An integrated study of a gearbox failure

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Abstract

Gearbox failures have a significant impact on the operational reliability. Therefore, plant manager's biggest concern is how to get the equipment running again. However, it is equally important to getting it back to operate. In this research, a Hansen transmission gearbox is installed at one of the main sanitary drainage stations at Great Cairo "Helwan” which suffered a significant, premature failure. The gearbox failure has occurred after 5 years of operation although its design life is 20 years. There are three other cases of failures at the plant gear boxes. This paper is a case study of failure analysis of a gearbox of an aeration unit. This aeration unit had replaced its original gearbox after it reached its end of life span. Also, the fan of this aeration unit was changed to have a larger diameter than the original one. The aim of this research is to investigate the main causes that leading to the gearbox failure. Also, how such a failure can be prevented in the future. So the investigation should be planned carefully to stop the gearbox failure as soon as possible to limit the damage. Standard investigation procedures were employed in the analysis. Stress analysis was performed to determine the stress distribution and deformation in gearbox casing. Results of investigations confirmed that the new gearbox is incompatible with the operating conditions of the aeration unit. This led to overloading and overheating problems and then, resulted in damage and failure. Recommendations pointed to change the gearbox according to the actual design of aeration units and install predictive maintenance program.

Keywords: Gearboxes, failure analysis, stress analysis.

INTRODUCTION

Gears and gearboxes are generally robust and reliable devices. However, gears and gearboxes failed and many of them are caused by unforeseen system problems or as a result of improper operation& maintenance rather than design or manufacturing/ material defects. Preventive maintenance is defined as a structured periodic maintenance action that prevents breakdown of an equipment and thus avoids prematurefailures. The first step in any preventive maintenance program is to identifing the causes of failure. Once the root cause of failure is determined, one can take necessary steps to avoid the problem in the future. “Toshita Dhande and R. B. Patil, determined and validate the vibration characteristics of the gearbox top cover using both analytical and experimental techniques. They used ANSYS software used to determine natural frequency response for gearbox casing. This analysis finds the natural frequency of casing. The results obtained are validated by FFT analyzer. the simulation and experimental results were in close agreement with each other. [1]”.

“Shrenik M. Patil and Pise, performed the analysis on differential gearbox casing of a pick up van vehicle for modal and stress analysis. The theoretical modal analysis was validated with experimental results from Fourier frequency transformer analysis. Dynamic correlation, comparison of mode shapes and natural frequencies, is a robust tool for evaluating the accuracy of a finite element model. [2]”

“Mohsen Azadbakht et al., designed a 3D model of a gearbox in MF285 tractor using finite elements method in ANSYS WORKBENCH 11 software. The values of exerted stresses were calculated by Von-Mises theory in both engaging gears together. Maximum stress values were estimated by ANSYS WORKBENCH 11 and in proportion with those points, a safety factor was obtained. The result showed that increasing numbers of gear, maximum stress value will increase and in the edge of gears is more failure than the rest. [3] “

“R. V. Nigade et al., used the numerical modal analysis based on Finite Element Method to determine the vibration characteristics, such as natural frequencies and the associated mode shapes of a structure. He addressed finite element analysis and modal testing of gearbox top cover of an integrally geared centrifugal compressor. The goal was to determine, verify and validate the vibration characteristics of the gearbox top cover using both analytical and experimental techniques. The 3-D solid model of the gearbox top cover was built using Autodesk Inventor. ANSYS workbench 13 was used for preprocessing, solving and post- processing. The results indicate that the natural frequencies of gearbox top cover predicted by FEA are within 8 percent of the measured natural frequencies of the modal test data, thus confirming the close agreement between FEA and experimental data. [4]”

“Pravin M. Kinge et al., studied how to improve the life of a gear. He focused on stress analysis of gearbox used in sugar industry using ANSYS. Investigation of the reason for failure was done. He found that the reason for the failure of the gear was due to wear of gear teeth edges. This is caused due to high- stress concentration along the gear teeth edges. To relieve these stress concentration three modifications in the design of gears were done and after that again stress analysis of the modified gears carried out. It was observed that the stress relieved from edges and got concentrated to the edges of the holes provided at the roots of the teeth. [5]”

“Vijay. N.A, concerned with the analysis of a gear box casing used for Permanent magnet D.C. motors with the help of ANSYS workbench software. The objective of the project is to build the model (Gearbox casing) and to analyze the gear box casing used for permanent magnet DC motors for Static stress and Modal analysis. The load for static stress analysis is calculated by Rope and pulley method setup. The gearbox casing is modeled using CATIA V5 software and analyzed using ANSYS workbench software. [6]”

“M. Mahesh Babu1, Y. Rameswara Reddy, designed and analyzed a three wheeler gearbox cover. They found out the stresses in gearbox cover because of internal pressures like gear shaft pressure and crank pressure. Modeling is done by CATIA software and analysis is done by ANSYS Workbench. design modification and material change were used to reduce stresses. [7]”

PROBLEM DESCRIPTION & PROCEDURES

Helwan Waste Water Treatment Plant capacity is 550000m³/day. The plant includes disposal of the solids, impurities, and sludge through the filters and the separation of oil and sand. Sludge deposition through the Mechanical Filtration, transferring of the treated water to the basin of chlorine and disbursement to the pumping station then to the discharge lines leading to the settling tanks and at last transfer to El Saff Canal. The plant consists of 6 basins; each one of them consists of 12 units, to become 72 units in the station.

The aeration units consist of three main parts motor, gearbox, and fan. The main problem is that the original design of all aeration units was changed by replacing the original motor of 90 kW by a new more powerful 132 kW one. Also, the fan diameter 2.40m was changed to a larger size diameter 2.58m. Vibration measurements recorded dangerous and not permissible levels. So the task is to investigate the reasons of failure the gearbox. Firstly, the damaged gearbox was visually inspected then; a sample of the broken gear was checked for hardness measurements, chemical analysis, power examination, thermal examination, and aerator speed design examination. The gearbox fails when stresses exceed their safe limit. So, it is necessary to define the maximum stress that affects gearbox casing under a specified loading by using stress analysis. The main goal of this research is to investigate the main causes that leading to the gearbox failure and stop it. Also, investigate how such a failure can be prevented in the future.

INVESTIGATION PROCEDURES & RESULTS

Results of visual inspection

The gearbox was disassembled and inspected for all internal components, both failed and undamaged. Visual inspection is a certain procedures to indicate installation and configuration factors that related to gear failure such as, oil leakage and loose hardware. The main goal of visual inspection is to investigate and check all parts of the gearbox as much as possible. The visual inspection concentrates on potential mechanical and environmental effect on the gearbox failure. The damaged components of the broken gearbox were visually inspected. The gearbox top cover casing is totally broken as shown in Fig1.

Fig1. *Gear box top cover casing is broken into two parts*.

The first shaft and pinion set had a polishing surface damage, particularly in the middle. The asperities of contacting surfaces are gradually worn out. This appears to be consequences due to metal contact during operation. Polishing occurs when elastic- hydrodynamic lubrication film is not sufficiently thick and the gears are operating near boundary lubrication region. Also, bearing failure was indicated as shown in Figs2, 3.

Fig2. *Pinion surface polishing.*

Fig3. *Bearing surface failure.*

The second shaft carrying the helical spur gear showed severe damage and failures on all the teeth of the pinion spur helical gear. Fractures were readily seen.

The third shaft was broken initially by fatigue failure starting at the root of two adjacent teeth which lead to tooth breakage as shown in Fig. 4. Broken tooth pieces coming between the gears and caused shaft failure and consequently body failure. As shown in Fig. 5.

Fig4. *Shaft is broken by fatigue failure.*

Fig5. *Bearing was pushed progressivelyout the casing.*

The lower roller bearing of the third shaft was pushed progressively out the casing. This appears to be due to gear interactions resulting from shaft misalignments and the generation of excessive axial force component. All spur gears show irrevocable damages and all other components show irrecoverable serious damages, as shown in Fig. 6. The whole tooth, or part of the tooth, breaks away. As a result of overload, the tensile strength exceeds the gear material safe limits and led to teeth breakage. The break showed evidence of being pulled apart abruptly as shown in Fig. 7.

Fig6. *Spur gear teeth damage.*

Fig7. *Broken teeth damage.*

Results of hardness measurements

Hardness measurements were made on the failed gear, particularly within the hardened surface layer and at tooth root near the point of crack initiation. The results revealed that the hardness at the broken tooth is 60 HRc on surface and 36 at the core. Hardness measurement of surface and core revealed that the surface was harder than the core.

Results of chemical analysis

The chemical composition of the gear material showed that the material of the gear is most likely to be 36CrNiMo6 as shown in Table 1. The following tables show the chemical composition of the failed gear materials. The compositions indicate that the gear was made from low alloy steel to 36CrNiMo6.

Table1. *Chemical composition of damaged gears*

Material	Failed gear	36CrNiMo6
c	0.64	0.30-0.38
Si	0.17	0.4
Mn	0.46	0.5-0.8
Cr	1.45	1.30-1.70
Mo	0.2	0.15-0.30
Ni	1.28	1.3-1.70
Cu	0.12	0.12

Results of power selection examination

According to Hansen power selection check, the condition regarding mechanical power rating must be as the following:

Pm and/or $Pa \times SF \leq P$

According to Hansen gearbox technical specifications:

P_m: motor power = 132 KW

P_a: absorbed power = 110.3 KW

SF = service factor = 2.45

P: mechanical power rating

The mechanical power rating of the gearbox in this case study (type QVPF 3) equals 232 KW.

So $P_a \times SF = 110.3 \times 2.45 = 270.5 >$ Mechanical Power rating.

$P_m \times SF = 132 \times 2.45 = 323.4 >$ Mechanical Power rating.

It could be seen that the selection of the motors of the new project at the station is a wrong selection and very high capacity motor was installed compared to actual requirements. The old motors power was 90 kw. According to the mechanical power rating calculations of the gearbox (type QVPF 3); it was compatible with the power of the old motor.

$P_m \times SF = 90 \times 2.45 = 220.5 <$ Mechanical Power rating (232 kW)

Results of thermal power rating examination

According to Hansen thermal selection catalog, the condition regarding thermal power rating must be as below:

$Pa \leq Ptn.\ a.\ b.\ c$

According to Hansen thermal technical specifications:

Ptn: thermal power rating for gear unit = 120 KW

Factor a for ambient temperature without forced cooling = 0.74

Factor b for duration of service = 1

Factor c for air circulation (without fan) = 1

$P_{tn}.\ a.\ b.\ c = 120*0.74*1*1 = 88 < Pa$ (110.3 kW)

It could be seen that the thermal rating is incorrect selection. Thermal power rating must be selected to overcome heat sources. Therefore this wrong selection leads to overheating.

Results of aerator speed design examination

The peripheral speed of the aerator must be designed as following:

Where D: fan diameter in m (2.58m)

N: fan RPM (41.9 rpm)

Those diameters can be higher to achieve a much better mixing. The peripheral speed of the aerator must not exceed 5.5 m/sec according to the standard specifications. In this case V = 6.25 m/sec > 5.5 m/sec so, the peripheral speed design of the aerator is not compatible with the standard value.

MODELING AND FEM ANALYSIS OF GEARBOX CASING

Gearbox casing analysis is necessary to predict casing behavior under different operating conditions. The gearbox top cover casing is totally broken so, a 3D modeling of gearbox top cover was designed using SOLIDWORKS 2010 then it was modeled and analyzing by finite elements method using ANSYS WORKBENCH 14 software. Structural analysis is used to define maximum stresses and deformation. Exerted stresses were calculated by Von-Misses method. Maximum stress values and deformation were estimated.

The Von- Mises yield criterion predicts that yielding will occur whenever the distortion energy in a unit volume equals the distortion energy in the same volume when uniaxial stressed to the yield strength.

From this theory Von-Mises equivalent stress is derived as:

$(\sigma_v)^2 = \frac{1}{2} [(\sigma 1 - \sigma 2)2 + (\sigma 2 - \sigma 3) + (\sigma 3 - \sigma 1)]$.

The material properties of gearbox cover were taken from the Hansen catalog. Appropriate meshing is selected to get the accurate results. This mesh is applied to the whole object as one body meshing as shown in Fig. 8. Boundary conditions are applied to the casing. A fixed support is applied to the lower edge of the cover exactly as the same condition in Fig. 9.

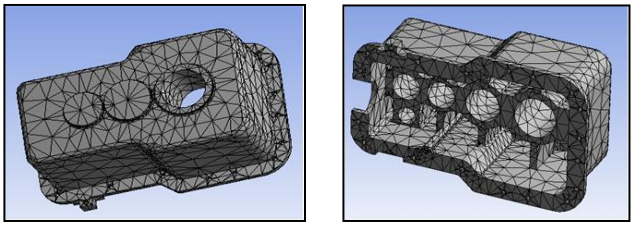

Fig8. *Finite element model.*

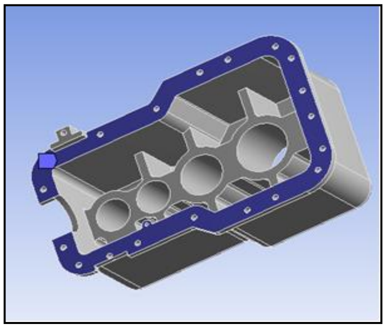

Fig9. *Fixed support of gearbox casing.*

Bearing pressure is applied to the bearings locations in the gearbox. The total load acting on the casing is also applied. Deformation occurs in gear box casing is shown in Fig. 10. Von- Misses stresses occurred on gearbox casing are shown in Fig. 11. Validation established by comparing the results of the simulation with the actual data that was founded indeed. The results show that the deformation of the gear box casing is found to be maximum at the same place that the actual failure happened. The Von Misses stress or equivalent stress was found to be maximum in a region where the gears attached to the bearing, this region where the failure occurred. Verifying the model established by comparing the maximum Von Misses stress (184.74 Mpa) with the actual yield stress of the cast iron (170 Mpa). It could be seen that the Von Misses stress exceed the yield stress of the industrial material of the gearbox casing. This is verifying the main theory of the failure occurrence.

The proposed FE model can be used to predict maximum stress of all other gearboxes in the station under different operating and environmental conditions.

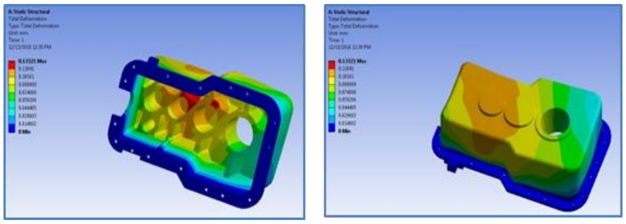

Fig10. *Deformation occurs in gear box casing.*

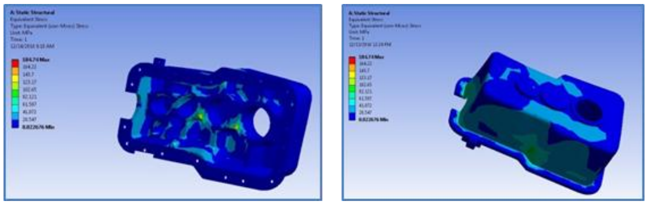

Fig11. *Von- Misses stresses occur on gearbox casing.*

DISCUSSIONS

Depending on all the previous analysis it is clear that there are some factors that have caused the gearbox failure. The wrong selection of mechanical power rating led to excessive loads which caused high stresses at the gearbox body and led to failure. The gearbox is overloaded which caused gear wear and finally gear failure. Thermal power rating must be selected to overcome heat sources. As mentioned above the selection of thermal power rating is wrong and that has led to the presence of an overheating problem. The formation of an explosive vapor from lubricating oil is greatly accelerated by rising the lubricating oil temperature. The capability to form acids increases when the viscosity of the lubricating oil greatly reduced. At high temperatures that greatly exceeding the thermal stability point of the lubricant, larger molecules break into smaller molecules. This thermal breakdown leading to side reactions, produce gaseous by-products, destroy additives and generate insolubly.

The repeated cyclic loading promotes fatigue failures of the shaft cross section. The intensified stresses in the shaft caused ductile fracture and complete shaft collapse.

Hardness measurements indicated that Hardness measurements indicated that the surface is basically harder than the core. At high cycle levels, the contact stress exceeds the material's endurance limit, so the cracks moves from the surface to the core and then to the gear surface leading to fall of large pieces of material. Also, it is necessary to install predictive maintenance program include vibration monitoring, temperature monitoring, and lubricant analysis.

So it is recommended firstly to change all gearboxes according to the new design and check the design of the aerators. Also, it is necessary to install predictive maintenance programs that include vibration monitoring, temperature monitoring, and lubricant analysis.

CONCLUSION

The root cause of gearbox failure is improper replacement of the original gearbox and fan of the aeration unit. The new gearbox was more powerful than the original one. Also, the new fan diameter was larger than the original one. The wrong selection of mechanical power rating led to excessive loads which caused high stresses at the gearbox body and led to failure. The wrong selection of thermal power rating led to the presence of an overheating problem. The diameter of the new fan is not compatible with the standard value. Hardness measurements indicated the occurrence of material fatigue failure. Intensified stresses in the shaft caused ductile fracture and complete shaft collapse. The von misses stress or equivalent stress was found to be maximum at a point where the gears attached to the bearing. It must be careful when replacing any components of machines. Any replaced component must be compatible with the design consideration.

RECOMMENDATIONS

- Protect all gearboxes from the sun and use forced air cooling.
- Lubricating oil of all gearboxes must be analyzed.
- Install predictive maintenance program includes vibration Monitoring, oil analysis, and temperature analysis.

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