowledge the co-operation of the Test Department and the management of RABA, in making it possible to produce this Application Note.

References

[1] R.B. Randall, "Cepstrum Analysis and Gearbox Fault Diagnosis", Brüel & Kjær, Denmark, Application Note 233-80.

[2] R.B. Randall, "Frequency analysis",
Brüel & Kjær, Denmark, 1987.

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