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Preventive maintenance of industrial gearboxes

Abstract

Reliability of industrial gearboxes is highly important for efficient production in many applications. Frequently, machines are operated at demanding conditions twenty-four hours per day 7 seven days per week; hence, any expected breakdown will have enormous commercial impact – not only because of repair of the machine itself but especially because of production loss.
Analysis of lubricants, inspection with endoscopy and vibration measurement are powerful methods that help for early detection of possible damages and thus allow for properly planning and scheduling the required actions. This article describes how these methods work, their strong points and limitations and what needs to be considered for their proper application. Apart from that, recommendations on inspection frequency are given which are based on experience of Elgeti Engineering related to both inspection itself but also to failure analysis.

Motivation

If production lines are continuously operated, any breakdown of a component causes significant commercial impact, especially because of production losses. If repair of equipment can be scheduled early, production capacity can be arranged much easier than in case of a sudden damage. Apart from that, downtime will be shorter if spare parts can be ordered on time and scope of repair can be planned. Furthermore, costs for both spare parts and service might be significantly higher if one needs them immediately instead of within common lead time.

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Concerning gearboxes themselves, especially fatigue damages on gears and bearings may occur because of demanding operation conditions. If damage can be detected early, scope of repair can be limited to the defective and maybe their interacting parts while in case of further propagation, the complete gearbox might collapse and in worst case input and output aggregates might get damaged too.

Figure 1 and Figure 2 show the difference of early and propagated gearing damage. In the first case, there is only slight wear on the teeth which can be detected by inspection and requires exchange of the gear stage. In the second case, tooth fracture occured already because of which the gearbox cannot be operated any further. Apart from that, large debris caused damage on further gears and bearings for which reason those need to be replaced too.

Similar to that, Figure 3 shows an early stage bearing damage which could have been detected by endoscopy. In this case, the bearing still is functional and keeps the shaft in position. In case of the bearing in Figure 4, however, spalling propagated around the complete circumference because of which the shaft got displaced and subsequent gearing damage was induced. Again, further operation of the gearbox was no longer possible.

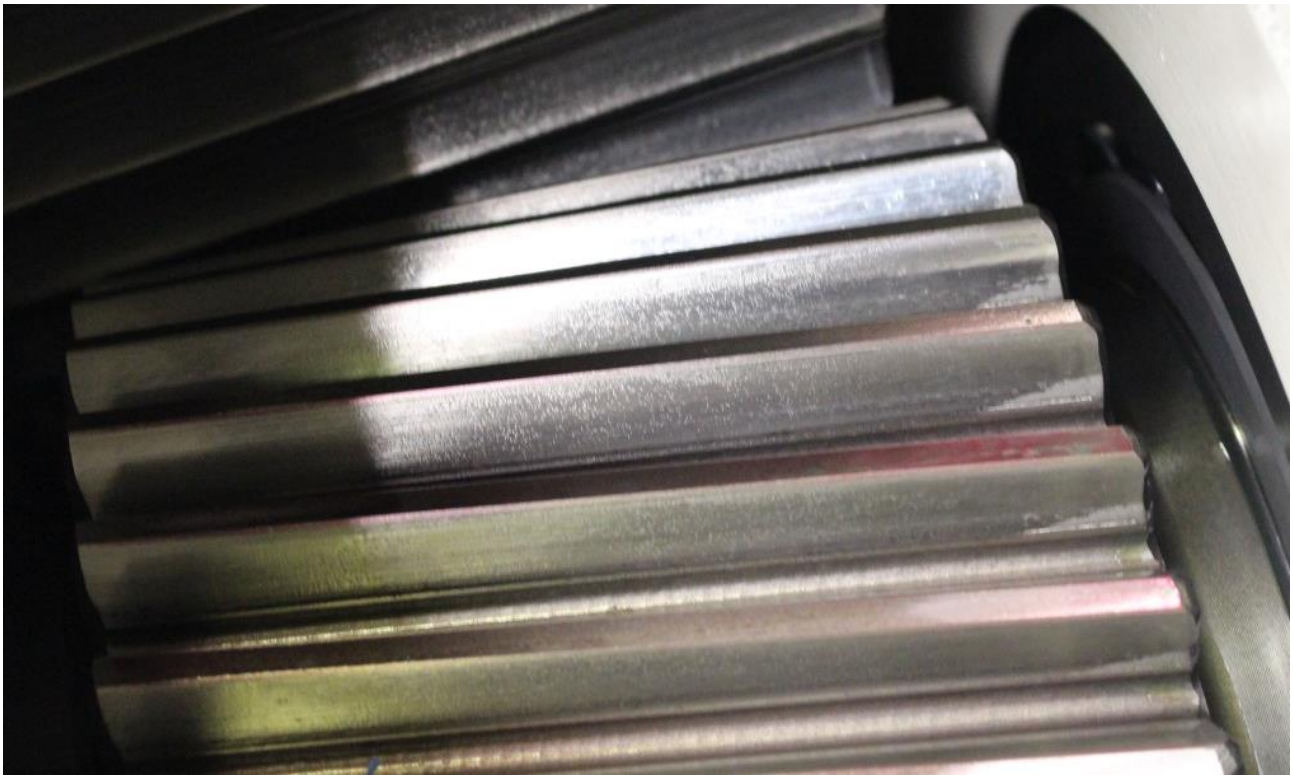

Figure 1: early stage gearing damage

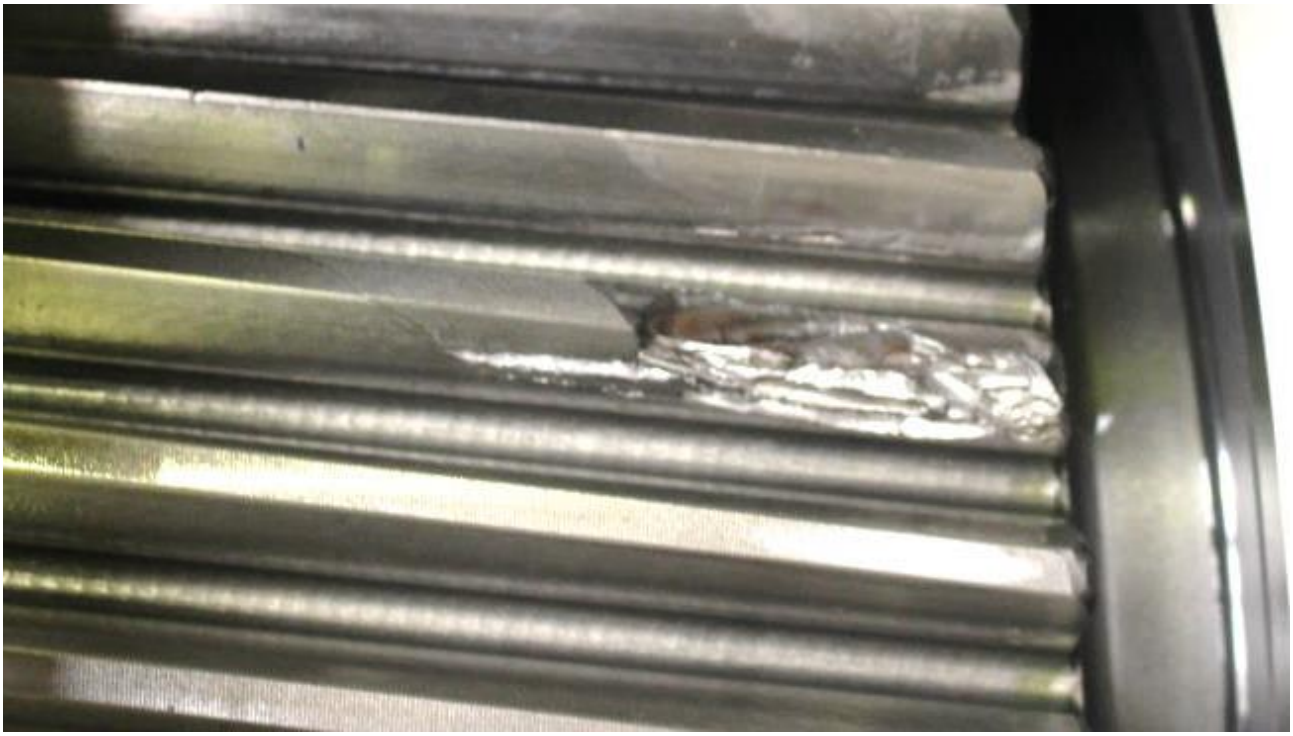

Figure 2: fatal gearing damage

Figure 3: early stage bearing damage

Figure 4: propagated bearing damage leading to ring fracture, misalignment of the shaft and subsequent gearing damage

1 Oil sample analysis

Regular analysis of oil samples is one of the easiest and cheapest methods for condition monitoring of gearboxes. Most early stage damages will leave their traces in the oil while detection of any possible alteration of oil conditions can trigger oil change and thus prevent damages caused by insufficient lubrication properties.

Especially in case of gearboxes that can be easily accessed by maintenance personnel like in production plants (in contrast to wind energy converters where somebody has to climb on the tower first), taking oil samples can be done within a couple of minutes with minimum impact on operation. Nevertheless, there are some points to be considered in order to ensure reliable results and detection of possible trends:

- Samples shall be taken during operation or shortly after stopping at normal temperature in order to avoid segregation.
- Position and method have to be always the same.
- When taking samples by a valve, the first flow shall not be used (segregation in related pipes).
- Inspection covers shall be cleaned thoroughly prior to opening in order to avoid contamination of the gearbox and thus invalid analysis results.
- Overall cleanliness of sample container, tools, location of sampling etc. is highly important.

As one can see in Figure 5, oil sample analysis provides data on especially concentration of wear particles, contamination as well as on viscosity. Apart from that, the infrared spectrum indicates possible alteration of the oil especially due to degradation. If analysis is conducted regularly at sufficiently short intervals, significant changes of particular values will lead to early detection of failures. In case of slight changes, however, one has to consider any possible uncertainty due to limited repeatability of sampling method for which reason more than two values would need to be compared for a clear trend detection.

For large industrial gearboxes, the following proposal on inspection intervals shall therefore be considered as orientation:

- One week after start of service
- One month after start of service
- Every three months
- More frequently in case of increased risk
- Less frequently in case of increased effort for sampling (e. g. wind energy converters)

GESAMTBEWERTUNG						
Untersuchungsdatum			**16.10.2009**	04.05.2009	24.09.2008	23.04.2007
Datum Probenentnahme			**27.08.2009**	20.03.2009	07.08.2008	21.02.2007
Datum letzter Ölwechsel			**21.02.2007**	21.02.2007	21.02.2007	-
Nachfüllmenge seit Wechsel		l	**25**	-	-	-
Laufzeit seit Wechsel		h	**49053**	18000	12000	-
Laufzeit gesamt		h	**21813**	67054	61694,7	49072
Öl gewechselt			**Nein**	Nein	-	-
VERSCHLEIß						
Eisen	Fe	mg/kg	**70**	58	13	12
Chrom	Cr	mg/kg	**1**	1	0	0
Zinn	Sn	mg/kg	**0**	0	0	0
Aluminium	Al	mg/kg	**0**	0	0	0
Nickel	Ni	mg/kg	**0**	1	0	0
Kupfer	Cu	mg/kg	**1**	1	1	1
Blei	Pb	mg/kg	**0**	0	0	0
PQ-Index	-		**OK**	OK	OK	OK
VERUNREINIGUNG						
Silizium	Si	mg/kg	**8**	7	14	10
Kalium	K	mg/kg	**1**	0	0	0
Natrium	Na	mg/kg	**0**	2	0	0
Wasser	%		**< 0.10**	< 0.10	< 0.10	< 0.10
ÖLZUSTAND						
Viskosität bei 40°C	mm²/s		**287.95**	283.80	333.40	307.50
Viskosität bei 100°C	mm²/s		**33.33**	33.12	37.15	34.67
Viskositätsindex	-		**160**	160	160	158
Oxidation	A/cm		**5**	6	2	3
ADDITIVE						
Kalzium	Ca	mg/kg	**0**	0	0	0
Magnesium	Mg	mg/kg	**0**	19	3	0
Bor	B	mg/kg	**0**	1	0	0
Zink	Zn	mg/kg	**12**	23	8	0
Phosphor	P	mg/kg	**367**	384	427	441
Barium	Ba	mg/kg	**0**	0	0	0
Molybdän	Mo	mg/kg	**0**	13	5	0
Schwefel	S	mg/kg	**3737**	4042	4215	4173
ZUSATZTESTE						
Neutralisationszahl	mgKOH/g		**1.08**	0.89	0.83	0.83

Infrarot-Spektrum

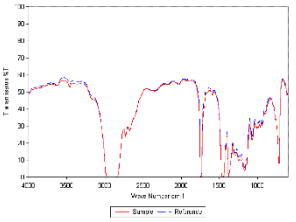

Figure 5: example of oil sample analysis

2 Inspection and endoscopy

Gearbox inspection typically requires between one and three hours per unit, depending on accessibility of parts. Apart from that, one needs some further time for cooling down and dripping of the upper parts prior to inspection. High temperature is not only inconvenient for the inspector; oil mist would affect the inspection itself. Apart from that, oil on gear flanks as well as on bearing raceways would make it difficult to detect small damages. Hence, one needs to consider up to one shift for the gearbox to be out of operation for inspection.

Prior to open any inspection cover, it is very important to clean it as well as the top surface of the gearbox in order to avoid any contamination. Using a tarpaulin would be very beneficial too; especially in case of very dirty environment like rubber mixing plants. The inspector shall approach the gearbox with empty pockets and tie up his camera, pen, lamp or any other tools in order to ensure that nothing can fall inside. For the same purpose, the bolts of the covers have to be brought out of operation radius of the inspector.

During inspection, one might have the option of cleaning some teeth if accessible. For this purpose, one shall only use some alcohol or similar cleaning liquid which completely vaporizes at ambient temperature and thus cannot contaminate the oil. Here, it is essential to not spray the liquid on the part itself, one shall apply it on rags by which one can carefully clean the related parts.

As far as one has the option of (manually) turning the input shaft, it is typically possible to inspect each tooth of each gear one by one. For the bearings, the options for inspection are limited. If external bearing covers could be opened, one might get access to e. g. outside raceways of spherical roller bearings (see Figure 1) while inside raceways need to be inspected by endoscope. That way, it is possible to check a few positions, which at least give some indication of the bearing condition.

As one can see by Figure 8, it is not necessary to see a bearing damage directly. If there would be beginning flaking, the related raceways would be significantly influenced by particles getting between rollers and rings and resulting wear. Apart from that, one has to consider that resolution of an endoscope is significantly less than a common digital camera; nevertheless, because of the fact that it helps to access bearings which otherwise could not be inspected, it is a very powerful tool.

Referring to experience from related projects, Elgeti Engineering recommends the following frequency of inspection:

- Prior to start of service (for documentation of delivery shape)
- One month after start of service
- After that, once per year or in case of any indication

Figure 6: typcially, gears can be inspected completely if the input shaft can be turned slowly

Figure 7: bearing inspection under bearing cover

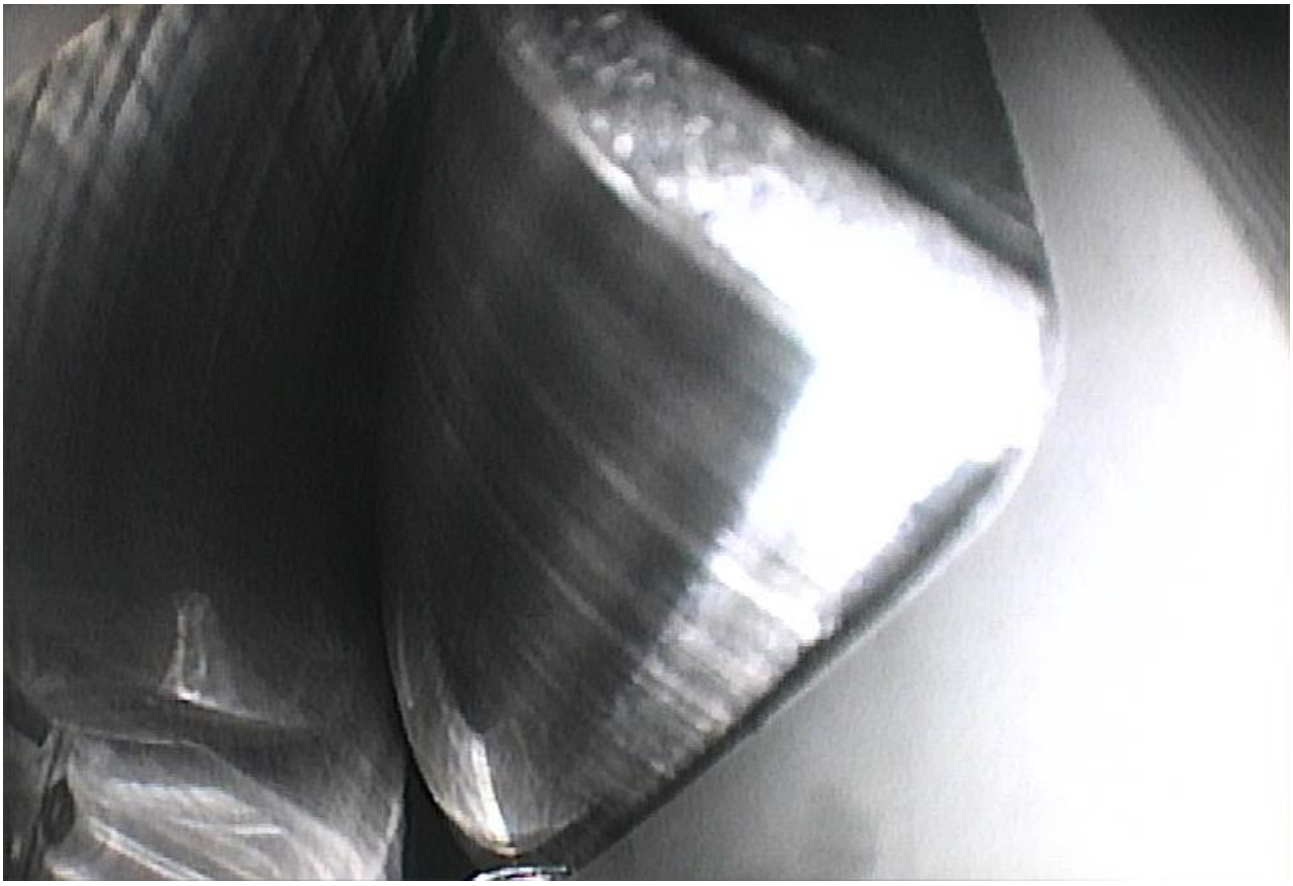

Figure 8: bearing inspection by endoscopy

3 Vibration measurement

Vibration measurement is another powerful tool for condition monitoring of gearboxes that can be applied permanently or temporarily. Permanent condition monitoring can be part of the control system of the complete technical system and in best case trigger automatic shutdown if vibration behaviour changes. Temporary measurement is significantly cheaper as it is neither required having the expensive equipment for each gearbox nor implementing a sophisticated control setup which is capable of distinguishing defects from changes in operation conditions which would influence vibration behaviour, too.

Figure 9 describes the general setup of vibration measurement. By accelerometers that can be applied to the housing, a time dependent signal is obtained. By Fast Fourier Transformation (FFT), this time dependent signal will be converted into a frequency dependent signal. The mathematical background behind this is that any periodic function of time can be converted into a superposition of sine and cosine functions with different frequencies. Accordingly, FFT gives a frequency spectrum by which the predominant frequencies of vibration can be identified.

Knowing that any possible defect excites vibrations at characteristic frequencies, FFT might lead to identification of the defect without inspection. This applies to both electric influences from the feeding inverter and to mechanical defects like gearing or bearing damage. For the latter ones, the frequency of

which the damage gets into contact with another part directly corresponds to speed and geometry and will lead to a periodic signal with exactly this frequency.

Apart from detection of significant defects, vibration measurement might also be useful for assessment of overall vibration behaviour and detection of possible trends. However, this requires operation at highly repeatable reference conditions (speed, torque, external vibration behaviour) which in many cases can hardly be achieved. Furthermore, many gearboxes are operated with non-continuous working cycles with varying speed and torque.

As long as such working cycles are repeatable, vibration assessment could be done by means of class counting. This means that certain thresholds have to be defined and then, it is counted how frequently those are exceeded. Accordingly, this method gives some indication of overall vibration load within a certain time period (see Figure 10) which does not only help for evaluation of the gearbox itself but also for assessment of the working process. Frequently, some process parameters can be slightly modified without significantly influencing overall performance; however, if such modifications might lead to significant reduction of shock loads, the overall endurance of the mechanical equipment might be improved.

If there is no permanent vibration measurement, it is recommended to measure at least one month after start of service and after that, once per year, together with the inspection. In this context, the first measurement shall give some reference data after running-in of all parts.

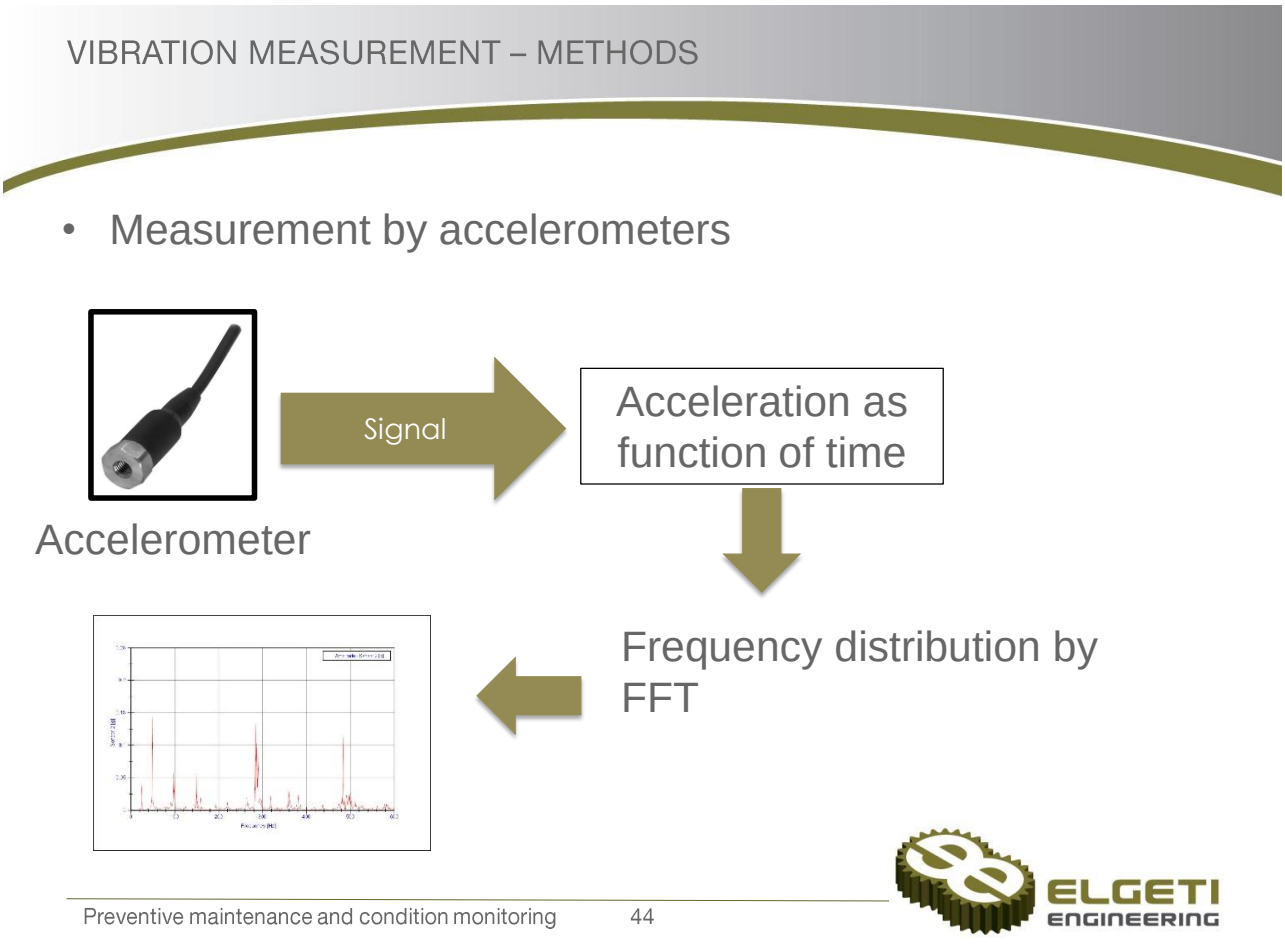

Figure 9: method of vibration measurement

Test 6 - Material 1				
Sensor 1	Sensor 2	Sensor 3	Sensor 4	Threshold limits [g]
134006	152729	108542	102384	0,3
121360	128658	76046	84545	0,45
107362	115649	53139	72631	0,6
76703	72670	31897	48463	1
49218	27637	20568	26278	2
36421	14811	17348	20342	3
29601	8198	14993	15532	4
11911	1059	10291	1778	8
3732	85	4780	15	12
258	0	373	0	20
0	0	0	0	30
0	0	0	0	40
0	0	0	0	50

Figure 10: class counting

4 Conclusion

Oil sample analysis, inspection with endoscopy and vibration measurement are powerful tools that allow for detection of possible damages at early stages. Hence, possible down time can be reduced and necessary repair actions can be scheduled and planned properly. In this context, it has to be mentioned that inspection and vibration measurement complement each other since endoscopy requires a minimum size of bearings why it might not be applied to the input shaft while vibration measurement works best at maximum speed and this is strongest where endoscopy is weak and vice versa.

Apart from that, vibration measurement can help to assess working cycles in order to minimize shock loads on mechanical equipment. For this, class counting method provides valuable data on overall vibration load for a certain time period.