Artículo de investigación

Relationship between reliability centered maintenance and condition monitoring (Case study)

Relación entre el mantenimiento centrado en la confiabilidad y el monitoreo de condición (Caso de estudio)

Relação entre manutenção centrada em confiabilidade e monitoramento de condições (estudo de caso)

Recibido: 9 de abril de 2017. Aceptado: 30 de mayo de 2017

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Abstract

In this paper, the effective role of and the relationship between reliability centered maintenance (RCM) and condition monitoring (CM) techniques (vibration analysis, sound, and oil and failure analysis) are considered in one of the vital petrochemical equipment. Given the critical role of MX-840 extruder in the production of the Tabriz Petrochemical Complex, the machine is a critical machine with a degree A and a sensitivity score of 92 to 100. As a result, the RCM method was applied to the machine and was under the care and condition monitoring. By observing the increase in sound and the first failure symptoms, the weekly monitoring of the equipment was placed on the CM unit agenda. By examining the trend of increasing the wearing index in the oil analysis results, the increase of HDm (High Definition Technology) in the data acquisitions of Shock Pulse technology and also the observation of the failure frequency of one of the gears with the mid-shaft harmonics, the CM department reported an increase in the clearance of the bearings and the beginning of failure. After the technical meetings, the study of the process behavior of equipment and technical and repair data, it was decided to take the equipment apart and its internal parts be inspected. Observations inside the equipment during its maintenance process and the results of post-repair analyses

Resumen

En este trabajo, el rol efectivo de y la relación entre el mantenimiento centrado en la confiabilidad (RCM) y las técnicas de monitoreo de condición (CM) (análisis de vibración, sonido y análisis de aceite y falla) se consideran en uno de los equipos petroquímicos vitales. Dado el papel crítico de la extrusora MX-840 en la producción del complejo petroquímico de Tabriz, la máquina es una máquina crítica con un grado A y un puntaje de sensibilidad de 92 a 100. Como resultado, el método RCM se aplicó a la máquina y estaba bajo el cuidado y la supervisión de la condición. Al observar el aumento en el sonido y los primeros síntomas de falla, el monitoreo semanal del equipo se incluyó en la agenda de la unidad del CM. Examinando la tendencia de aumentar el índice de desgaste en los resultados de análisis de aceite, el aumento de HDm (tecnología de alta definición) en la adquisición de datos de la tecnología Shock Pulse y también la observación de la frecuencia de falla de uno de los engranajes con el eje medio armónicos, el departamento de CM informó un aumento en el espacio libre de los cojinetes y el comienzo de la falla. Después de las reuniones técnicas, el estudio del comportamiento del proceso de los equipos y los datos técnicos y de reparación, se decidió desmontar el equipo y inspeccionar sus partes internas. Las observaciones dentro del equipo durante su

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showed that the RCM, CM, and Failure Mode Effective Analysis (FMEA) applications are of great importance in care and are well suited for timely diagnosis of defect, and can be used by the above tools and experienced technicians to stop and prevent financial, safety and environmental damage.

Keywords: Shock pulses, Vibration, Oil analysis, Reliability, Gear box

proceso de mantenimiento y los resultados de los análisis posteriores a la reparación mostraron que las aplicaciones de análisis efectivo RCM, CM y Failure Mode (FMEA) son de gran importancia en la atención y son adecuadas para el diagnóstico oportuno de defectos, y ser utilizado por las herramientas anteriores y técnicos experimentados para detener y prevenir daños financieros, de seguridad y ambientales.

Palabras clave: Impulsos de choque, Vibración, Análisis de aceite, Fiabilidad, Caja de engranajes

Resumo

Neste artigo, o papel efetivo e a relação entre a manutenção centrada na confiabilidade (RCM) e as técnicas de monitoramento de condições (análise de vibração, som e análise de óleo e falhas) são consideradas em um dos equipamentos petroquímicos vitais. Dado o papel crítico da extrusora MX-840 na produção do Complexo Petroquímico de Tabriz, a máquina é uma máquina crítica com um grau A e uma pontuação de sensibilidade de 92 a 100. Como resultado, o método RCM foi aplicado à máquina e estava sob os cuidados e monitoramento de condições. Observando o aumento do som e os primeiros sintomas de falha, o monitoramento semanal do equipamento foi colocado na agenda da unidade de CM. Examinando a tendência de aumentar o índice de desgaste nos resultados da análise de óleo, o aumento de HDm (High Definition Technology) nas aquisições de dados da tecnologia Shock Pulse e também a observação da frequência de falha de uma das engrenagens com o eixo intermediário harmônicos, o departamento de CM relatou um aumento na folga dos rolamentos e no início da falha. Após as reuniões técnicas, o estudo do comportamento do processo de equipamentos e dados técnicos e de reparo, foi decidido desmontar o equipamento e inspecionar suas partes internas. Observações dentro do equipamento durante seu processo de manutenção e os resultados das análises pós-reparo mostraram que as aplicações RCM, CM e Análise Efetiva de Modo de Falha (FMEA) são de grande importância nos cuidados e são adequadas para o diagnóstico oportuno de defeitos. ser usado pelas ferramentas acima e técnicos experientes para parar e evitar danos financeiros, de segurança e ambientais.

Palavras-chave: Pulsos de choque, Vibração, Análise de óleo, Confiabilidade, Caixa de engrenagens.

Introduction

Given that extruder gearbox has been defined as part of the company's sensitive equipment in terms of both the key role in the production in the petrochemical complex and the high cost of spare parts as well as the thick shell of the machine that affects the accuracy of data acquisition from the shell, the manufacturer has been commissioning Shock Pulse sensors made in SPM Co. so as to enable us to monitor the conditions of 21 bearings of the gearboxes. However, the difficulty of supplying spare parts due to external sanctions and the lengthy continuous operation of the machine, led the CM unit to the provision of a more up-to-date machine made in SPM, Leonova Diamond model to provide accurate interpretation of the Shock Pulse sensor data. A project to install the online monitoring system was also requested. Based on thorough and comprehensive studies (using three parallel methods of vibration analysis, Shock Pulse technology and oil analysis), since the first signs of failure were observed, and during the whole period when the equipment was subjected to weekly, and even occasionally daily monitoring, regarding the high risk of conditions due to the difficulty of spare parts, the CM unit recommendation was the overhaul of the equipment with a diagnosis of an increase in the clearance of bearing No. 15 and the probability of the effect of this problem on the lack of proper and balanced engagement of gears.

The Complex management, despite the importance of continuing the work of this equipment in the production, due to the trust with CM unit, ordered the overhaul of the machine.

Upon stopping the work of the machine and opening the equipment, the initial evidence indicated that there was no failure. Due to the disagreement between the experts regarding the continuation of the repair process or the decision on the non-overhaul, an immediate meeting was formed and because of the expert opinion of the CM unit, based on the accuracy of the investigations, the decision was made to continue disassembling. With the continuation of repairs and removal of the shell of the upper part of the gearbox, as well as the transfer of the mid shaft to the workshop and the demounting of the barring no.15 in the inner ring, as well as the fracture of one of the gear 4, with the replacement of two bearings 15 and 20 and parts of the gear in the inspection test, cracking was observed. The equipment was assembled (due to the lack of spare parts for the gear), and in subsequent analyses, the reduction of the vibration with the source of the bearing (due to the replacement of the bearing 15) and the non-decreasing of the tangential vibrations of the bearing origin (due to lack of replacing the gear) were evident.

Literature review

Petrochemical companies are operating to use the reliability centered maintenance (Simoes, et.al, 2011) and (Chattopadhyaya. et al. 2016) , risk based inspection (API, 2016), total productive maintenance (Nejad and, Keshtkar , 2018) and (Tewari and Rawat2017) and business process reengineering (Campbell, 1995) methods, but there is deep gap between them and optimal using and deploy of the mentioned methods. Some similar cases were studied about subject by many authors that some of them are as bellow: Sarkar and Behera (2012) have worked on the reliability in Rukhia plant of India. Reliability was examined by using the failure data of past 5.5 years. They have counted Compressor, Combustion Chambers (Heated Gas), and Gas Turbine, Generator and Electrical Systems cases. Keshtkar (2013) has worked on continuous improvement program of gas turbine made by Siemens Company Series 600 (SGT-600 / 25MW / Siemens) and has been looking for following items: Emissions reduction, extension of gas turbine life cycle, extension of time between overhauls and remote monitoring and diagnostic. Keshtkar (2011) has studied about RCM approach to maintain a nuclear power plant. Every year in France, 14 billion francs are paid to maintain 55 nuclear power plants that generate about 70000 MW / hr. electricity. RCM methodology is selected to maintain 450 nuclear power plants in compliance with safety regulations and system reliability. It is concluded that RCM method should be accepted and adopted by all employees the same as TQM and TPM, otherwise it will be useless in the long time. The results of RCM several years study show that RCM is a valuable and effective method to maintain equipment. Optimizing the activities of the PM by keeping the accessibility and reliability is one of the RCM advantages. Jia and Christer (2003) have compared RCM approach with modeling approach in a chemical plant in China. In that complex, 3000 people are working approximately 24 hours and 600 tons / day are produced. Boiler of the complex had a problem, Jia could solve the problem of boiler in practice by using quantitative models with RCM concept, and he suggested DTM Model (Delay Time Modeling). Kotlyer and Barringer (1996) have worked on the turbo compressor reliability. Due to factual information and distribution Weibull , they can find the relationship between turbo compressor system life and the reliability. Reliability is the possibility that equipment can provide its function to defined conditions (MIL - STD - 721) (12) and MTBF is the index to measure reliability for repairable equipment. They obtained optimal replacement of parts in 4 years and reliability of the system was 49.1 in 49 months. FMEA analysis was used to determine the criticality of the equipment. Conditioning monitoring includes: Vibrations analysis (Mobley, 1999 , ISO – 17359 ,2011, ISO – 13373 -1 ,2002 , ISO – 13373 -2 ,2016 , ISO – 13373 -3 ,2015) , Oil Analysis (ISO – 4406, 1999), Sound(, RCFA/FEMA(Shasfand and seyed hosseini, 2016) ,Condition Based Maintenance (Sinha,2015).

Case Study

Critical Equipment. Top - ten critical equipment of polyethylene unit is indicated in table2. As 80 experts judgment, the extruder in placed in the second critical equipment of unit.

Table 1. Top ten Critical *equipment of polyethylene unit judged by 80 Experts*

No.	Equipment	Type Of Equipment	Quality	Production	Safety	Environment	Operational Risk	Reliability	Availability	Maintainability	Energy	Cost	Sum	Criticality Type
		Primary Criteria	11	10	12	10	9	10	9	10	8	11	100	
1	11-C1	Compressor	10	10	10	8.8	9	9.5	8	9.8	8	11	94	A
2	11-MX	Extruder	8.5	9.5	11	9.3	8.5	9.5	8.5	9.5	7.8	10	92	A
3	11-MMX	Electrical	9.8	9.5	11	8.8	8.5	9.3	7.5	9.3	8	11	92	A
4	11-E1	Exchenger	9.5	10	10	9	9	9.8	8.5	9.5	6.8	9.3	92	A
5	11-E2	Exchenger	9.5	10	10	9	9	9.8	8.5	9.5	6.8	9.3	92	A
6	11-MC	Electrical	9.5	10	10	8.5	9	9.8	7.8	8.3	8	11	92	A
7	11-R1	Reactor	11	9.3	9.8	8.8	9	9.5	8.8	8.8	6	10	91	A
8	11-C2	Compressor	8	9	11	9.5	7.8	8.8	7.8	9.3	6.3	8	85	A
9	11-C3	Compressor	8.5	6.8	11	8.8	6.8	8.5	8.3	9.8	7.3	9.5	85	A
10	11-C4	Compressor	8.5	9.8	9	7.8	7.3	8.8	8.3	8.8	7	9.3	84	A

Applying RCM Method. Table2 shows five steps on Extruder. Failure Mode Effective Analysis (FMEA) is one of the most important steps of RCM Method.

Table2. RCM five Steps on Extruder MX-840

No	Component	Function Definition	Failure Modes	Failure Effects	Failure Consequences
1	GEAR BOX ROTOR	Rotary instruments are set on the rotor	Erosion of bearings' seat Erosion of shafts Curvature	Damage of gearbox bearings Sudden and sequential TRIPS Entering Imbalance and impact load Gearbox function in abnormal conditions	Increasing vibrations Increasing unusual sound Serious damage to gearbox gears
2	BEARING	Control of rotor motor and rotary equipment	Curvature and aging Fracture	Increasing abnormal vibrations Lack of proper lubrication Entering impurity from oil Oil pressure fluctuations	Increasing vibrations Increasing unusual sound Serious damage to gearbox gears
3	THRUST BEARING	Moving rotary devices gearbox in axial direction and adjust the rotor axial movement	Curvature and corrosion fracture	Increasing abnormal vibrations improper lubrication Immediate impurity from oil Oil pressure fluctuations	Increasing gearbox vibration Serious damage to rotating and fixed parts Increasing unusual sound
4	OIL SEAL	Oil Seal of gearbox Container	Corrosion and fracture of the edges of the seal	Long-term operation Use of a low quality piece Impurities in oil Abnormal vibrations	gearbox oil leakage Reducing oil level Environmental contamination with leaked oils

5	LUBE OIL PUMP	Circulation of the oil in the lubrication path and creation of the required pressure in the oil path	Failure of bearings Mechanical failure of the corresponding seal Corrosion and failure of SCREWs	Long-term operation Operation in abnormal conditions Abnormal vibrations	Oil pressure drop Increasing unusual sound Damage to bearings of gearbox Service off the gearbox

Extruder gearbox specifications (Flender, 1993) (21)

- Manufacturer: Flender/Germany
- Model: 261 F 130
- Construction Year: 1993
- Deriver: Electro-Motor
- Power: 4.3 Mw
- Oil viscosity: ISO VG 320
- Oil Quantity: 2000 liters
- Started to operation : 1375 (1996)
- Operation: Continuous
- Capacity: 16 tons/hour

As the equipment has been under control and monitoring of the CM unit since the launch (1996), no major overhauls have been made on the gearbox. Only one of the bearings was replaced twice, and gearbox oil was also replaced twice.

Equipment condition monitoring techniques .The gearbox condition monitoring is done using the following methods:***Measuring shock pulses through SPM sensors***

The manufacturer has installed 21 series of 40000 Series of shock pulse sensors next to each bearing (Fig.1) inside the gearbox, and has sent a T2000 shock pulse meter (Fig.2) along with a gearbox(Fig.3) to measure the shock pulses, and it has been done since the gearbox was launched. The machine only measures dB_M and dB_C, where dB_M is the maximum value for shock pulse which indicates the deflection of the bearings (in the inner ring, the outer rim, rollers, shelf, etc.), while dB_C is more representative of the lubrication and the severity of the loads. Recently, a vibration measuring machine called Leonova Diamond made in SPM Co. for measuring and analyzing defects was purchased with shock pulse Technology and Cond master software.

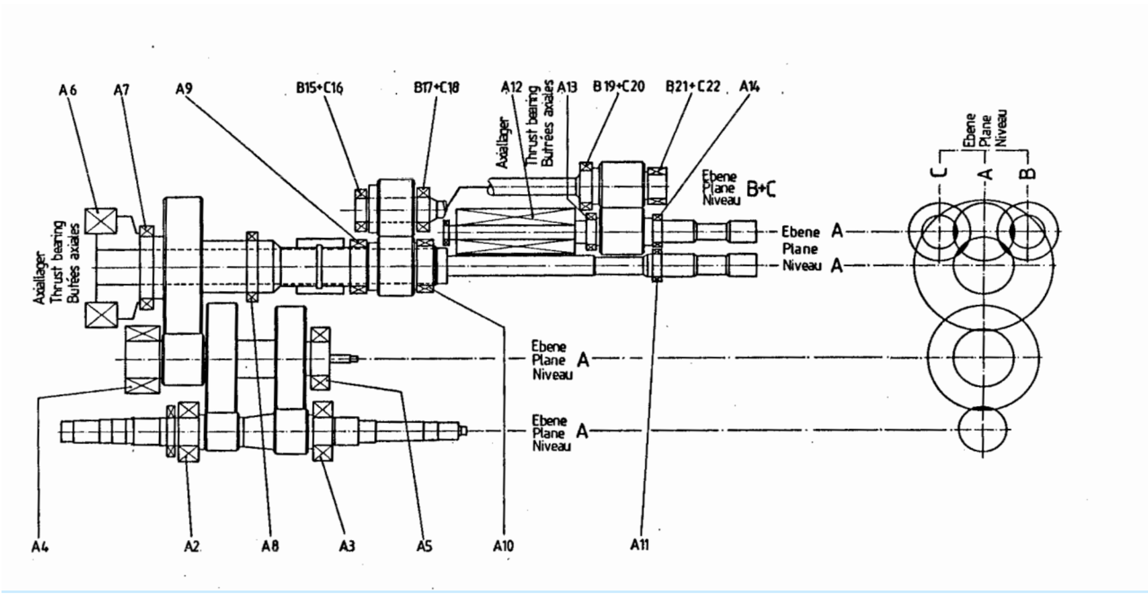

Figure 1: The position of the SPM sensors inside the gearbox

Figure2. T2000 Machine

Figure3. Termination Box

In the gearbox documents, the manufacturer has provided this material on the measurement of shock pulses and suggested that it be monitored in the following way.

- dB_M = Maximum shock value
- dB_C = Carpet (Low) value
- dB_I = Initial value (1 st measurement)
- dB_N = Normal value (Increase of value compared with dBI)
- determined by: $dB_M - dB_I = dB_N$
- When the peak or maximum value $dB_M \leq dB_I + 15$, The bearing condition considers good condition
  Example:
  If dB_I = 30 dB and dB_M = 42 dB (after running time)
  Means dB_N = 12 within range of dB_I + 15 (good condition)
  if dB_M value approach to the index mark dB_I+20, indicates a drastic deterioration a bearing. The monitoring should be down every 2-4 days
  If the steady increase is confirmed by short intervals measurements, indicates progressive deterioration of the bearing. There is enough time for planned shut down
  If dBM value increase as the dBM - dBI>20, this could be indicate a serious problem a bearing. It might be required emergency shout down.

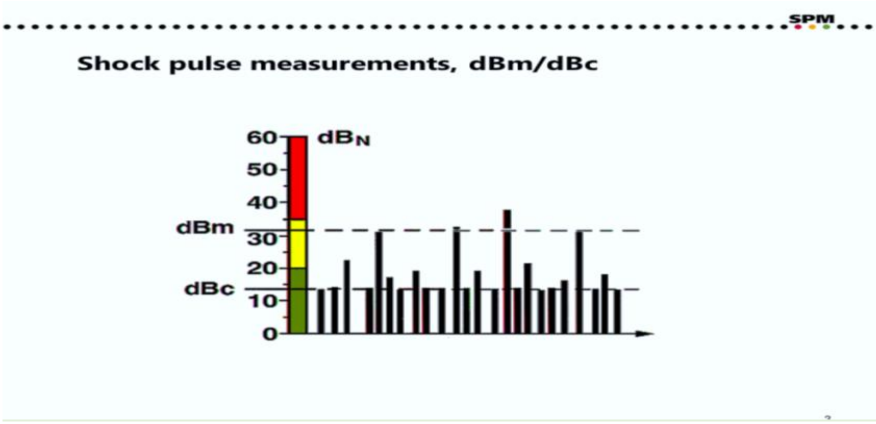

Figure4. Shock pulse ranges

The above concepts are the definitions of DB_M and dB_I and dB_N indices. For the level of energy received by the SPM sensors, the safe, boundary and warning ranges are separated by green, yellow and red colors, respectively as indicated in fig.4.

Given the fact that the T2000 did not have the capability of spectrum analysis and time waveform, the CM unit commissioned the purchase of the new Leonova Diamond model(figure5), which SPM Co. added the Spectrum function, time waveform, balance, etc., based on the above calculations and defined the HDm index for the newer model so that the user can control the state of the bearings easily and without the need for calculations, and only by examining the process changes and the energy range of shock pulses(Condmaster,2016 and (Brunner and Ganga-Contreras, 2017).

The bearing-15 shock pulse. The HDm index of the shock pulse for the bearing-15 is shown below (Fig.6), (Condmaster, 2016), which indicates the high energy level of the shock pulse in the pre-repair time range and the decrease from 10/09/2017 (after repairs)

Figure 5. New Leonova Diamond model

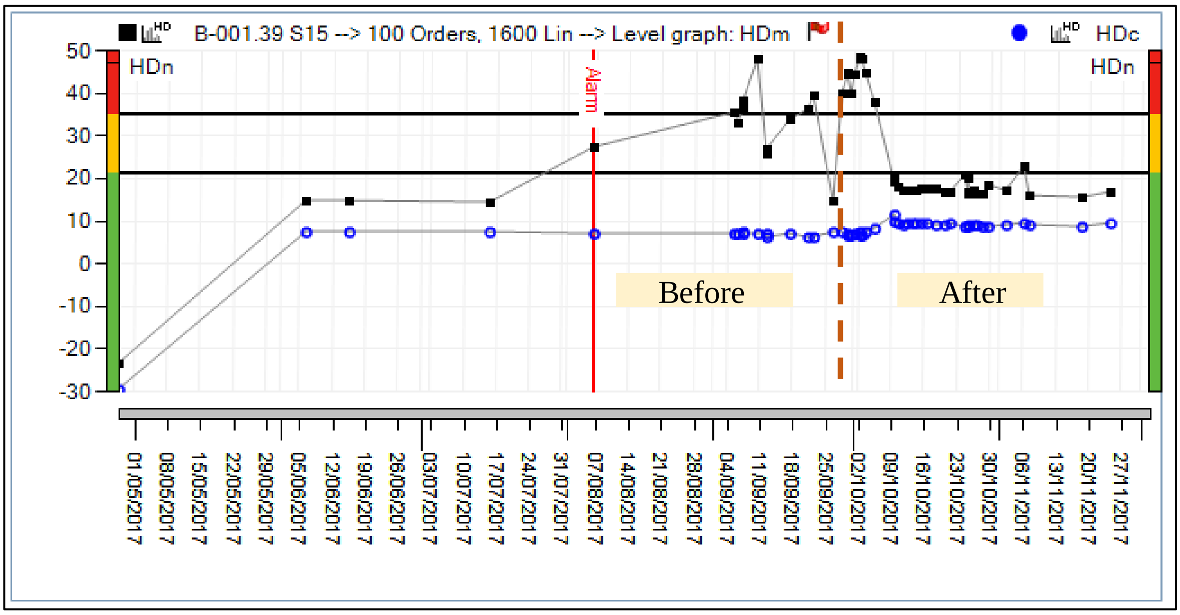

Figure6. Changes in the HDm index of the Bearing-15 before and after the repairs

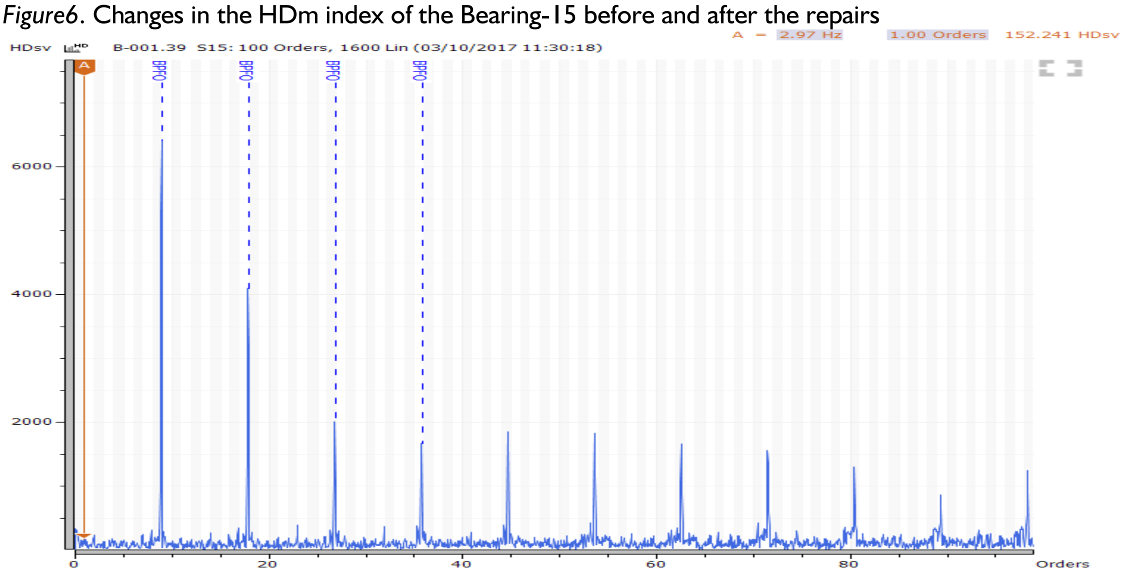

Figure7. Spectrum of Shock Pulse of Sensor 15 - before repairs

Fig. 7 shows well the alignment of the vibration peaks on the BPFO, which, after changing the bearing, this vibrating amplitude had clearly been eliminated. (Fig. 8)

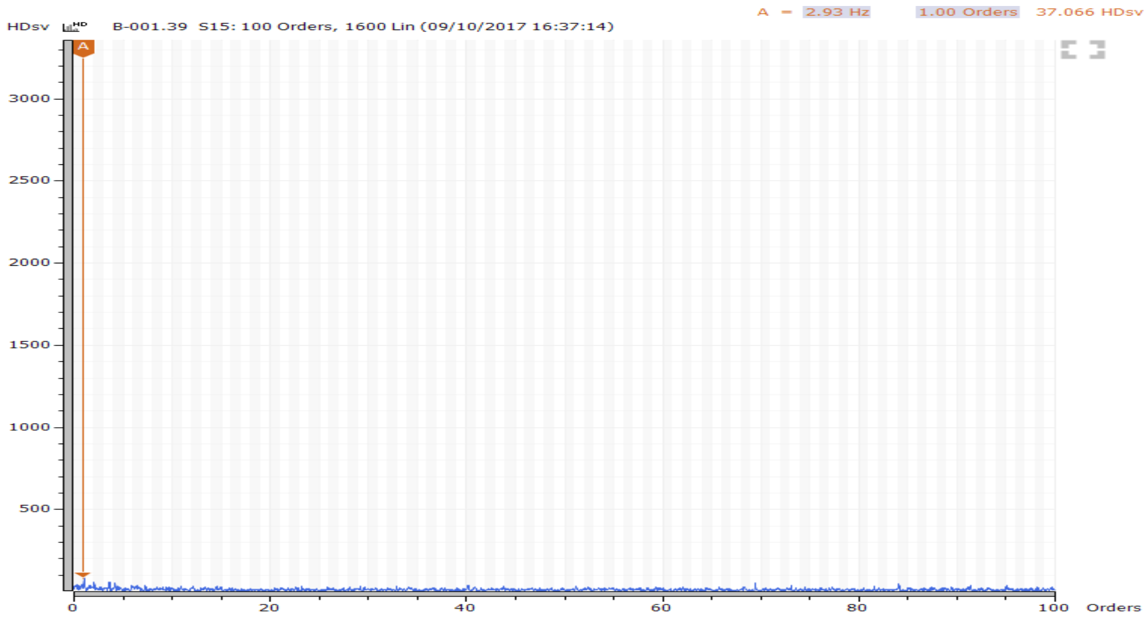

Figure8. Spectrum of shock pulse of sensor 15 - after repairs

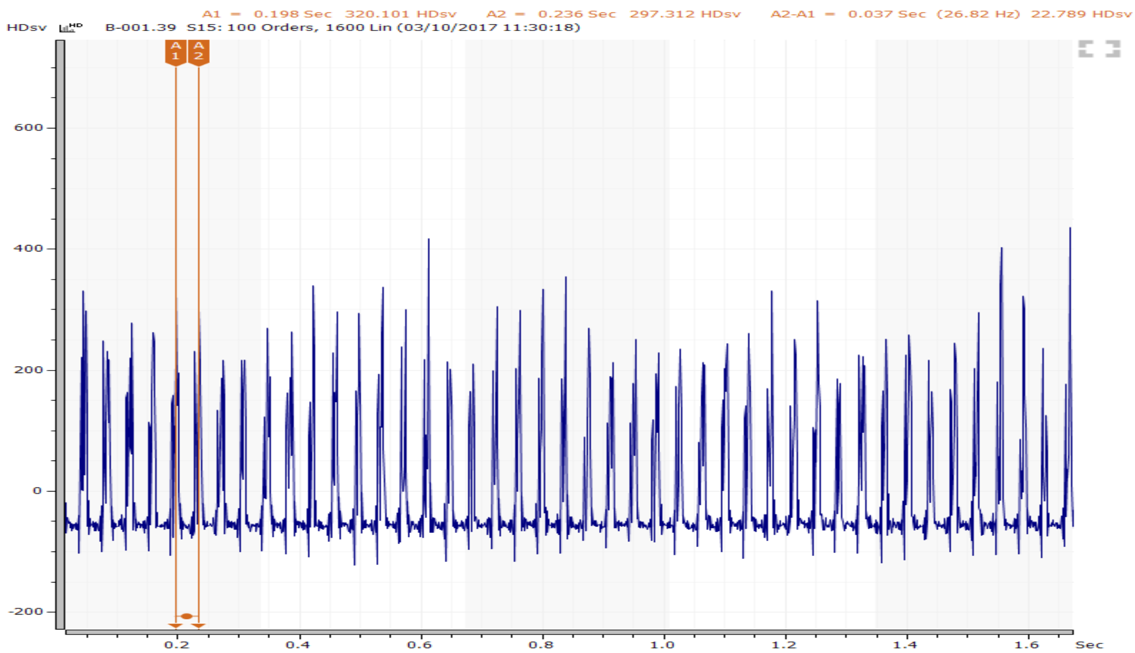

Figure9. Time waveform of shock pulse of sensor 15 - before repairs

Figure 9 shows the time waveform of the appearance of pulse peaks at 0.037s, which is equivalent to the failure frequency of the outer ring bearing (26.82 Hz), eliminated by the switching of the bearing of these pulse peaks.

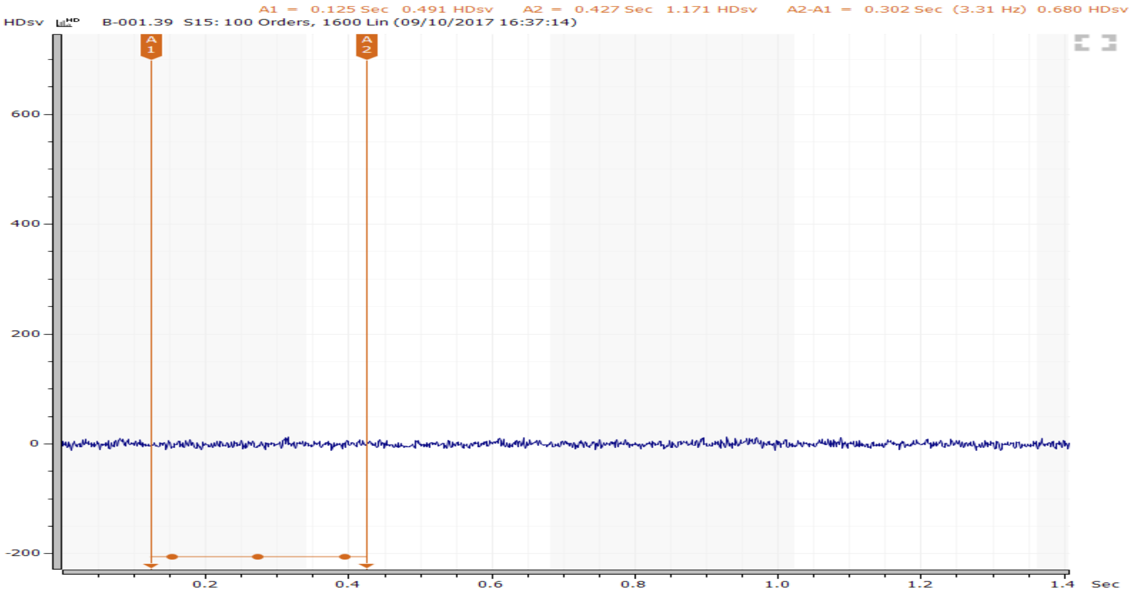

Figure 10: Time waveform of sensor 15 after repair

As shown in Figures 7, 8, 9, and 10, after the repairs and with the bearing replacement, all specifications related to the failure frequencies have been reduced, and the shock pulse energy has also reached the normal range. Bearing damaged evidence on roller bearings and outer ring is evident in the figure 11.

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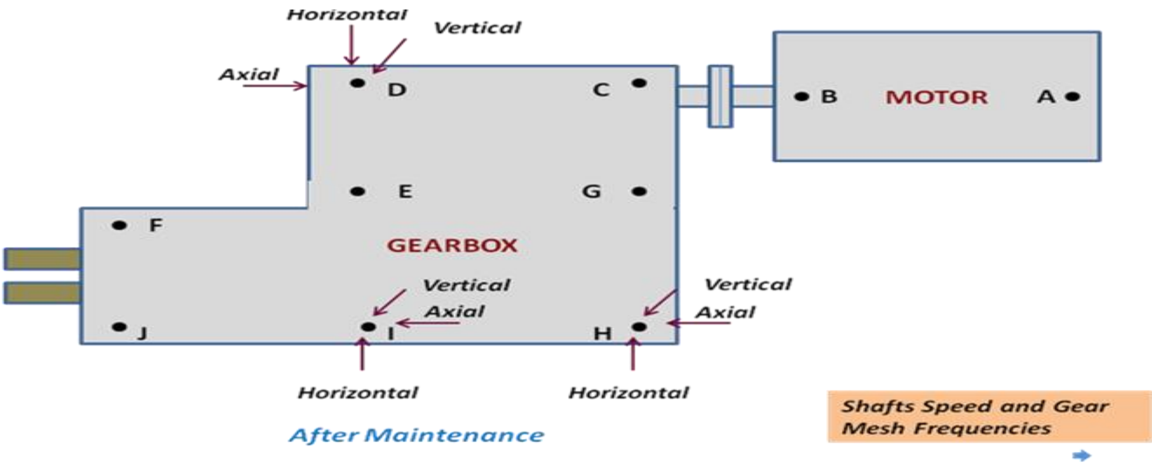

Figure12. Vibration data acquisition locations from gearbox shell

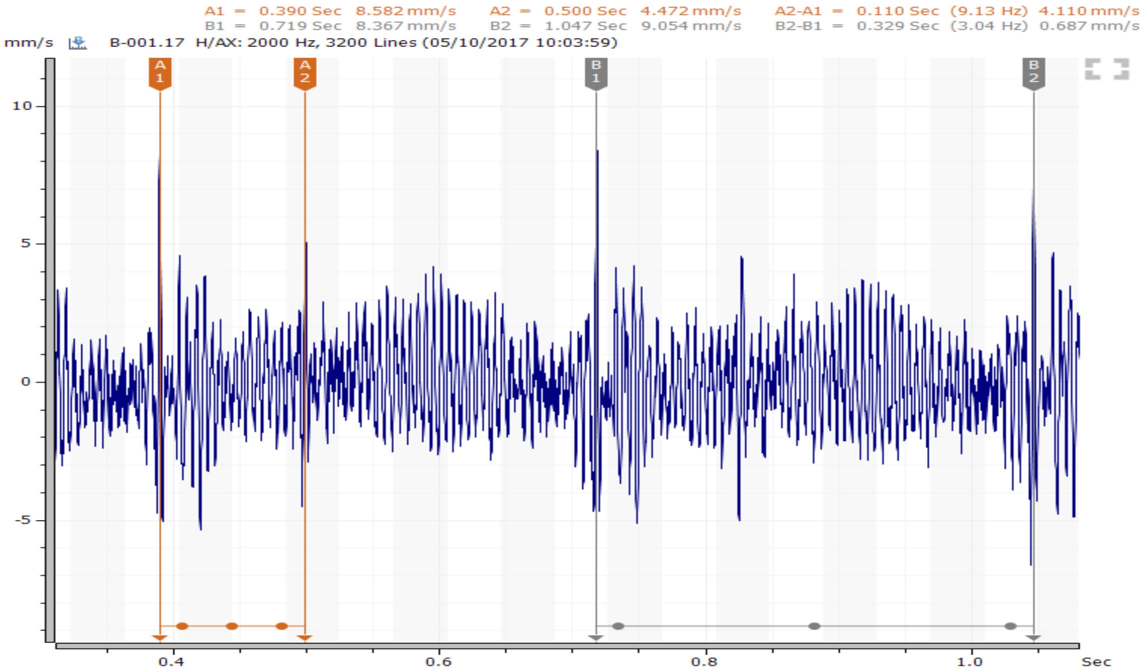

Figure13. The vibrational waveform data acquired from the shell – before the repairs

As can be seen in Fig.13, the presence of vibration peaks of the gears (frequency 173.75 Hz) that are repeated with the associated rotational range of both shafts (3.04 Hz and 9.13 Hz) can be detected. This problem occurs in the vibrating spectrum (Fig.14) with the appearance of the mid-shaft Gear Mesh Frequency (173.75 Hz) and its harmonics that correspond to the mid-shaft (3.04 Hz). In the vibration analysis method, in addition to the manufacturer's recommendation (Flender, 1993) in accordance with ISO-10816 standard recommendations (ISO - 10816-3, 2009) (24) analysis was performed (Rao, 2000) (25).

The results of the analysis were sent to the management as a technical report, with the identification of the early stages of the failure in bearing No.15 and the mid-shaft gearbox. During the overhaul, all evidence proved the detection by the CM unit, which was later presented to the management with the final report along with the illustrations.

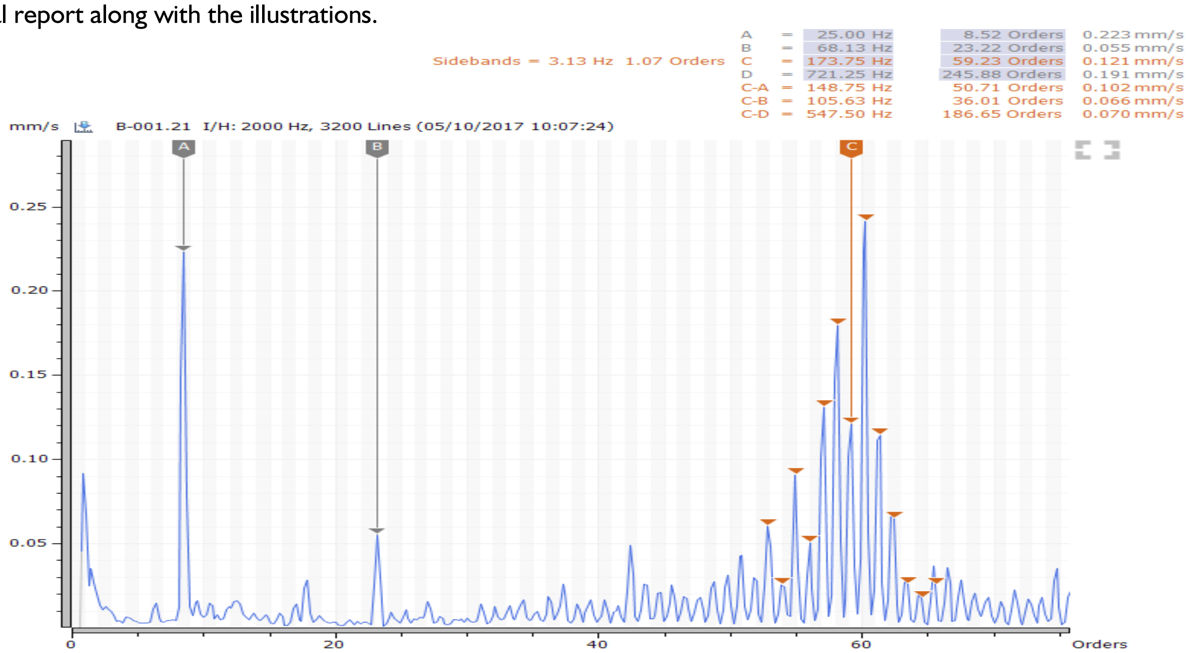

Figure14. Vibrational spectrum related to the measurement of the mid-shaft of the shell – before repairs

(A: Input shaft speed, B: Gear meshes frequency low speed shaft, and C: GMF intermediate to low speed shaft)

Gear mesh frequency. In the figure 15, the gear mesh frequency of the gears is calculated and inserted as the most important criterion for detecting the cause of vibration in gearboxes. If the range of the gear mesh frequency of each of the gears is high, the involvement of those gears should be investigated.

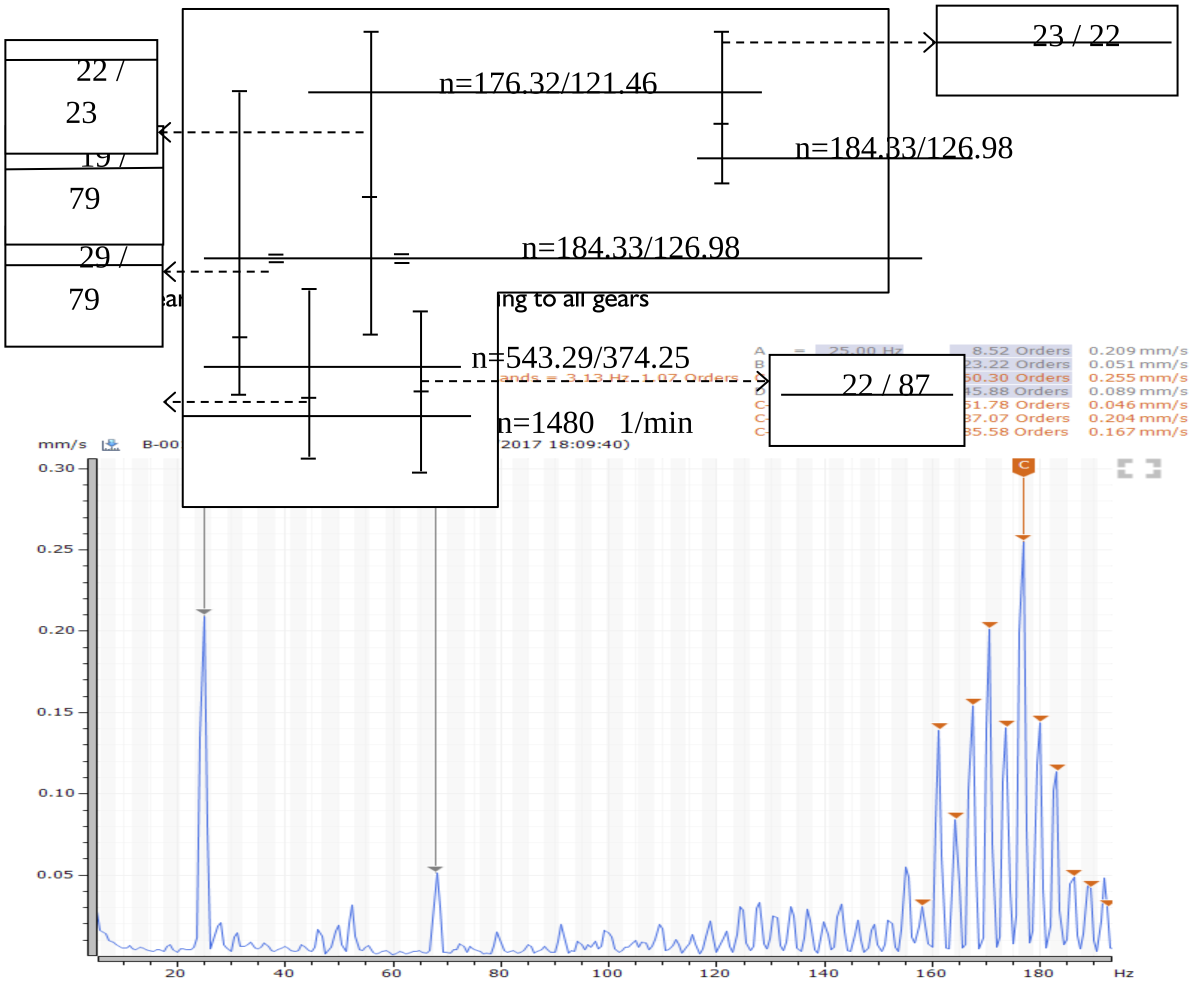

Figure16. Vibrational spectrum for the mid-shaft dimension of the shell - after repairs

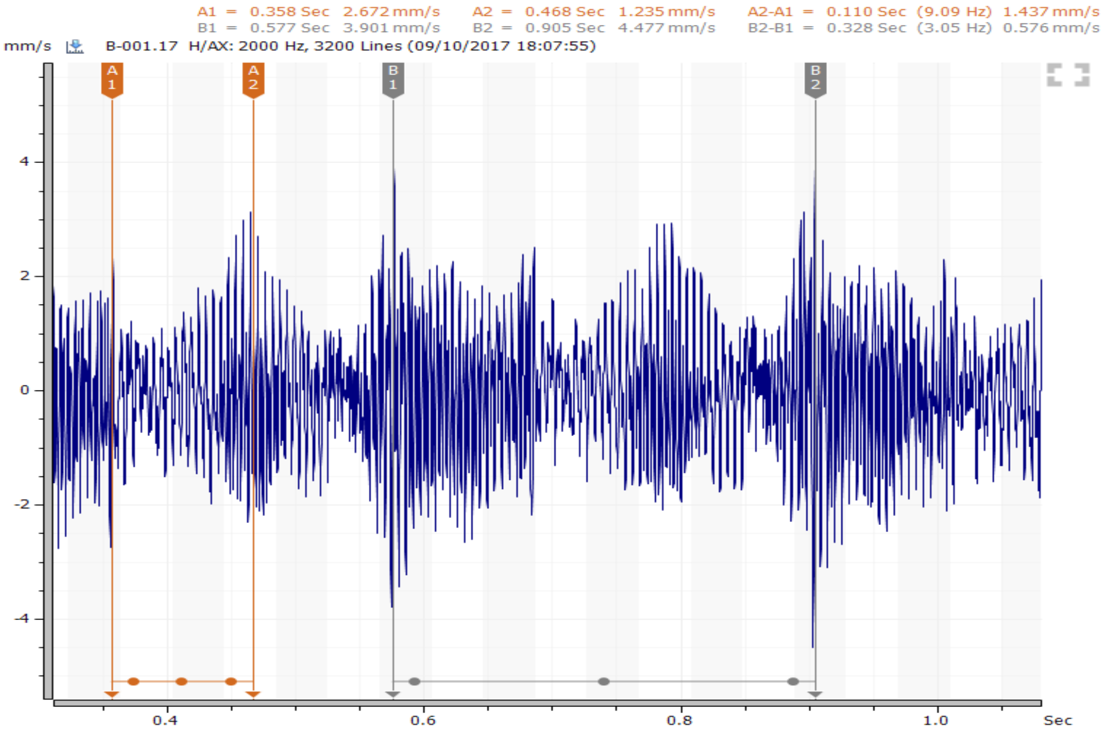

Figure17. Time waveform related to the measurement of the mid-shaft of the shell - after repairs

As the comparison of Figures 13 and 17 together and Figures 14 and 16 show that the damping frequencies associated with the Gear Mesh are still evident due to the damaged gear being not replaced and merely being rolled up to remove the crack.

Defected Gear.As in the figures 18 and 19, it is clear that fracturing is part of a gear 500 and the other gears are impacted by the inappropriate involvement of the shaft 500 with the shaft facing.

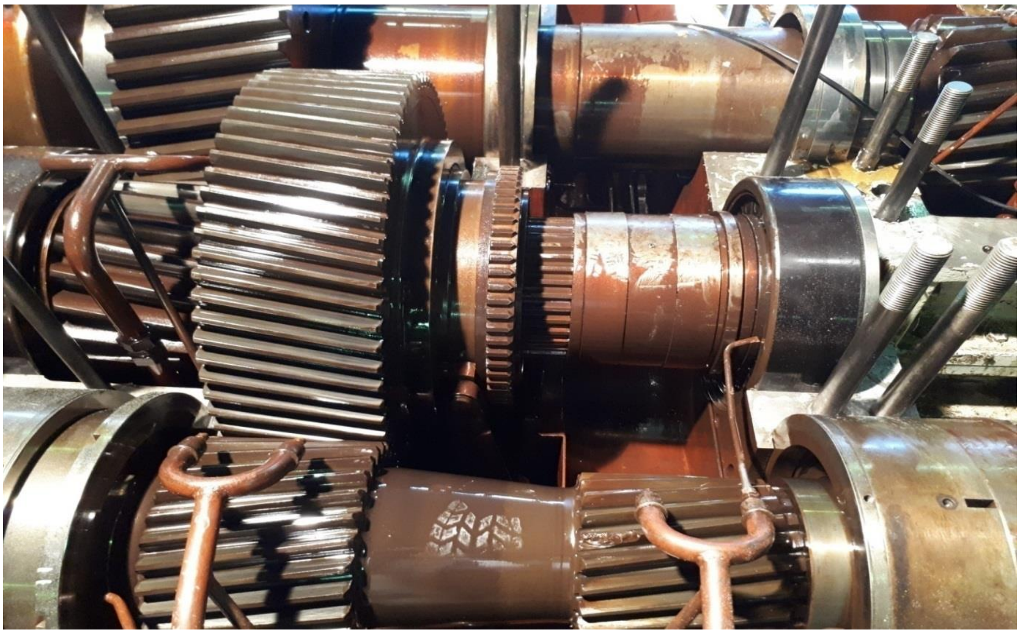
Figure18. Gears orientation

Figure19. Defected teeth of Gear

***Oil test and Analysis*.**Each month a sample of oil is sent to an expert company to carry out the necessary tests. Below is an illustration of one of the oil analysis results (Table3).

Investigations showed that the increase of the Index of Severity (IS) and Particles Quantification (PQ) wearing index and the number of iron particles is significant (Table 3). The high erosion index and the increasing trend of the number of iron particles, especially the large particles, indicate a serious problem in gearbox(ISO – 4406, 1999) , that confirm the existence of a failure in the equipment .

Table 3: Changes in oil analysis indicators

Date/Oil	17.05.07	17.06.14	17.08.15	17.09.11
Fe	14.6	19.7	25	80
Cr	0.9	0.5	0.7	1.4
PQ	10	12	12	28
DL	41	48	63	59
DS	20	22	32	33
IS	1281	1820	2945	2392
VIS40	316	314	315	313
TAN	0.18	0.23	0.23	0.27

Conclusion

This case study shows the importance of RCM and CM's role in risk management decision making on the one hand and high technical value of precise scientific and comprehensive analyses based on three parallel methods of vibration analysis, Shock Pulse technology and oil analysis by experts on the other hand. In troubleshooting and timely detection of equipment failure before unwanted stopping production, the parallel use of different methods will be effective in providing a more definite view. It also helps to increase the reliability of equipment and reduce the risk. By generalizing this process to all the key equipment in all equipment-oriented industries, reliability of the equipment can be improved and thus the total efficiency of the complex. The existence of software, methods, and certified specialists raise the efficiency and effectiveness of maintenance. It is suggested that critical equipment with grade A be monitored on-line.

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