# MAINTENANCE AND ONLINE DIAGNOSTICS ON GEARBOXES IN THE PETROCHEMICAL INDUSTRY

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## ABSTRACT

As a result of cost reductions, there are fewer and fewer gear specialists in compressor and turbine companies, as well as in the maintenance groups of users. Therefore, these groups rely on the gear manufacturer's expertise for gear maintenance.

This paper is based on the authors' field experience. It uses examples and case studies of investigation and troubleshooting. The use of vibration analysis for gearboxes having multiple sources of excitation is examined. The paper proposes different solutions to increase reliability and availability of gearboxes installed on turbo units. An important chapter deals with modern equipment for condition monitoring, which offers a direct Internet link between site and gearbox diagnostic specialists.

## INTRODUCTION

Gearboxes, whether used for turbo units or for low-speed applications, are unique. Gearboxes are passive units, installed between drivers and driven machines, with excitations coming from two directions through both shafts and couplings. The gearbox base is fitted on a skid that can be excited by foundation vibrations. Gearbox performance is also influenced by the quality of the oil, e.g., oil flow, correct input of oil pressure and temperature, constant oil physical properties, no contamination by water or metallic particles, sufficient aeration time in oil tank, etc. Sometimes, transient changes in the process conditions can influence gearbox behavior, for example, during startup with torsional torque, or in case of false electrical coupling on the generator, compressor surge, entry of water in the compressor, or when casing thermal expansion produces misalignment between machines.

For reasons such as these, troubleshooting on gearboxes is often difficult. A well-known methodology is to go step-by-step from quality claim to measurements and research of correlations between parameters, from measurement to diagnostics, and at the very least, from a correct diagnosis to improvement.

In correlation research between the parameters, some effects of a secondary cause can hide the primary cause. To avoid problems, investigation on gearboxes requires a good knowledge of gear and sleeve bearing operation, as well as skill in the use of modern measurement tools. The first step in diagnosis is the analysis of pertinent measurements, inside and outside the gearbox. Sometimes, service companies carry out this first step, but they often record information that is not sufficient for correct diagnosis of the problem. Gear manufacturers, with experience in the turbo market, are not only able to collect the data required for problem diagnosis, but also have the experience necessary to decide the most effective course of action. The gearbox manufacturer is not only the supplier of one component, he is a specialist working in partnership with the OEM, engineering companies, and end-users.

## INSTRUMENTATION ON GEARBOXES

Gearbox protection and maintenance are mainly based on vibration measurement (shafts and casing) and on bearing temperature measurement.

Probes are commonly used for the monitoring of complete turbo units. Typically gearboxes for the petroleum industry are monitored with many probes, for protection or for maintenance. Information that is available can detect abnormal operations. With time, the probability failure increases. Troubles in gearbox protection and maintenance can be due to a lack of reliability of probes, or trouble in measurement. The power generation industry, on the other hand, uses specification that tends to reduce instrumentation cost by limiting the number of probes installed on the gearbox. For example, gearboxes between turbines and generators are often protected by only thermal probes in sleeve bearings and thrust bearings with one accelerometer on the casing. Investigation in this case cannot be aided by information from multiple sources, and diagnosis will require the use of portable probes or the use of new temporary probes installed on provisional points that were designed by the gear manufacturer and used for initial shop testing.

### *Vibration Measurements*

Vibration investigation is probably the best tool to detect the origin of a gearbox malfunction, but most monitoring systems detect overall vibration values on a large frequency band. Unfortunately, gearboxes containing multiple shafts can generate excitations at different frequencies. Each shaft has its own critical speed. Bearings on each shaft can generate fluid film instabilities at different frequencies.

A simple spectrum analysis in low frequency range will indicate the part each shaft plays in the global vibration level and/or detect subsynchronous instabilities in bearings. In the high frequency range, fast Fourier transform (FFT) analysis of the casing vibration can also identify the difference between, for example, mesh frequency, a natural frequency, or a cavitation frequency generated by a mechanical oil pump. Accelerometer information in low frequency range can confirm shaft displacement measurement and improve unit protection reliability for alarm and trip. A rapid detection of the main vibration components in the FFT spectrum can be very useful to focus an investigation on the root causes of a problem.

### *Temperature Measurements*

For sleeve bearing temperature measurements, flexible resistance temperature detector (RTD) probes are often specified. This type of probe has good precision, but is more fragile than a thermocouple. The sensitive end of the RTD probe is brittle and can be broken by vibrations. This can cause a unit shutdown and involve maintenance action for its replacement. To avoid equipment shutdowns due to a broken probe, install two separated simplex probes at each temperature measurement point, on the radial bearing or thrust pads, with a voting logic on the monitoring system.

In many cases today, the gearbox is inside a closed package without a crane for ease of disassembly. Special mechanical designs allow bearing thermal probe replacement without casing disassembly (Figure 1). From a general point of view, small increases in capital cost, similar to this example, could considerably reduce the maintenance costs and production downtime during the operating life of turbo units (accessibility to machines, cranes, etc.).

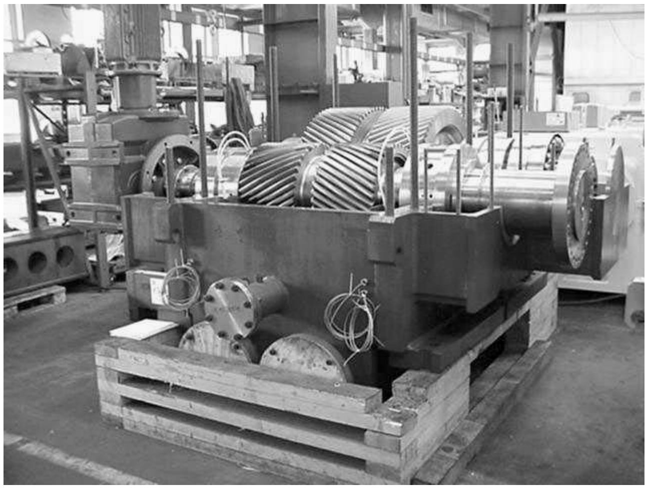
## OPERATING DIAGNOSTICS ON GEARBOXES

The cases below illustrate problems encountered by a gear specialist while diagnosing vibration levels on site.

### *Overall Vibration Measurements on Gearbox Casing Are Not Sufficient for Diagnosis*

As explained above, gearbox shaft vibration can be detected on the casing. But external forces that are transmitted through the foundation and gearbox skid can also excite the casing. For these reasons, the casing overall vibration measurement on the gearbox alone will not yield a correct explanation of the origin of a problem.

Some years ago, the authors were asked by their direct customer to solve a problem of a high vibration level on a gearbox casing that was detected during a string test. The gearbox was installed between a gas turbine and a pump. A water loop with a booster was installed to simulate the pump operating conditions. The gearbox and pump were installed on the same skid. Only one vertical accelerometer was used on the unit and was fitted on the top of the gearbox casing (Figure 2).



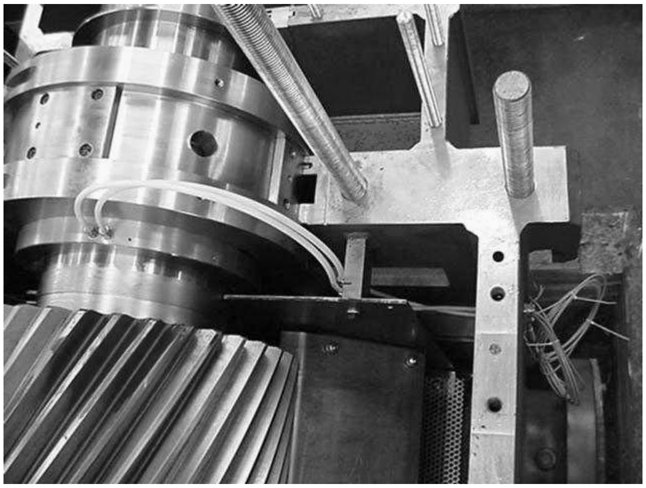


*Figure 1. Example of Bearing Thermal Probes Installed from Casing Outside.*

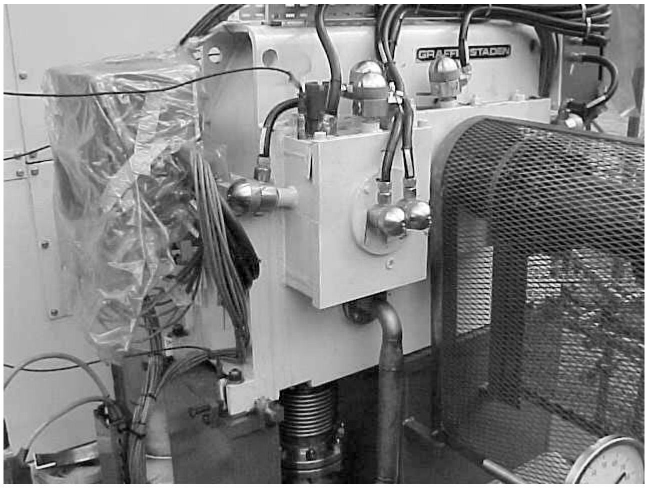


*Figure 2. Gearbox Installation During String Test.*

Shaft vibration levels were correct on both high-speed (HS) and low-speed (LS) shafts, but seismic measurement on the gearbox casing indicated alarm levels at full speed. The first step of the investigation was to obtain FFT spectra for the seismic probe installed on the top of the gearbox casing and at other points. Casing vertical accelerations were measured near the fixed specified accelerometer and on the baseplate of the skid.

Waterfall spectra were recorded during the startup on both points (variation of turbine speed from 9100 rpm to 13,000 rpm). Similar phenomena appeared in Figure 3 (vertical vibration velocity on the gearbox top casing) and Figure 4 (vertical vibration velocity on gearbox base skid). In both figures, the single spectrum at the bottom is record Number 117 of the waterfall. The records show the advantage of measurements in transient condition and how they aid in the diagnosis of the problem. Obviously, the main velocity peaks are due to structural vibration and not related to the shaft excitations.

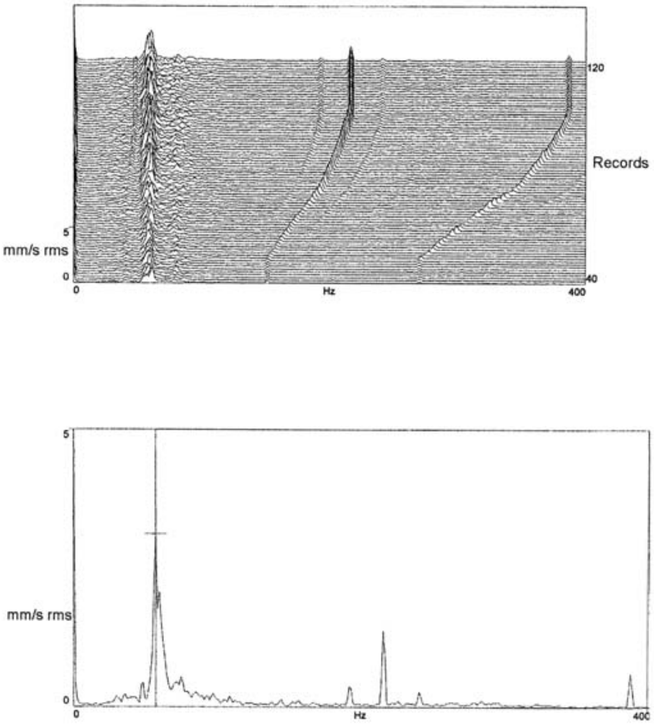


*Figure 3. Gearbox Vibration on Top Casing During Startup.*

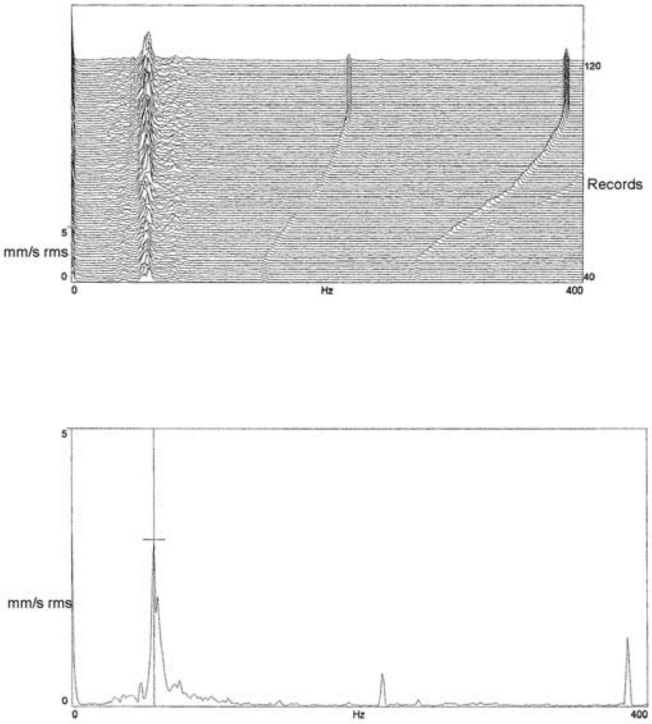


*Figure 4. Gearbox Vibration on Casing Base During Startup.*

Comparison between the measurements on the gearbox top casing and on the gearbox base skid indicated also that peaks in velocity were similar, and vertical vibration phases on both points were close together. A second immediate conclusion was that the whole gearbox was excited vertically on its base. But the next step was to find out the origin of the vibrations of the structure.

Just after shutdown, when the turbine shaft was stopped, seismic vibration records indicated a low level of residual peaks. An amplified record is shown in the top record in Figure 5. A peak appeared at a frequency very close to the structure vibration detected during rotation of the unit. After investigation, it was detected that excitation was coming from the booster, which was still running after complete shutdown of the unit. Residual vibration disappeared when the booster was stopped. The last investigation was to verify if the base structure could have a natural vibration mode, which amplified the excitation coming through water loop pipes.

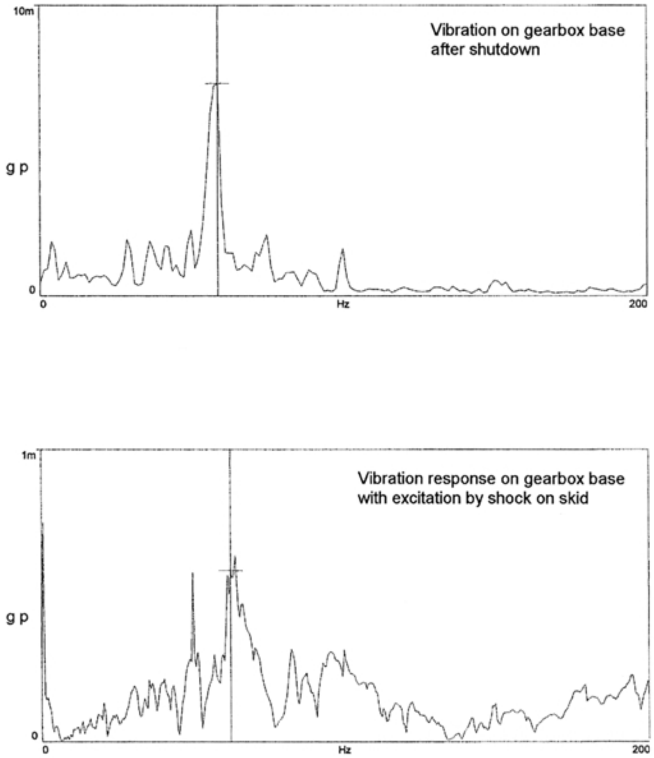


*Figure 5. Vertical Vibrations on Base After Turbine Stopping.*

When both unit and booster were stopped, vertical shocks with a piece of wood were applied on the skid, near the gearbox base. The bottom record in Figure 5 shows the average vertical vibration measurement on the gearbox base, obtained during the shock period. This measurement closed the investigation loop with the identification of the structural mode of vibration and the origin of the excitation.

This case illustrates the disadvantage of using global vibration levels for monitoring and maintenance and the advantage of vibration measurements during transient conditions on the unit, like startup and shutdown.

### *Are You Sure of Probe Measurement Credibility?*

The following case is an example of an initial diagnostic mistake because of an incorrect shaft vibration measurement on a turbogear installed in the Middle East.

The first information coming from the site was that, during the startup of the turbocompressor units, trips occurred due to shaft vibration peaks on the gearbox HS drive end (DE) bearing. The turbocompressor unit had a rated power of 29 MW, with a speed ratio between gas turbine and compressor of 2.26.

A spectrum record was obtained with the local monitoring system when the shaft speed approached the trip value (Figure 6). Unfortunately, no waterfall records were supplied, and spectra had a rough resolution. Nevertheless, the spectra indicated that when the vibration global values were increasing up to trip, a vibration peak at half the shaft frequency was appearing. The first diagnosis was to suspect an instability on the gearbox HS DE side bearing.

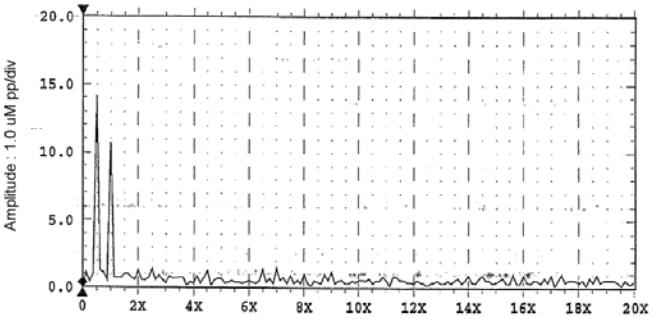


*Figure 6. Shaft Vibration on HS DE Side.*

This first hypothesis was very strange and very incredible for a five tilting pad bearing, loaded by the gear reaction forces. For this reason, the first investigation of the bearing design was discarded, and a new direction was decided using a multichannel FFT vibration analyzer. During this new investigation, data were obtained during startup and shutdown, using the different gearbox shaft vibration probes.

The first important result for diagnosis was that trips on the HS gearbox (GB) shaft did not appear when the unit started in cold condition or after two or three hours of standby. But in case of a restart a short time after trip, HS shaft vibration was higher than trip level. Bode diagrams confirmed this assumption: the runout at slow roll was correct during shutdown, but was very high during a hot startup. Figure 7 shows two Bode diagrams that were recorded during a hot startup.

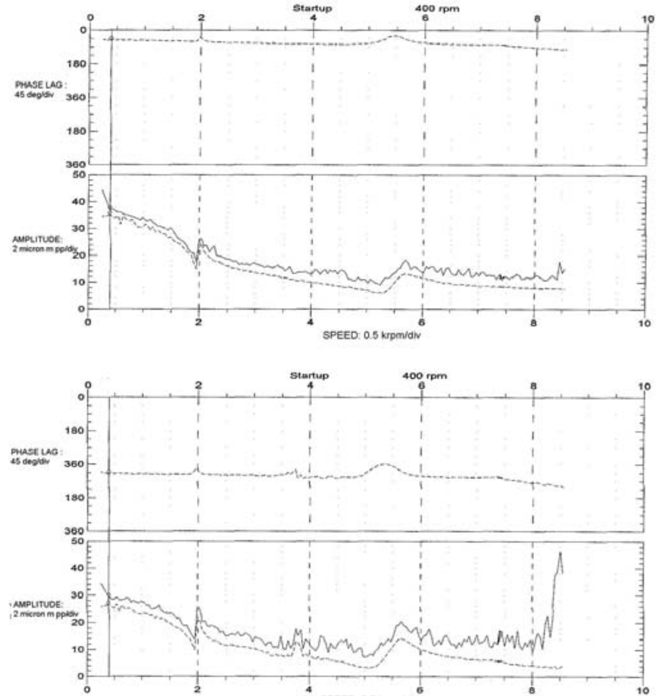


*Figure 7. Bode Diagram for HS Shaft Vibrations on NDE and DE Side During Startup.*

HS shaft displacement probes are located at the same radial position, one on the nondrive end (NDE) side (top diagram) and the other one on the DE side (bottom diagram). We can observe that the runout phases are very similar.

With all these observations, we suspected that the thermal shaft unbalances were responsible for the differences in the peak vibration during startup, but it was unusual that this peak was not a synchronous vibration and occurred at half shaft frequency.

In case of a startup without trip, cascade spectra were recorded up to maximum speed. It appeared (Figure 8 and Figure 9) that the vibration peaks were maximum for a compressor speed of approximately 8500 rpm. A better analysis of the cascade plots during the startup indicated a natural mode of vibration at this frequency, which could explain that the peak of vibration was due to a mechanical structure resonance and not to a bearing instability.

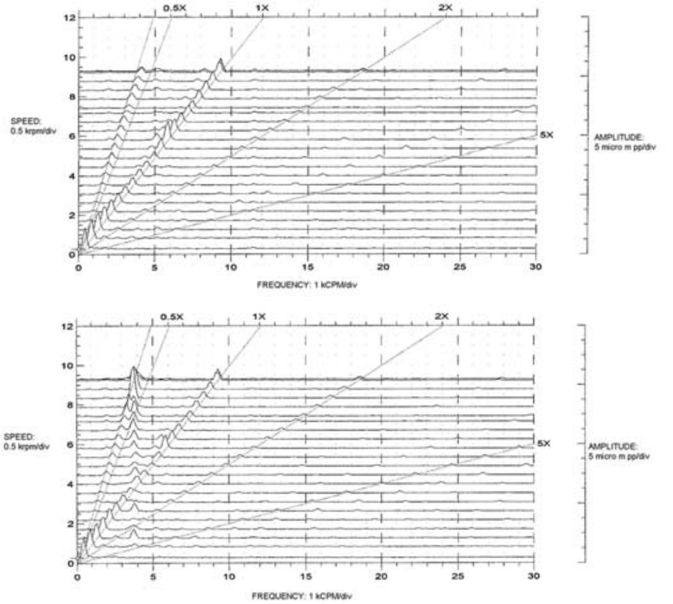


*Figure 8. Cascade on HS DE Side for X and Y-Ways During Cold Startup.*

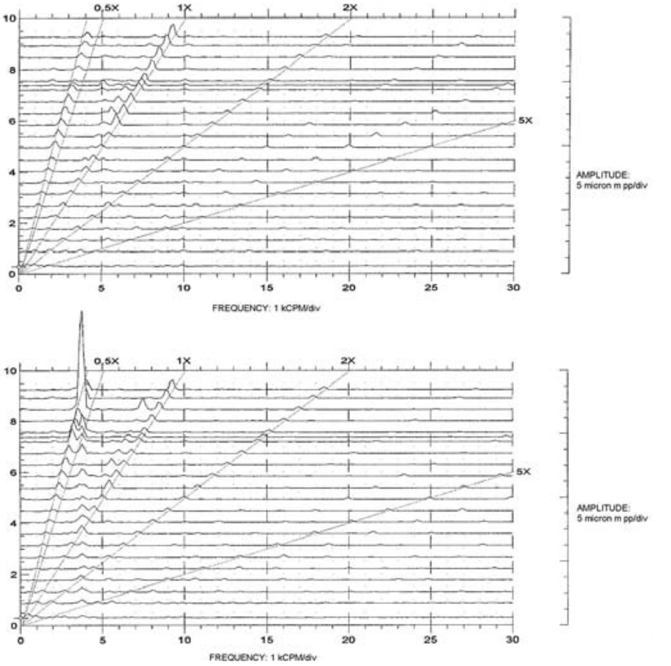


*Figure 9. Cascade on HS DE Side for X and Y-Ways During Hot Startup.*

We observed two important phenomena on cascade records:

- Resonance appeared only on one probe (Y-way)
- Excitation frequency was not fluid instability but low-speed shaft frequency at 0.44 times the HS shaft frequency (= 1/2.26)

Progress was made with these different measurements, which led to a coherent explanation. One vibration probe holder was suspected of having a resonance mode of vibration during startup. Variation of resonance response during startup was not due to the thermal unbalance on the high-speed shaft, but on the low-speed shaft. Vibrations at low speed frequency were transmitted to the probe holder through the casing. The intensity of this excitation was a function of the initial thermal unbalance on the shafts.

Investigations of the drawings confirmed that the probe holder sleeve on the DE Y-way was designed longer than the three others installed on the HS gearbox shaft, and could have a lateral mode of vibration at a frequency around 62 Hz.

The compressor units were on duty for gas reinjection, and it was very difficult to schedule special tests, modifications, or repetitive startups. During one short stop of the unit, it was possible to modify the Y-way probe holder in order to increase its lateral rigidity. The new startup confirmed the origin of the resonance. No trips occurred, even when the unit restarted immediately after a shutdown.

Troubleshooting took a long time, not only because of the fact that investigation results were difficult to understand, but also for process conditions. A gear specialist was onsite for an extended period of time to obtain pertinent measurements. The next paragraph describes how new electronic devices installed on the gearbox can allow online diagnosis by gear specialists in the manufacturer's offices.

## ONLINE DIAGNOSTICS— A NEW TOOL IN GEAR SERVICING

Investigations on gearboxes require specialists who are able to understand or carry out measurements and who have knowledge in gearbox design, in order to find the correct diagnosis and to decide what should be improved. In many cases, it is difficult to have a gear specialist onsite for extended periods or when specific operating conditions arise.

For these practical reasons, an Internet technology gear-controller has been developed for remote monitoring of standard industrial drives and turbodrives via the Internet and online diagnosis by gear manufacturing technical teams.

A moto-compressor unit with synchronous motor, coupling, single-stage turbogear unit, centrifugal compressor, and attached electronic box containing the gear controller device are shown in Figure 10. Misalignments, unbalances, coupling faults, electrical interference, damages to sleeve bearings, and gear tooth damages are just a few of the problems that might show up on this drive and can result in reduced availability of the machine or even an unexpected complete breakdown.

Figure 11 shows local tooth damage on the gear running in sleeve bearings. The damage can be detected by vibration measuring technology based on frequency analysis, whereas the reasons for this damage can only be found by applying torque measurement technologies.

Shaft vibration analysis is the first thing that comes to mind to detect irregularities in the tooth meshing or in bearings, as well as to measure their growth over time. Due to the high speed and the relatively short growth time of the damage, it is operationally safer to apply an autonomous diagnostic system for the turbodrives that automatically monitors the state of vibrations, detects and analyzes deviations in the frequency spectra, and transmits e-mails via the Internet. The gear controller device in Figure 10 enables frequency analyses with 8200 lines and a resolution rate of 102 dB, combined with measuring times of up to 10 minutes.

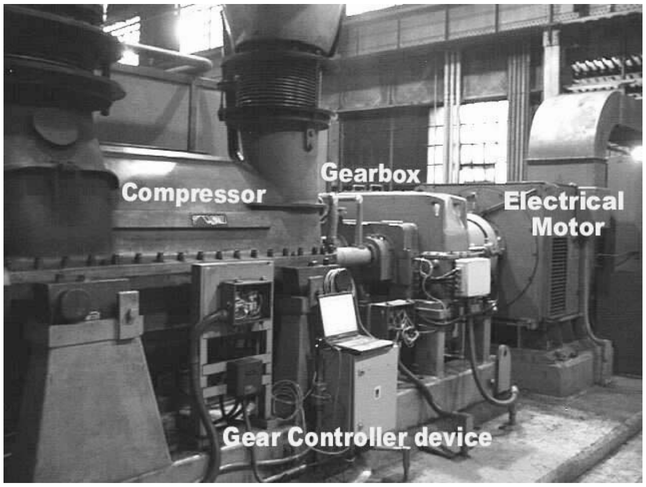


*Figure 10. Moto-Compressor Unit with Attached Gear Controller Device.*

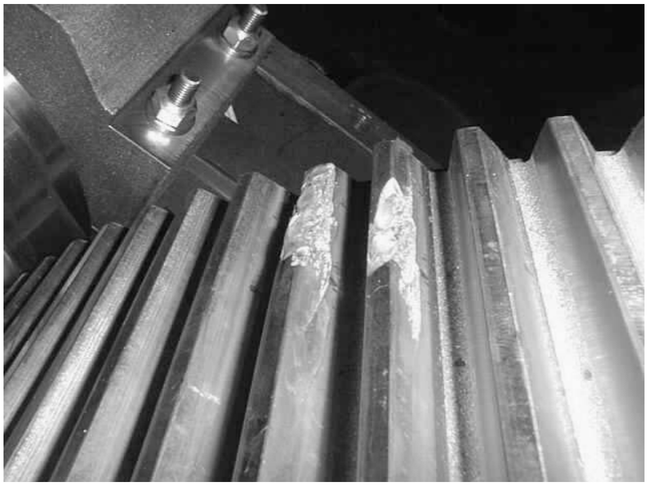


*Figure 11. Local Damage on Gearbox Teeth.*

Some machine operators want to know the time that the machine can still be operated safely, e.g., to a planned yearly shutdown after the gear controller has signaled the first signs of damage. To analyze the degree of the damage to the drive, the diagnostic specialists should always have access to the diagnostic system. In the case of pending damages, the specialist can remotely start additional measurements that provide additional data for a precise evaluation of the problem.

Analysis can become more difficult if startup or torque-oscillating modes are also included in the evaluation. Torque measurements with strain gauges may be required. The monitoring system then load-dependently triggers these nonstationary operations, e.g., torque measurement during startup. Measuring results are then automatically transmitted to the gear unit specialist via the Internet.

Gear controller devices in Internet-technology are autonomous and contain robust embedded measuring, analysis, and control systems in modular design. They implement the functions of an intelligent data logger, an event-recorder, a classifier, as well as an analysis and diagnostic computer. All commercially available vibration sensors and even strain gauges can be directly connected to the device without the addition of special interfaces for data preparation or sensor supply.

Hardware components have been especially designed even for application in the petrochemical industry. They have been tested for tropical design as well as for electromagnetic compatibility;

operating temperatures are between −40°C (−104°F) and +70°C (158°F); components withstand shock and vibration loads of up to 30 g. Explosion-proof designs are also available and several systems have been used in the petrochemical industry.

A real-time multitasking operating system in the autonomous gear controller monitors the parallel operation of data logging, triggering, controlling, calculation, analysis, storage, and communication.

As browsers and e-mail programs are available for all hardware platforms, the gear controller can operate totally independently of the user's own operating system. When a contact is established with the gear controller device via the Internet HTML, pages from the webserver are automatically uploaded into the browser of the user and can thus be operated there, in order to avoid conflicts of versions and incompatibilities of operating systems.

As transmission control protocol/Internet protocol (TCP/IP) has also become a standard with the Intranet, local area network's (LAN) online diagnostic systems can also be easily upgraded as shown in Figure 12.

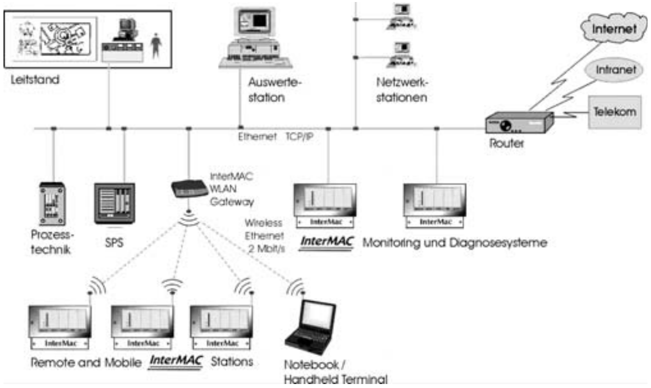


*Figure 12. Gear Controller Integrated into a LAN/Intranet of Turbo Unit End-User.*

TCP/IP communication may be established via standard telephone modem, ISDN, GSM, RS232, RS485, or even via wireless Ethernet. All transmission modes may be changed at any time.

Remote connection was established between Chile and Germany, over a distance of more than 12,000 km (~7500 miles) via the Internet by standard analogue modem and standard Internet account. Several users may even access the gear controller at the same time as the real-time operating system allows in carrying out condition monitoring and online service of these users in parallel.

*Basic Functions with an Autonomous Gear Controller System*

Based on numerous mobile measurements on different turbo unit types, specific compiled software programs for continuous condition and vibration monitoring can be implemented in the gear controller, using different relevant measurement values. For example, on a moto-compressor unit in Chile, the input information to the system was:

- Two input ways for load and compressor pressure for recording of the actual state of the turbo unit and to allow for the interpretation of nonstationary operating conditions. The load signal is also used as a trigger signal for starting of the automatic diagnostic routines.
- One input way for motor bearing vibrations (measured with an accelerometer). Data from an accelerometer are generally used to evaluate alignment, operation, and bearing conditions of the motor.
- Two vibration ways on gear unit housing, measured with accelerometers. Gathered data are being used to evaluate vibrations relative to bearings, tooth meshing, and torsional vibrations.
- One bearing temperature way to monitor the axial bearing temperature. Moreover, this value is used as a trigger value to measure data only from a gear unit with standard operating temperature.
- One casing vibration way on compressor bearing to enable the early recognition of changed load cases and to generally monitor compressor vibrations.

Customers' maintenance instrumentalists can easily carry out sensor installation. Figure 13 shows two accelerometers attached to the gear unit housing (left) and the compressor bearing (right). The customer has to provide a standard telephone line, a stabilized power supply, the additional values to be measured (preferably as a standardized 4 to 20 mA signal), and an Internet access similar to the ones used by home Internet connections. Data and warnings can thus be transmitted via e-mail and the Internet network. All necessary functions, formulae, and algorithms are included in the program.

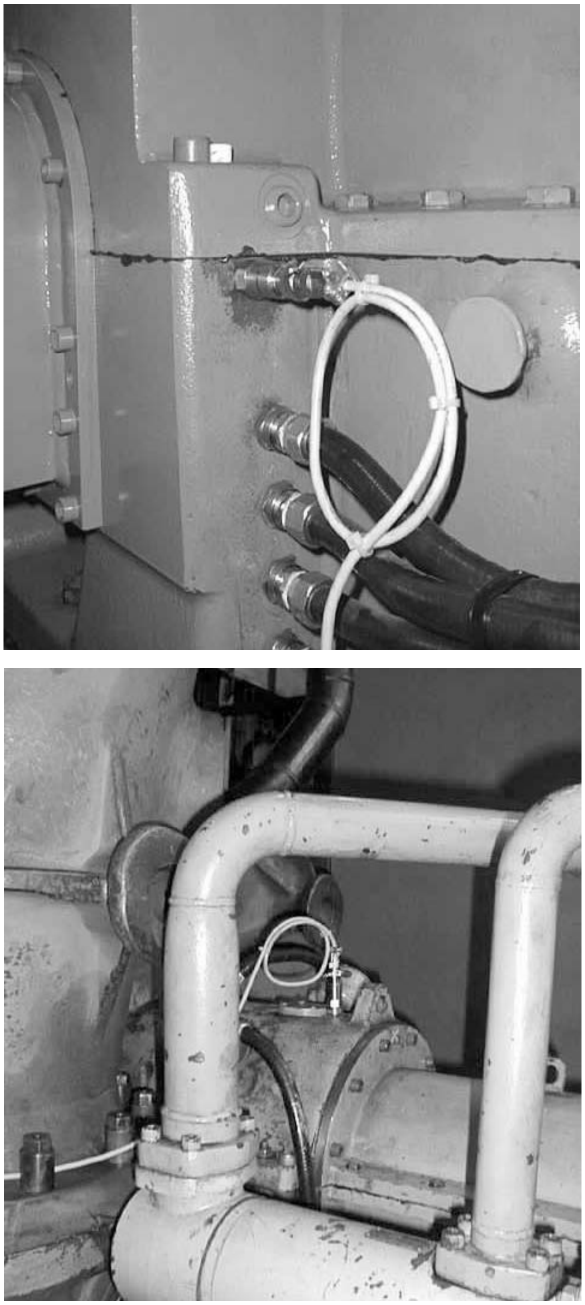


*Figure 13. Arrangement of Accelerometers on DE Side Housing of Gear Unit and on Compressor DE Side Bearing Housing.*

An example of a frequency spectrum for gear tooth meshing analysis is shown in Figure14. Once the threshold value of the set characteristic frequencies in the traffic light frequency spectra is exceeded, the system will automatically send an e-mail. This can be compared to the procedure of bearing monitoring with enveloping curves.

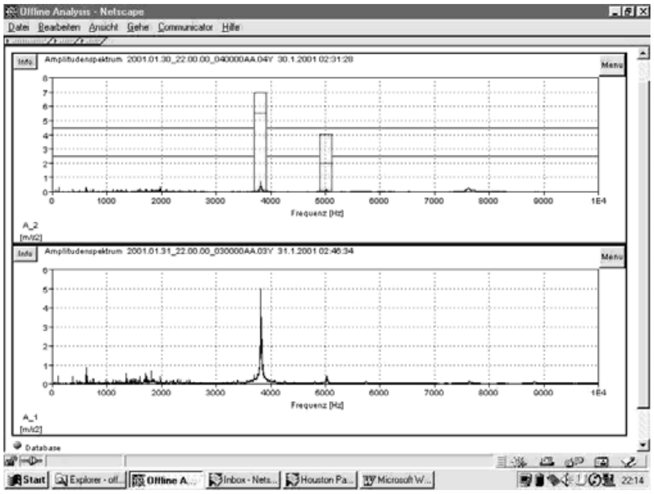


*Figure 14. Traffic Light Frequency Spectra for Automatic Monitoring of Tooth Meshing Specific Excitations in Frequency Spectra.*

Hidden vibration problems can be clearly detected by the implementation of logic mathematical combinations, similar to the onsite work of a diagnostic specialist.

This system also allows updating of programs via the remote Internet access once new data as well as service data become available. Thus, the customer always has an up-to-date system that keeps on improving, for a low cost of system maintenance.

### *Special Monitoring with an Autonomous Gear Controller System*

Service companies and diagnostic specialists have been asking for years to analyze and monitor the changes of operational parameters other than vibrations, e.g., temperatures, pressures, and/or other load parameters, and to have a remote access to them, for automatic analysis.

For example, strain gauge equipment is fitted on the turbo unit in Chile. The installation of strain gauges on the gearbox input shaft and the appertaining telemetry are shown in Figure 15. In addition to continuous monitoring of torque, this installation allows the early detection of very small overloads in the millisecond range. Recorded events are automatically transmitted to the mechanical specialists via e-mail.

Figure 16 shows two records obtained during startup. In this instance, the torque was measured by the gear controller system with a scanning rate of 1000 Hz; the data were automatically transmitted to Germany via e-mail. Even late at night, the drive specialist, thousands of miles away, was in a position to judge and evaluate the changes that occurred during the startup regime and the loading of the drive.

Starting torque of a synchronous motor is shown in Figure 16. Very clearly seen is the oscillating torque typical for a synchronous motor—that, on the other hand, also transfers these oscillating torques into the gear unit. The maximum generated value in the meantime was decreased—a limiting torque of 15 kN.m was set as the trigger value. The startup procedure with a duration of 50 seconds was recorded with a scanning rate of 625 Hz. The e-mail files had a size of 123 kB. It took the data approximately five minutes from Chile to Germany via the Internet. The gear specialist now even gets the information concerning these startup procedures transmitted to his work assignment procedure (WAP)-mobile phone.

*Figure 15. Installation of Strain Gauges and Telemetry-Components on Moto-Compressor for Automatic Monitoring of Load.*

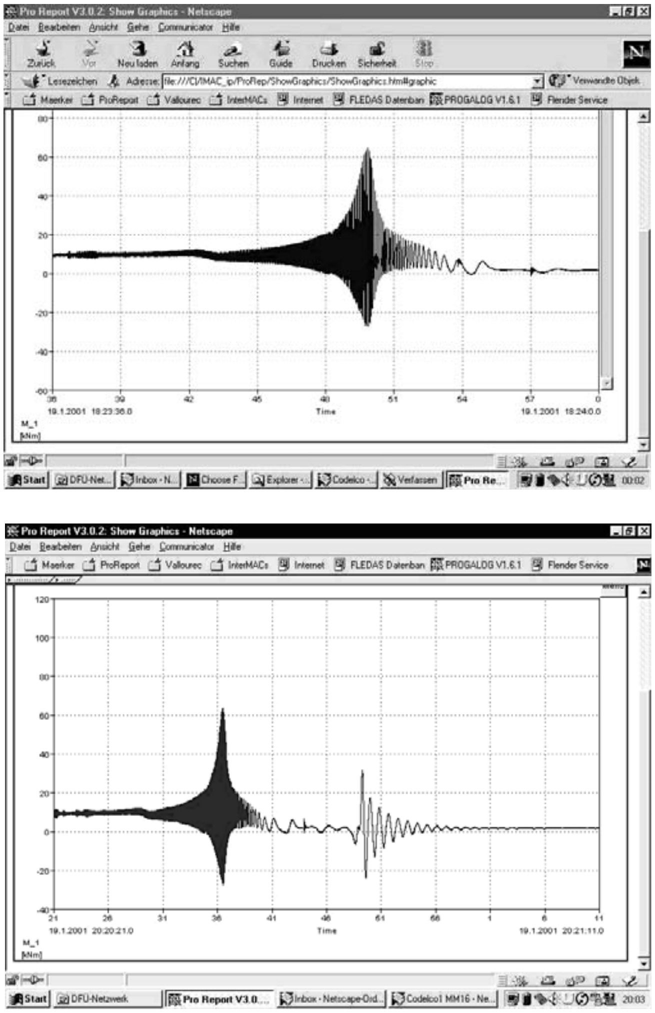


*Figure 16. Two Automatic Torque Measurements, Recorded During Moto-Compressor Startup and E-Mailed.*

Similar gear controllers, with specific software for gear protection and maintenance, can be installed on standard industrial drives using smaller gears, for example on pumps, conveyers, extruders, etc., and can allow operators access to the services of gear specialists. An entire area of the plant can be supervised in a remote process, whereas thresholds can be set for automatic contact with the gear specialist.

## CONCLUSION

As a result of cost reductions, there are fewer and fewer gear specialists in the compressor or turbine manufacturing companies, as well as in the maintenance groups of users. Gear investigations onsite and maintenance analyses are often difficult, and depend on a good relationship and partnership between OEM, the engineering company, and the gear specialists. Gear servicing by gear manufacturing specialists is the best way to solve gear troubles or problems due to the influence between the machines of the unit.

Field experience is necessary to fulfil this purpose and to avoid mistakes or incorrect diagnosis, as described in this paper. Thanks to new online diagnostic tools, gear specialists can troubleshoot with low travel cost and short investigation time. Improvement decisions can be made rapidly.

All these evolutions in gear diagnosis, associated with efficient maintenance tools for rapid intervention on machines, will save time and money to all the partners involved in servicing.