DEVELOPMENT AND EVALUATION OF A THERMAL BASED FAILURE DETECTION ALGORITHM FOR USE ON AVIATION POWERPLANT GEARBOXES

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Abstract - Many light aircraft powered by automotive engines are equipped with a propeller speed reduction unit (PSRU). Often geared units, PSRUs lower the engine output shaft speed to allow the propeller to function at its most efficient rotational speed. Many of these units have no observable indicator of mechanical health, but some have lubrication oil temperature monitoring installed. One such temperature monitored gearbox experienced shaft spline damage requiring the operator to replace major components. While no abnormal temperatures had been observed on the cockpit temperature readout, recorded flight data has been processed to determine if a significant temperature deviation between the damaged and undamaged conditions could be found. A model was developed to simulate the oil temperature of a healthy PSRU based on a variety of conditions, and the measured temperature of the damaged PSRU was then compared with the model. No meaningful difference between the flights was found. The normal condition flights exhibited a 14.9 degree C maximum difference between the measured temperature and the model, while the damaged condition flights exhibited a 14.2 degree C maximum difference. Average differences vary insignificantly, with the normal condition averaging a 0.961 degree C difference between the measured temperature and the model, and the damaged condition averaging -0.728 degrees C. It is concluded that unless a more accurate model can be developed and proven, alternate equipment monitoring methods are recommended.

Keywords - Aviation Gearbox, Condition Monitoring, Engine Health, Temperature Prediction.

I. INTRODUCTION

In the United States, light aircraft registered in the experimental category are exempt from many traditional certification rules, and as a result may use any powerplant they choose. Some builders of experimental aircraft choose to use automotive engines in their aircraft, which they convert to drive a propeller. Almost all these conversions use a single ratio speed reduction system to turn the propeller at a slower speed than the engine. This maximizes the power output of the engine while allowing the propeller to remain at its optimal speed. Most of these Propeller-Speed-Reduction-Units (PSRUs) are approximately a 2:1 ratio, with the engine spinning nearly twice as fast as the propeller. Various types of units are used, with the most common being toothed belts or geared units. Geared units are generally robust and capable of withstanding high loads, but several geared designs have been known to experience mechanical failures. Depending on the severity of the failure, the pilot may experience loss of power in flight, potentially leading to severe injury or death.

In this type of life critical application, monitoring the mechanical health of the gearbox is highly desirable. Several methods are widely used to monitor geared systems, including vibration analysis, acoustic emission monitoring, oil analysis, and thermal observation. Vibration analysis is one of the most information-rich methods of monitoring, often allowing users to identify specific bearing or gear component faults. Frequency analysis even allows faults in complex planetary systems to be identified as shown by Miao and Zhao in [1]. Acoustic emission measurements can also indicate gearbox faults as demonstrated by Sharma and Parey in [2], though noisy backgrounds make the analysis much more difficult. Oil analysis ranges from simple magnetic plugs installed in the gearbox lubrication system to complex oil property analyzer probes such as Coronado and Kupferschmidt discuss, intended for use in wind turbine gearboxes [3]. In [4], Touret et al. nicely review efforts that have attempted to use thermal measurements to observe mechanical damage prior to catastrophic failure. Success varies depending on method and application.

Monitoring of oil for ferrous particulate with the use of magnetic chip detectors has long been common practice in many aviation applications. As early as 1984, extensive tests were carried out on US Army helicopters equipped with burn-off chip detectors which showed great success [5].

But of all these methods, thermal monitoring may be the most appealing for use in light aircraft gearboxes due to its simplicity and low cost. Temperature probes are normal equipment on light aircraft and are easily integrated into the PSRU lubrication system allowing the pilot to monitor temperatures throughout the flight from the cockpit. This avoids the complex software and hardware combinations required for vibration and acoustic emission monitoring.

Thermal measurements on mechanical equipment have been used extensively as indications of malfunction or failure. However, most of these indications only alert the operator once the failure is quite developed. If the temperature does not vary significantly until catastrophic failure has already

occurred, the temperature readout will only indicate the failure. It will not be helpful in preventing catastrophe by detecting early stages of mechanical damage unless these early stages produce enough temperature deviation to be observed before complete failure occurs.

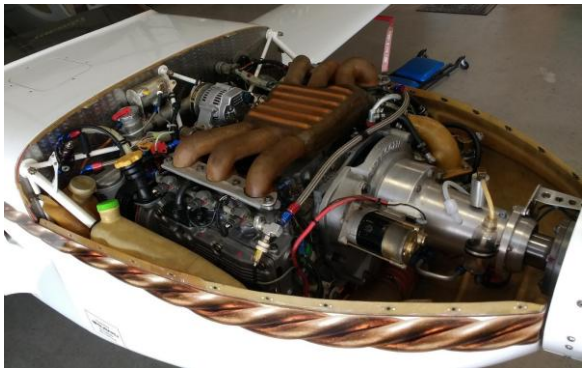

Figure 1 – Aircraft powered by Subaru EG-33 engine mated to a Marcotte geared speed reduction unit.

This work explores a case study in which a geared PSRU experienced mechanical damage in the form of drive spline wear on the output shaft of the gearbox. The PSRU oil temperatures are examined for deviation from normal in the flights preceding the replacement of the worn shaft. This is done by creating a mathematical model predicting the PSRU oil temperature. The model is compared to flight data in the undamaged condition and then to the flights in which damage was known to be present.

II. AIRCRAFT, EQUIPMENT, AND DATA

The aircraft from which these data were obtained is a Glasair, a two place, single engine, low wing, composite structure kit airplane. The aircraft builder chose to power the airplane with a Subaru EG-33 automobile engine. This is a six cylinder, horizontally opposed internal combustion engine with a displacement of 3.3 liters. The PSRU is a geared model manufactured by Guy Marcotte. The gearbox is lubricated with gear oil in a closed system separate from the engine oil. Measured engine and operation parameters are recorded by an Electronics International digital engine monitor.

Numerous parameters are recorded in the flight data files including:

- Timestamp
- Propeller speed
- Intake manifold pressure
- Fuel, oil, and coolant pressures
- Exhaust gas temperatures for all cylinders
- Coolant temperature
- Engine oil temperature
- Ambient air temperature
- PSRU oil temperature
- GPS speed, altitude, and position

Figure 2 shows some recorded flight data for a normal flight plotted against flight time. This allows the general flight profile to be easily observed.

Flight data for 12 flights have been examined, with the first eight being under normal operation. The final four flight data files correspond to the four flights preceding the replacement of the worn components in the PSRU.

III. MODEL CONSTRUCTION

As Touret et al. note in their survey, many mechanical applications contain numerous factors affecting the temperature of the system. System temperatures can vary widely depending on these factors, and this makes observing a small temperature deviation from normal difficult to observe. Therefore, a model representing ideal operation is developed, to which the actual measurements may be compared [4].

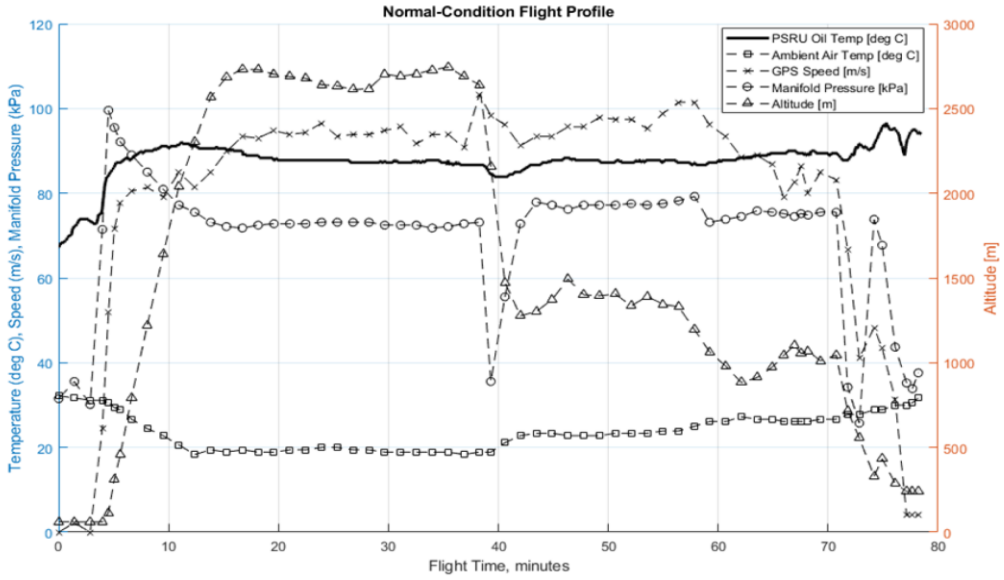

Figure 2 – Normal-condition flight profile showing several measured parameters.

Zhao and Zhang successfully used a multiple linear regression method to generate a model which simulated wind turbine gearbox temperature as a function of other system parameters [6]. They were then able to detect failure by observing a deviation in temperature from this prediction model. Unfortunately, the PSRU in this study operates in a highly transient system where temperature cannot be accurately derived from the instantaneous measurements of the system. A time based model was therefore developed which accounts for heat transfer between system components and component heat capacities. Three distinct heat-containing masses are considered in the model: the engine block, the PSRU Case, and the PSRU oil. (Note that the engine block mass is not simulating the entire engine but rather some arbitrary portion near the bell housing to which the PSRU is bolted.) The temperature of each of these masses is a function of the total heat energy contained by the mass (in kJ) and the heat capacity of the mass (in kJ-K^{-1}). Heat energy is imparted to, removed from, and transferred between these three masses as illustrated in Figure 3. Heat is added to the lubrication oil by inefficiencies in power transfer through the gearbox, and it is removed from the oil by contact with the gearbox case as well as air cooling the external oil lines. Heat is added to the gearbox case from the warmer oil inside, as well as by conduction from the engine block it is bolted to. Heat is removed from the gearbox by air cooling. Air cooling is provided by airflow vented into the cowling by a small opening. The model steps through time, calculating the total heat energy in each of the masses as a function of the heat flow rate, the change in time, and the initial energy value as shown by Equation 1. Then, the temperature of the mass is calculated as shown in Equation 2.

$$H_{k+1} = H_k + \dot{Q} * \Delta T \quad (1)$$

$$T_{k+1} = \frac{H_{k+1}}{C} \quad (2)$$

In this way the time dependent nature of the system and the damping effect of the thermal masses are taken into account.

The calculation of the heat flow rates ($\dot{Q}$ in Equation 1) account for the environmental conditions and flight profile. Table 1 outlines which measured parameters are used to calculate the various heat transfer rates.

Heat transfer rate equations take several forms in the model. Most are of the form shown in Equation 3, simply driven by a temperature differential and a constant representing conductivity and other system properties.

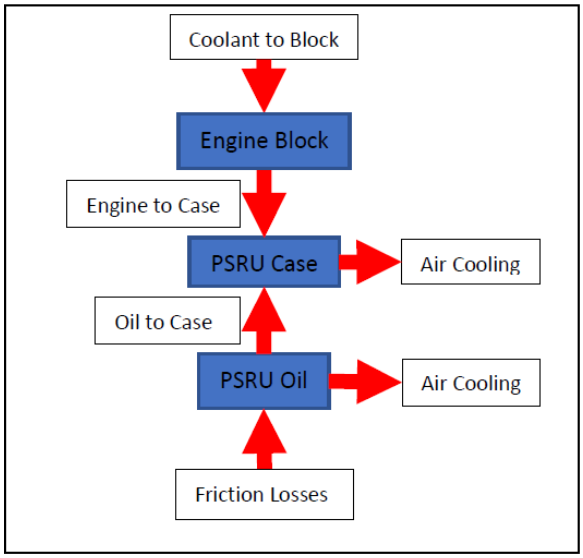

Figure 3 – Heat flow paths affecting the three relevant thermal masses.

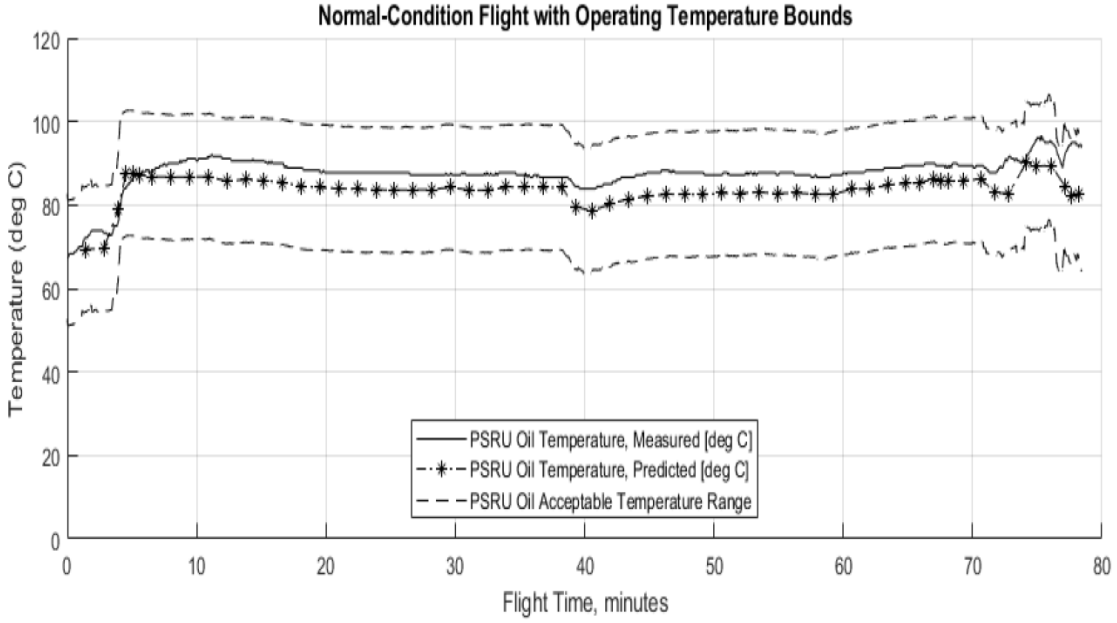

Figure 4 – Normal-condition flight profile indicating the safe operating zone.

$$\dot{Q} = C * \Delta T \quad (3)$$

Heat transfer between the coolant and the engine block, between the engine block and the PSRU case, and between the PSRU case and PSRU oil are calculated in this way.

Heat transfer estimation between the PSRU case and the air, and between the PSRU oil and the air is more involved, as shown by Equation 4. The V^C term indicates a nonlinear relationship between cooling and air velocity, with the constant exponent being less than 1, as indicated by [7]. The fourth term in the equation is an altitude compensation factor accounting for reduced air density as altitude increases. The last constant is a value to represent some level of air cooling at all times since the propeller will provide some airflow as long as the engine is turning.

$$\dot{Q} = C_1 * \Delta T * V^{C_2} * (1 - C_3 * h) - C_4 \quad (4)$$

Heat input to the oil from friction losses is considered to be more largely a function of gearbox speed (ω) than torque (related to intake manifold pressure, p_m), and is calculated as shown in Equation 5. As in Equation 4, there is an added constant representing some level of heat input to tun the gearbox at any speed.

$$\dot{Q} = C_1 * \omega * p_m + C_2 * \omega + C_3 \quad (5)$$

An initial heat energy value was given to the PSRU oil, PSRU case, and engine block based on initial PSRU oil temperature and initial coolant temperature. The model then progresses through time, adding and removing heat from the thermal masses based on the above mentioned conditions. Heat flows based on each condition were summed and added to the mass's heat value for each time step.

It should be noted that the heat transfer phenomena taking place is quite complex, especially the fluid interactions such as heat transfer between the oil and case and the heat transfer to the outside air. Therefore, the constants used in this model were determined empirically through trial and error in an attempt to make the model match flight data as closely as possible for the undamaged flight conditions.

IV. RESULTS

The model described above was compared to the recorded PSRU oil temperature with mixed results. Encouragingly, the model predicts most of the temperature fluctuations observed in the recorded data. However, the degree of temperature change does not always match the measured data, nor does the steady state temperature.

Heat Transfer:	*Function of:*	*Relevant measured parameters:*
To/From Oil		
From inefficiency	Power Transfer	Rotational speed, Manifold pressure
To case	Internal flow, contact, and temperature differential	N/A
To air	Temperature differential, airflow, air density	Ambient air temperature, speed, altitude
To/From Case		
From oil	Internal flow, contact, and temperature differential	N/A
From engine block	Temperature differential, conductivity	Coolant temperature
To air	Temperature differential, airflow, air density	Ambient air temperature, speed, altitude
To/From Engine Block		
From Coolant	Temperature differential, conductivity	Coolant temperature
To PSRU Case	Temperature differential, conductivity	N/A

Table 1 – Incorporation of measured parameters in heat transfer paths.

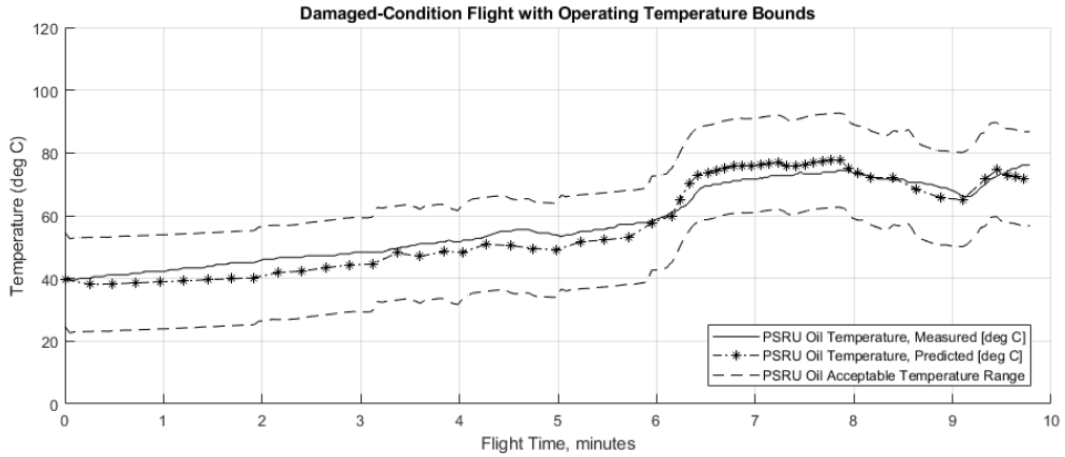

Figure 5 – Damaged-condition flight profile showing temperature remained within the safe operating zone.

Across the eight normal-condition flights, the model deviated from the recorded data by an average absolute value of 2.22 degrees C. The maximum deviation was 14.9 degrees C. The standard deviation of the difference averaged 3.4 degrees C. Figure 4 shows the predicted PSRU oil temperature plotted with the measured PSRU oil temperature on the same flight shown in Figure 2, as well as error bars set at 15 degrees C from the predicted value to ensure that all the measured values fall within this range. As can be seen, the model represents the trends and changes, but with such a large margin of error it does not allow for a low warning threshold to be set.

When the model was compared to the final four flights, no meaningful change can be observed in the model's correlation to the measured data. Figure 5 shows the model with the 15 degree margin compared to the measured PSRU oil temperature values on the final flight before the damaged component was replaced. As can be seen, there is no greater discrepancy between the model and the data than was observed in the normal-condition flights.

The average absolute difference between the recorded data and the model's prediction in the last four flights is 3.97 degrees C, with a maximum deviation of 14.2 degrees C. The standard deviation of the variation averages 3.79 degrees C. Note that the maximum deviation for the flights in the damaged-condition is not greater than the corresponding values under the normal-condition flights. There is, however, a significantly higher average absolute difference and standard deviation in the difference on the last four flights. This can be accounted for by the short length of the last three flights. The model is least stable in the most transient portions of the flight, and this is often where the greatest errors are observed. Such short flights prevent a steady state condition from occurring, giving significant room for wider spread in the deviation.

Comparing mean deviation values from the two flight sets, as opposed to absolute value means, the finding is confirmed which indicates no observable damage. The mean deviation in the normal-condition flights is 0.961 degrees C, and is -0.728 degrees C in the damaged-condition flights. This indicates that there is only a very slight increase in measured temperature compared to the predicted PSRU oil temperature across the damaged condition flights, and is insignificant compared to the maximum variations observed.

V. DISCUSSION

As may be seen in the results outlined above, no significant difference was observed between the early flights and the four flights preceding replacement of the damaged component pictured in Figure 6. Clearly any additional heat input to the gearbox oil as a result of the damage is less than the range of error of the prediction model. Further refinement of the prediction model may deliver a narrower margin of error and therefore allow a smaller heat increase to be detected. There are several potential sources of error suspected to be contributing to a large percent of the model error.

First, the gearbox temperature is highly dependent on airspeed since airflow through the cooling duct is the primary source of heat dissipation. Unfortunately for the purposes of this model, the only speed data available is GPS speed. This is an accurate reflection of ground speed but may be substantially different from true airspeed if headwinds or tailwinds are encountered. This variation could be a key factor in the discrepancies between the prediction model and the measured data, especially under steady state conditions.

Another phenomenon which may be causing discrepancy is the reversing of power flow through the gearbox. In some situations it may be possible for the propeller to transmit power to the gearbox as airflow over it causes it to turn faster than the engine would idle. This would be similar to engine breaking in a car. It is believed that several model discrepancies in this study are caused by this phenomenon. Since the model only accounts for power flow from the engine to the propeller, heat input from this reverse power flow is not accommodated.

VI. FUTURE WORK

There are many improvements which could be made to the PSRU oil temperature prediction model. Further study of heat transfer between the engine, PSRU, and PSRU oil would greatly increase the accuracy of the model. Contact temperature sensors placed on the engine block and PSRU case would be highly beneficial for verifying heat flow paths in the system.

The beginning and end of a flight typically contain the most variation in temperatures and are the most difficult to model accurately. Further studying these periods should improve the model's robustness across all flight profiles.

As mentioned above, incorporating airspeed information instead of GPS ground speed should improve the model, as would further study of the reverse power flow scenarios and their effect on the gearbox oil temperature.

Beyond this, using flight data to train a neural network would likely create a more robust model and therefore a more accurate fault detection. This may remove the simplicity of temperature monitoring and make it less useful to general aviators, but it could be promising in many diagnostic scenarios.

Additionally, it would be highly valuable to test the model developed in this work against a variety of mechanical faults, including gear tooth damage and bearing damage. Both surface level defects as well as deeper structural defects such as tooth root cracks

should be compared. These tests would ideally be conducted under a variety of power settings, speeds, and temperatures to provide the most complete picture of temperature variation under a multitude of conditions.

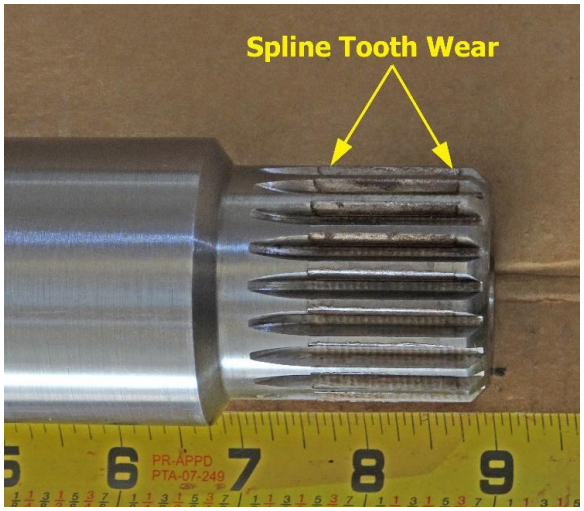

Figure 6 – Spline damage on the output shaft.

VII. CONCLUSIONS

The model used to predict PSRU oil temperatures in this study was not able to detect spline damage on the gearbox output shaft. While temperature monitoring of gearbox oil is still highly recommended, it should not be relied upon as the only indicator of mechanical health. As is common practice in many aviation transmissions, a chip detector should be installed in the lubrication system to provide the pilot an indication when sufficient ferrous particulate accumulates. In this case the operator observed a color change in the oil due to metal particle shedding, and a properly installed chip detector in the system would likely have indicated the damage. While future work may establish a more robust and accurate temperature prediction model, significant testing will be required to validate its effectiveness.

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