IMPLICATIONS OF SIMULTANEOUS MECHANICAL AND THERMAL LOADS ON THE RHEOLOGICAL PROPERTIES OF THE GREASE IN AH-64 HELICOPTER GEARBOXES

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ABSTRACT

This paper deals with changes in the rheological properties of the grease used in the tail rotor and intermediate gearboxes of the Apache AH-64 helicopter when subjected to simultaneous mechanical and thermal loads within the operating temperature limits. From the steady shear rate sweep experiments on grease samples extracted from gearboxes, it was observed that there is a significant reduction in apparent viscosity over the shear rate range tested. This reduction in apparent viscosity might lead to inadequate lubrication in contact regions between teeth thus accelerating tooth wear. To verify if the change in properties was due to temperature alone, experiments were conducted on grease samples heated in convection oven at 195ºF±3ºF. From the results it was evident that the effect is not solely due to temperature. However when simultaneous mechanical and thermal loads are applied, there is a dramatic change in the rheological properties of the grease. From the experiments it was also observed that the grease reaches a stable or a metastable state and thereafter it does not seem to have much change in apparent viscosity either with operating conditions or time. This is evident from the similar flow curves for the TGB and the IGB grease samples even though they had different time histories. The grease in this stable or metastable state has significantly different rheological properties than the virgin grease. However, it still exhibits non-Newtonian behavior but power-law is not a good model to describe the flow curve for the TGB and IGB grease samples.

INTRODUCTION

Grease as a lubricant is common in situations where opportunities for frequent re-lubrication may not be possible or economically justifiable [2]. It is critical for any lubricant to provide adequate lubrication and meet the functional requirements for which it has been chosen. The changing properties of grease are of great concern as they would significantly influence the health of the components that are being lubricated, and the condition-monitoring algorithms and analysis which might not account for it. At the University of South Carolina (USC) various Apache AH-64 helicopter (Boeing corporation) tail rotor drive train components are being tested to provide scientific understanding of various failure modes and other parameters that can be harbingers of failure of a component [16]. The tail rotor gearbox (TGB) and intermediate gearbox (IGB) of an AH-64 rotorcraft are grease lubricated. As part of the inspection procedure during testing of TGB, a grease sample is extracted from the TGB to inspect for wear debris after 200 hours of operation. This sample did not have significant wear debris inclusions but a drastic change in the physical state of the grease was observed. Since regular monitoring of the condition of a lubricant is essential in maintaining the health of the components, it is crucial to verify if the properties of the lubricant do change and to provide an explanation for this phenomenon. This has driven us to focus on the change in grease rheology when the TGB and the IGB are subjected to in-flight mechanical and thermal loads while still under grease operating temperature limits.

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Lubricating greases are colloidal systems in which a thickener is dispersed in a carrier fluid, generally oil. The characteristics of this suspending base oil, concentration and properties of the thickener (soap) particles and the structural network of the thickener formed during the manufacture of the grease influence the rheological properties of the grease [12]. The grease is expected to act as a sealant, resist leakage and undesirable throw-off from the lubricated surfaces besides providing adequate lubrication to reduce friction and prevent harmful wear [2]. Grease is vulnerable to the thermal and mechanical environment to which it is exposed. Most often this results in a change in the viscosity, separation of the base oil, oxidation of the base oil, and breakdown of the additives [12-15, 17].

The change in the properties of grease can be attributed to change in its physical structure and chemical composition in response to the environment to which it has been subjected [12].

The thermal degradation of greases has been studied by exposing grease to controlled thermal environments in oven-based tests. The effect of thermal loads degrades thickener structure in lithium-based greases but need not be the case always. Also research on grease has focused on changes in its properties at very low shear rates and high temperatures [8, 9]. In the current context we have exposed grease to temperatures below its operating temperature limits but have applied simultaneous mechanical loads. Since the grease in the gear box is exposed to temperatures within the manufacturer-specified operating temperatures, we should anticipate no chemical change and also expect that any change in rheological properties and consistency due to strain rate will be recovered when the mechanical loads are removed. However, in our experiments we noticed that when subjected to simultaneous mechanical and thermal loads the grease suffers significant permanent changes in consistency and its non-Newtonian behavior, which casts doubts on its ability to meet functional requirements. In this work we investigate the change in physical properties and try to address the possible reasons and its implications for the TGB and IGB.

EXPERIMENTAL

MATERIALS

Grease: NS-4405-FG
NLGI grade: 000
Operating temperature: -65°F (-54°C) to 275°F (135°C)
Thickener: Li Complex
Penetration, ASTM D217, worked, 60 DS: 450
Penetration, ASTM D217, worked, 10,000 DS, maximum: 460
Oil Separation, FTM 321.3, 30 hours at 212°F, maximum: 30%
Specific gravity, ASTM D1298, 60/60°F: 0 .906
Dropping point, ASTM D2265, minimum: 148.9°C
Evaporation loss, ASTM D972, 22 hours at 250°F maximum: 10%
Deleterious particles, ASTM D1404, maximum: 10
Corrosive preventive properties, ASTM D1743: Pass
Load Wear Index, ASTM D2596, minimum: 30 kgf
Weld point, minimum: 200 Kgf
4-Ball Wear, ASTM D2266, average wear scar, maximum: 60 mm

RHEOLOGICAL CHARACTERIZATION

Steady shear rate sweep measurements were performed in a Rheometrics Fluids Spectrometer, RFS II instrument manufactured by Rheometrics Inc., now part of TA Instruments.

A Parallel-plates geometry with each plate measuring 1.9685 in. (50 mm) in diameter and a 0.3937 in. (1 mm) gap between the two plates was used for the characterization. The Burger’s correction was applied for the experiment data generated to account for the shear rate gradient across the plate.

The shear rate sweeps were conducted on various grease samples: virgin grease, TGB and IGB grease samples, and grease samples heated in a convection oven at 195±3°F.

TAIL ROTOR DRIVE TRAIN TEST STAND

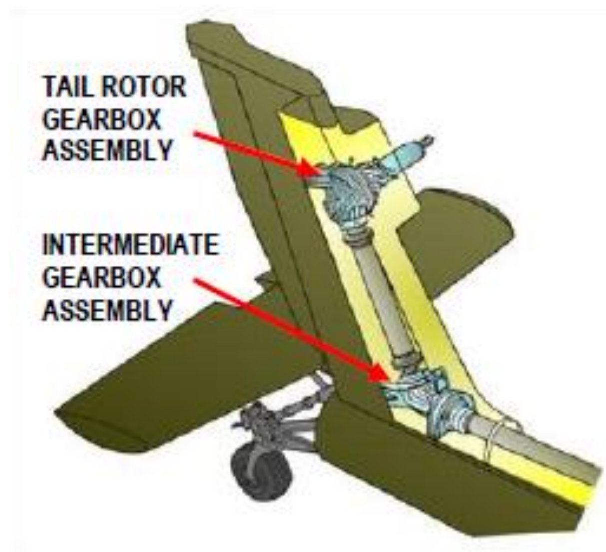

Figure 1. AH-64 IGB and TGB assembly locations

The USC tail rotor drive train test stand [16] is a constant-speed and dynamic-loading power transmission system like on the actual AH-64 helicopter. The tail rotor drive shafts are spun at 101% of the normal operating speed (4863 RPM) throughout the duration of a single test run, while the output motor changes its braking torques to produce specified load conditions, which match flight regimes as requested by the Army Engineering Directorate. Each test run lasts approximately 4 hours and implements the test sequence shown in Table 1. It can be observed from the table that the torque is ramped up from 0 ft-lb to 1223 ft-lb in the 4 hour test period with intermediate 10 minute cycles where the system is subjected to flat pitch ground loads at 101% of the operating speed (FPG 101) loads. The effect of this torque history on the temperature inside the gearboxes is shown in Figure 2. The temperature is measured with a thermocouple close to the gear mesh region in the TGB and near the input bearing for the IGB.

Table 1. Loading profile for a standard 4 hour test run

Output Torque (ft-lb)	Duration (min)
0	3
111	10
371	50
111	10
734	50
111	10
979	50
111	10
1223	50
111	10

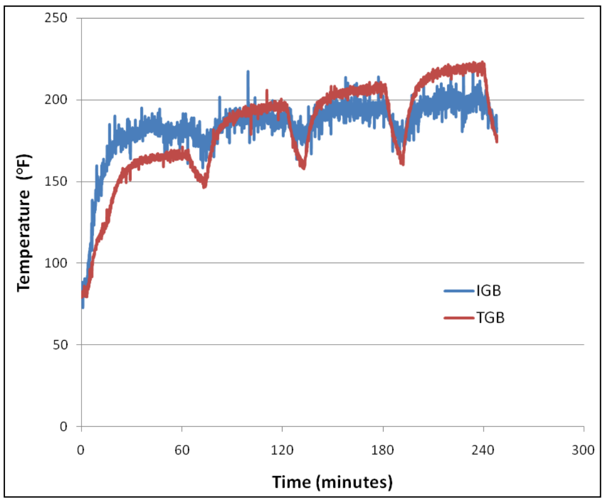

Figure 2. Temperature variations in IGB and TGB for a 4 hour test run.

RESULTS AND DISCUSSION

During the test run, grease in the TGB and IGB are subjected to intense mechanical deformation and thermal transients. The TGB and IGB have spiral bevel gears that mesh, hence mechanical deformation is not purely shear, rather it is complex with some zones being exposed to pure shear while other zones are exposed to extensional deformation and in certain regions a combination of both shear and extensional deformation is observed [5, 11]. At the beginning of the test run, when the speed on the drive train is increased, the grease trapped in the gear mesh region is exposed to increasing shear rate combined with constant stress proportional to contact pressure between the teeth in contact. This regime is similar to a shear rate sweep. Once the final speed is reached the grease is subjected to a steady strain rate of varying loads with intermediate strain sweeps involving of a relaxation torque to simulate the FPG 101 profile.

The increase in temperatures is due to the increase in torque in accordance with the test run sequence, and intermediate decreases in temperatures correspond to FPG 101 load settings. It can be observed from Figure 2 that the maximum temperature in the test cycle does not exceed 230ºF which is less than 275ºF, the upper limit of the operating temperature of grease. The possibility of local hot spots near the teeth could not be eliminated but since the test article did not have significant wear on the teeth the frictional contribution could not be significant [3, 4]. Also in spiral bevel gears, the flanks of the gear teeth mesh gradually resulting in lower shock loading. Hence the associated temperature rise due to compression (generated by shock loading) of the lubricant would not be intense [11]. Therefore, in our analysis we assume that the maximum temperature does not exceed the upper limit of the grease operating temperature, and that the temperature close to the gear mesh region can be a representative of the maximum temperatures in the cycle. We also presume the contribution of oxidation to be minor in this particular case.

Throughout the operation cycle the grease inside the TGB and IGB are subjected to simultaneous mechanical and thermal loads. Since it is assumed that the grease stayed within the operating limits its chemical composition is not expected to change and its physical properties are expected to recover after sufficient time is allowed. The samples were not extracted in the first few hours as there was no incident that prompted an inspection of the TGB. However, the grease samples extracted from the TGB after 200 hours and from the IGB after 400 hours show a significant change in consistency and reveal a marked deviation from the virgin grease. This is an important concern for the mechanical components from both the condition monitoring as well as operational perspectives. Since the final deformed lubricant does not preserve any semisolid nature, it cannot be trusted as a sealant and also it lacks the advantages for which grease was chosen. After a certain number of hours the deformed lubricant might not meet the original functional requirements.

For further comparison of the change in mechanical properties between virgin and deformed grease, shear rate sweep experiments were performed on the virgin grease and the samples extracted from the TGB and IGB. Before each test a pre-shearing phase was carried out to put the sample in a reference state and to hinder the structural alignment that is generated by the radial flow induced during its loading between the parallel plates.

The power law model [1] fits well with the experiment results obtained.

$$\tau = k\dot{\gamma}^{n};$$

$$\mu_a = k\,\dot{\gamma}^{n-1}$$

where: τ is the shear stress
$\dot{\gamma}$ is the shear rate
μ_a is the apparent viscosity
k is the measure of consistency of fluid and
n is the measure of the degree of non-Newtonian behavior

The shear rate sweep experiment results for virgin grease are presented in Figure 3.

The virgin grease in the tested shear region has power law parameters, *n*=0.221 and *k*=32.308. The results for the shear rate sweep experiments for the TGB and IGB are presented on logarithmic axes in Figure 3. If they were fitted to the power-law, the parameters would be k=0.986 and n=0.51 for the IGB and k=0.923 and n=0.52 for the TGB.

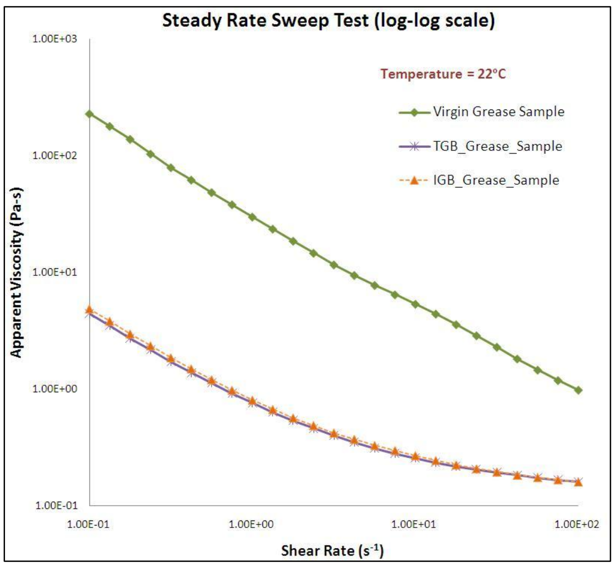

Figure 3. Steady rate shear sweep test results for virgin grease sample, TGB, and IGB grease samples

It can be inferred that there is a dramatic change in the rheological properties of the virgin grease when it is subjected to the simultaneous mechanical and thermal loads win the TGB and IGB. None of the sample exhibited Newtonian behavior (n=1 and viscosity is independent of shear rate). Their viscosity at shear rates range tested is much lower than that of the virgin grease. However, the plots are not linear, indicating that the power-law is not a good model for the TGB and IGB samples. The apparent viscosity suffered a sharp drop of over 1 decade at shear rates of 0.1s-^{1}.

Even though they had different number of load cycles (200 and 400 hours) it is interesting to that both the IGB and TGB grease samples have almost the same apparent viscosity values and similar variation in apparent viscosity vs. shear rate. This suggests that after a certain number of cycles there is a permanent change in the physical properties of the grease indicating this could be a stable or metastable state. Since no samples were extracted prior to 200 hours on the TGB it was not possible to identify the exact time period required to reach this state, and sampling at a high frequency is not advisable, since the overall lubricant quantity can be depleted inside the gearbox. If sampled and re-serviced to mitigate the depletion of grease, the resultant sample is a mixture of virgin grease and worked grease with different load and time histories. To address this we are in the process of designing a special test apparatus which can combine the effects of pure shear, thermal loading, as well as apply them independently.

For better understanding about the effects of pure thermal loads, we placed a sample of grease in a convection oven at 195ºF±3ºF for 500 hours which is longer than the resident time period for the IGB grease sample (400 hours). After 500 hours the oven heated grease sample had some discoloration but there was not much oil separation. The shear rate sweep experiments on this sample are presented in Figure 4 along with results from the other samples for comparison. It is evident from Figure 4 that this sample did not suffer much change in apparent viscosity and its variation in flow curve as well as magnitudes are similar to that of virgin grease. The power law parameters for this sample are *k*=22.172 and *n*=0.2. It can be seen that the effect of pure thermal loads in its operating temperature range does not alter the apparent viscosity of the grease with respect to shear rate.

The large reduction in the viscosity of the TGB and the IGB grease has important implication for the life of these gearboxes. The reduced apparent viscosity implies inadequate film thickness for elastohydrodynamic lubrication at the tooth contacts which could accelerate tooth wear and elevate the temperatures causing further oxidation of the lubricant. Since debris monitoring with grease lubricated systems is difficult to perform, the damage can progress at much faster rates resulting in failure of the system. Also the change in the shape of the apparent viscosity Vs shear rate curves suggests a loss of thickener structure and may cause the lubricant to be thrown off of the lubricating surface due to centrifugal forces [8] thus disabling its sealant functionality. This might also result in lubricant dripping which requires an expensive maintenance and in lack of operational availability of this rotorcraft for a mission.

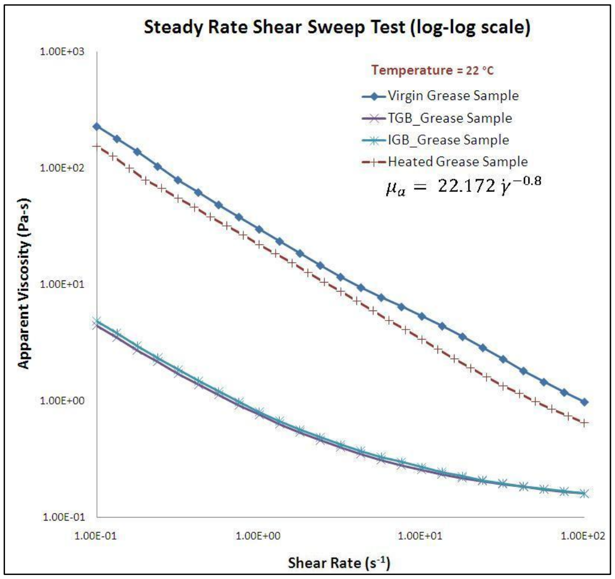

Figure 4. Steady rate shear sweep test results for virgin grease, TGB, IGB, and thermal degraded samples

This change in rheological properties under simultaneous mechanical and thermal loads might not be unique to this particular grease but could occur in other shear thinning fluids under similar conditions. This would be an interesting course to pursue in research on the rheology of non-Newtonian fluids.

The effect of simultaneous mechanical and thermal loading below the operating temperatures is an open problem. The higher temperatures might result in weakening of van der Waals and capillary forces even when the temperature is not higher than the operating limit. Thus some amount of base oil bleeds out of the thickener (soap) network and when shear deformation is applied the thickener network may fracture into smaller elements and creating a suspension of isolated elements in the base oil. These isolated elements form a new configuration which does not have sufficient capacity to hold the base oil in the network when the shear rate is reduced and thermal loads are removed.

CONCLUSION

Grease exposed to the in-flight operating conditions of an AH-64 TGB and IGB seems to undergo significant deviation in its physical and rheological properties after a certain period of time even when the temperatures are within operating limits, thereby warranting further investigation into whether or not the particular lubricant is fit to meet its operational requirements. Since lubricant condition monitoring of a grease lubricated components is difficult, it is essential to ensure that the grease satisfies all functional properties during the operation of the system. Rheological characterization of the TGB and IGB grease samples revealed reduction in their apparent viscosities when compared to the virgin grease at shear rates tested. The degradation of grease seems to reach a stable or metastable state wherein the in-flight operating conditions do not seem to affect the grease properties further. In this work we suggest one of the possible mechanisms responsible for the observed phenomenon when grease is subjected to simultaneous mechanical and thermal loads. However, further investigations are necessary to validate the proposed mechanism to explain the effects of the influence of high strain rates in conjunction with thermal loads within the operation temperature limits.

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