# CONDITION MONITORING OF COOLING TOWER FAN GEARBOXES

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**Abstract:** *To reduce visual and environmental impact, modern power stations are built with induced draft cooling towers replacing the large natural draft cooling towers previously used. The ability of the cooling towers to provide adequate cooling for the main circulating water of the power station is affected by the availability of the cooling tower fans.*

*A key component of the cooling tower fan is the gearbox. Maintenance of gearboxes is difficult and expensive, given the location and therefore condition monitoring techniques have been applied to detect common failure mechanisms. Future condition monitoring may be possible using low cost on-line techniques*.

## INTRODUCTION

### Cooling tower fan operation

Station main circulating water (MCW) provides the primary cooling for the station. Before being returned to the station by the MCW pumps, the water is cooled. As it flows over the baffles in the cooling tower, some water evaporates to provide the cooling. The upward airflow is provided not by natural draft but by horizontally mounted fans, arranged in cells. A 500MW Combined Cycle Gas Turbine (CCGT) station typically has 14 cells.

## Cooling tower fan gearbox location

The cooling tower fan gearbox is located inside the cooling tower cell, the vertical output shaft below the fan. A typical fan has 7 blades each of 3m radius. A horizontally mounted 3-phase induction motor, located on the top level of the cooling tower drives the gearbox via an input coupling, which extends outside the cell. In some examples, the motor and gearbox have a common mounting frame.

## Cooling tower fan gearbox construction

The typical speed reduction is from 1490rpm - 990rpm (from a 4-pole or 6-pole motor) down to 100rpm - 50rpm. The input gearmesh is a 90˚ bevel and there are either 2 or 3 single helical reduction gearmeshes on vertically mounted shafts. An integral oil pump, driven from an intermediate shaft circulates lubricating oil. Rolling element bearings are used throughout the gearbox.

Some designs have an axial cooling fan on the input shaft to force air over the casing of the gearbox. Another design feature on some gearboxes is a device to stop reverse rotation of the fan when not being driven, which may occur when the upward airflow from operational fans then returns down through the “idle” cell. Figure 1 shows a typical gearbox layout.

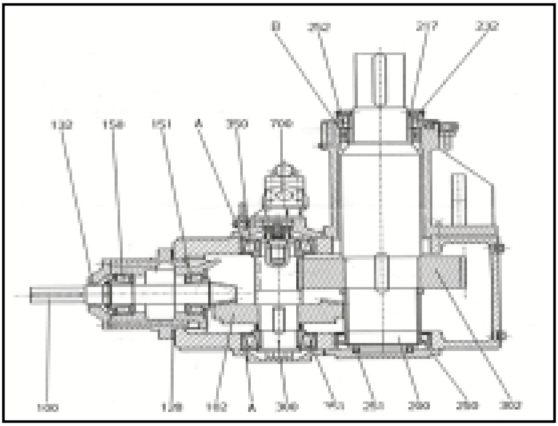

*Figure 1: Typical cooling tower fan gearbox layout*

## OBJECTIVES OF CONDITION MONITORING

The objectives of condition monitoring are as follows:

• To collect the minimum information needed to plan predictive maintenance and to avoid high cost breakdown maintenance.

- To assist in identifying appropriate actions when alarm levels are exceeded or significant changes are detected.
- To maximise proactive maintenance by the detection of faults in plant installation or reinstallation which, if left uncorrected, would lead to plant damage.

In many cases, a combination of techniques is required to fulfil these objectives.

## CONDITION MONITORING TECHNIQUES IN USE

### Hand held vibration monitoring

The majority of auxiliary plant on a power station is periodically monitored using hand held data collectors, collecting vibration data using a portable accelerometer. The data is then loaded into a software package on a PC in order to analyse the data.

Access to the cooling tower fan gearbox is prohibited during operation, so the only data available to the operator is from the driving motor. Experience has shown that the timely detection of gearbox faults from analysis of motor vibration readings alone is difficult, but readings at the drive end of the motor can be analysed to provide corroborating evidence.

### Location of permanently installed accelerometers on gearboxes

The attenuation of gearbox vibration signals (e.g. from a damaged rolling element bearing) through the gearbox, input shaft and motor housing to an accelerometer placed on the motor means that an accelerometer must be placed on the gearbox to obtain adequate information.

In most cases, accelerometers have been mounted on the gearboxes radially in line with the top output shaft (i.e. lowest speed) bearing. This location was initially selected due to concerns over failures of the top output shaft bearing, but experience has shown that this location is also suitable for monitoring of the higher speed input and intermediate shafts. The vibration signals from these shafts are higher in magnitude that from the low speed output shaft and, even with attenuation through the gearbox, are detectable at the output shaft accelerometer. Conversely, accelerometers mounted at the bearing locations of the input shaft are not able to effectively monitor output shaft vibration signals.

## Velocity vibration measurements

Vibration of auxiliary plant has traditionally been measured in units of velocity (mm/s RMS), which gives an indication of the condition of the plant relatively insensitive to speed (1). Initially, velocity readings on gearboxes were set up to detect 2 failure mechanisms:

- Fan and installation defects (e.g. unbalance, misalignment).
- Defects appearing in the vibration spectrum at gearmesh frequencies.

### *Fan and installation defects*

Fan and installation defects (e.g. unbalance, misalignment) appear at low frequencies, usually less at less than 10 orders (multiples) of running speed. For the case of the output shaft, the 1$^{st}$ order frequency can be less then 1Hz. Detection of the low frequency defects is difficult, firstly due to the poor response at low frequencies of standard accelerometers and secondly because there is significant low frequency vibration of the cooling tower structure, saturating the accelerometer input to the data collector.

### *Defects appearing at gearmesh frequencies*

The maximum frequency of data collected is above the 3$^{rd}$ harmonic of the gearmesh frequency (the product of the shaft speed and the number of teeth on the gear). In all cases of cooling tower fan gearboxes, the highest frequency of interest is less than 2000Hz, so high frequency accelerometers are not needed and data is collected in units of velocity mm/s RMS.

## Enveloped Signal measurements

Enveloped Signal Processing (2) is a well proven technique for the detection of defects in rolling element bearings. Despite the location of a single accelerometer at the output shaft top bearing location, it was hoped that rolling element bearing defects on other shafts within the gearbox could be detected. The envelope most commonly used is 5kHz - 10kHz and the maximum frequency of interest is 20 orders of input shaft speed. The data is collected in units of acceleration g's Peak.

## Motor current analysis

Motor stator current analysis (3) has traditionally been used to monitor the condition of induction motor rotors and the sensitivity of the technique to load fluctuations is known. A variation on this technique has been used, analysing the time waveform of the stator current over a short period (e.g. 10s). A normal cooling tower fan gearbox motor current has little variation of current over time but a gearbox or fan with a serious defect (e.g. sheared gearbox holding down bolts, unbalanced fan blades) shows modulation of motor current at output shaft frequency.

## Oil Analysis

Oil analysis has been a prime condition monitoring technique for gearboxes, often able to detect gearbox wear before vibration analysis (4). The difficulty in applying this technique to cooling tower fan gearboxes has been the collection of a representative, repetitive sample.

One station installed dedicated sample collection and return piping from the gearbox to a location external to the cooling tower cell. When a sample is needed, a sample pump is connected to the collection and return piping and, after allowing time to flush the sample piping, a representative sample can be taken. The disadvantage of this method is that the small bore piping connected to the gearbox is vulnerable to damage, which presents an environmental risk from 80l of oil leaking from the gearbox.

The other method in use is to use the oil filler pipe as the connection to the gearbox. The pipe is flushed into a container until warm oil is detected, so that the sample is reasonably representative of the oil inside the gearbox. The flushed oil is then put back.

Standard industrial tests are performed on the oil (kinematic viscosity, water content, total acid number, elemental analysis and particle quantifier).

The results of oil analysis have generally been good but an equally important use of oil analysis has been the ability to prolong oil life in gearboxes, based on the oil condition. In one application, the increased cost of using synthetic oil was justified because the frequency of oil changes was reduced (saving the associated maintenance costs of the oil change as well as the cost of the oil). Quadrupling of oil life was achieved.

## COMMON FAILURE MECHANISMS

It is not the intention of this paper to provide a list of the all potential failure mechanisms of cooling tower fan gearboxes. Some examples of the common failure mechanisms are included, together with the suggested condition monitoring techniques.

## Gear teeth failures

Some gearboxes experienced single teeth failures on the intermediate shaft bevel gear. Metallurgical analysis of the damaged teeth suggested a manufacturing defect or a transient overload on the gear, possibly when the motor was started.

The defect was detected using Enveloped Signal Processing of the signal from the accelerometer mounted at the output shaft. Figure 2 shows the envelope spectrum, with harmonics of intermediate shaft speed indicating the repetitive event of a single tooth defect.

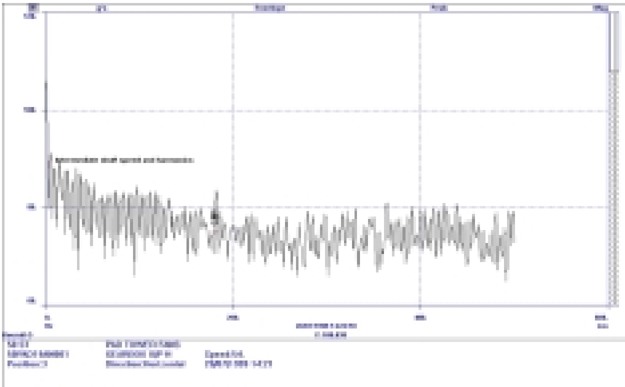

*Figure 2: Envelope spectrum of gearbox output shaft accelerometer*

The output shaft accelerometer signal is integrated to give a velocity reading. Figure 3 shows the velocity spectrum, with the 2$^{nd}$ harmonic of the input gearmesh frequency modulated by intermediate shaft speed, giving the characteristic

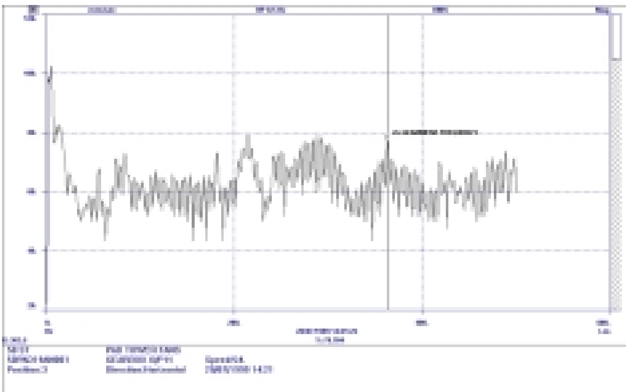

*Figure 3: Velocity spectrum of gearbox output shaft accelerometer*

“sidebands”. The precise nature of the defect cannot be determined from this spectrum, but the change from a “healthy” reading would lead to a maintenance intervention.

Figure 4 shows a typical gear with the damaged tooth clearly visible.

*Figure 4: Damaged tooth on intermediate shaft bevel gear*

## Input and intermediate shaft bearing failure

Possible causes of bearing failure are solid or water ingress via a shaft seal, poor lubrication or contamination of oil.

A gearbox was returned to service after repairs to gear teeth but failed soon after being installed. Using Enveloped Signal Processing an input shaft bearing defect was detected using the accelerometer mounted at the output shaft. Figure 5 shows the envelope spectrum, with harmonics of motor / input shaft speed and sidebands indicating impacting, typical of a rolling element bearing defect. In this case a more detailed analysis of the spectrum was needed, shown in Figure 6, to isolate the individual bearing component, but a defect is noticeable, even without such analysis.

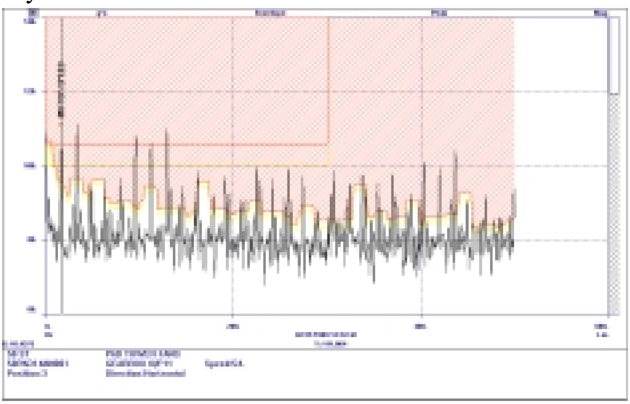

*Figure 5: Envelope spectrum with harmonics of motor / input shaft speed and sidebands*

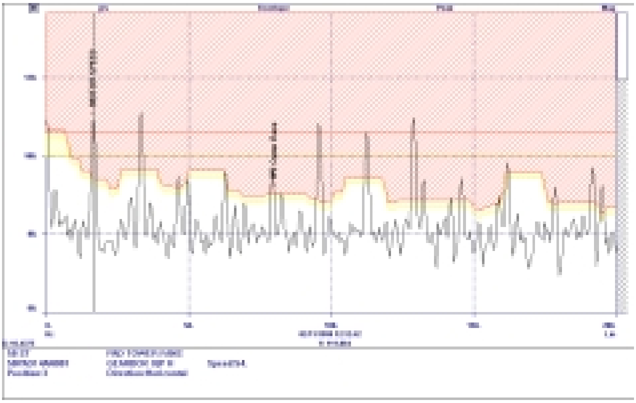

*Figure 6: Detailed envelope spectrum showing gearbox bearing defect frequency*

## Output shaft bearing failure

A number of different failure mechanisms are responsible for output shaft bearing failures.

Some designs of gearbox are prone to oil starvation of the top output shaft bearing when the fan rotates in reverse. This has been addressed by the fitting of anti-reverse rotation devices.

If the fans are left stationary false brinnelling damage can take place. Over long periods (>3 weeks) the thickness of the oil film reduces to the point where fretting corrosion can occur if water ingress occurs via the shaft seal. Such damage can occur during commissioning, when some fans run but others are left stationary for long periods.

Figure 7 shows an output shaft top bearing removed from a gearbox, with markings on the bearing outer race showing where the bearing had remained stationary. Enveloped Signal Processing is recommended for detection of these bearing failures.


*Figure 7: Output shaft top bearing with markings on the bearing outer race*

## Gearbox overheating

At one station, over half the gearboxes experienced failures of the output shaft bottom bearing. One of the root causes of failure was oxidation of the oil at the elevated temperatures at which the gearbox was running. The gearbox did not have a cooling fan mounted on the input shaft and the result was a “dead space” in the airflow around the gearbox. Oil analysis detected the oxidation and the grade of oil was changed from ISO VG220 to ISO VG320.

## Fan unbalance

Waterlogging of fan blades can cause fan unbalance. Porous GRP material delaminates and small pieces break off inside the hollow fan blade, lodging at the end of the blades and blocking the water drain holes.

With no accelerometer installed on the gearbox, vibration on the driving motor was monitored using a hand held accelerometer. A harmonic of the fan speed triggered an alarm on the motor drive end bearing velocity spectrum reading. Figure 8 shows the motor drive end velocity spectrum, with the harmonic of fan speed labelled. The fundamental fan frequency is below the high pass filter used for the measurement, and therefore does not show on the spectrum.

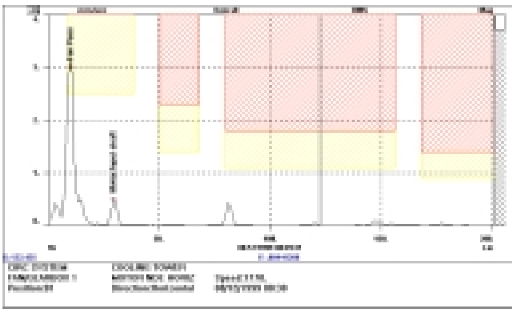

*Figure 8: Motor drive end velocity spectrum showing harmonic of fan speed*

## Unusual failure mechanisms in temperature extremes

At one station in the US, oil analysis detected the production of wear metals from gearbox teeth. Subsequently, high levels of vibration were detected on the drive end bearing of the driving motor. The gearbox was stripped down and severe adhesive wear was found on the back of the output shaft gear teeth.

During normal operation, the gearbox temperatures were over 90˚C and so ISO VG680 grade oil was used. A detailed investigation revealed that, while the cooling tower fans run forwards in normal operation, in extremely cold weather (-10˚C), the fans are run backwards at half speed in order to de-ice the cooling tower after a short period off-load. At this temperature, the kinematic viscosity of the oil is over 20000 centiStokes (cSt) i.e. near its pour point (the temperature at which it stops flowing). The splash lubrication regime for the gear teeth did not work resulting in severe adhesive wear.

## FUTURE CONDITION MONITORING

### Online vibration analysis

The advantage of using hand held data collectors for vibration monitoring is that it provides cost effective condition monitoring for the majority of auxiliary plant. On power stations, the periodic (e.g. weekly or monthly) vibration survey is backed up by the station operators during routine or ad hoc plant visits. A "noisy" bearing or change in vibration is logged and follow up instigated. With cooling tower fan gearboxes, as with other inaccessible plant, operator plant visits are less likely to be able to detect impending failures.

With the reduction in cost of Vibration Isolated Measurement Pod (VIMP) type technologies, on-line monitoring of cooling tower fan gearboxes is becoming cost effective. A 16-channel VIMP type unit wired up to accelerometers on gearboxes can monitor all the gearboxes on a 500MW CCGT station. The VIMP type unit is connected to an on-line version of the normal off-line vibration analysis software and the data displayed in the plant control room.

The correct setting of alarm levels is important. While an experienced vibration analyst looking at monthly collected data can disregard readings causing "false" alarms, the control room operator may be overloaded with alarms in the on-line system. The development of multivariable alarms in software packages may help solve this problem.

Laying communications cabling on an existing installation represents the biggest problem (and cost) of an on-line system. A number of condition monitoring companies are developing radio link technology to solve this problem.

### Online oil condition monitoring

As previously discussed, oil analysis is a potentially powerful diagnostic tool in gearbox condition monitoring, but can be limited by the ability to collect a sample. A recently developed product is on trial (5), which provides a continuous indication of oil condition.

The principle of operation is that the loss tangent (Tanδ) of the dielectric constant (ε) of oil is affected by oxidation degradation, liquid or solid contamination and wear metal production. The loss tangent is related to the dielectric constant (or permittivity) as follows:

$$\varepsilon = \varepsilon'(1\text{-}j\mathrm{Tan}\delta)$$

Where ε' is the real component of the dielectric constant.

A low voltage dc powered sensor is located in the oil flow and gives a voltage output and an alarm output when a threshold is exceeded. If successful, the units could be wired into the station distributed control system to prompt action once an alarm is triggered.

Recent experience with the online oil condition monitoring has been on coal mill gearboxes. The online sensor has produced a "fault" indication when ingress of pulverised fuel occurred, which would not have been picked up by periodic oil analysis until damage had been done to the gearbox.

## CONCLUSIONS

With a combination of techniques, correct setting of alarm levels and interpretation of data, gearbox failures can be detected, even if it is not possible to distinguish the individual components that are failing.

A combination of enveloped signal processing and high resolution velocity spectra are suitable techniques for detecting gear tooth failures, using vibration monitoring.

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