Spiral Bevel Gear Damage Detection Using Decision Fusion Analysis

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Abstract - A diagnostic tool for detecting damage to spiral bevel gears was developed. Two different monitoring technologies, oil debris analysis and vibration, were integrated using data fusion into a health monitoring system for detecting surface fatigue pitting damage on gears. This integrated system showed improved detection and decision-making capabilities as compared to using individual monitoring technologies. This diagnostic tool was evaluated by collecting vibration and oil debris data from fatigue tests performed in the NASA Glenn Spiral Bevel Gear Fatigue Rigs. Data was collected during experiments performed in this test rig when pitting damage occurred. Results show that combining the vibration and oil debris measurement technologies improves the detection of pitting damage on spiral bevel gears.

1 Introduction

Helicopter transmission integrity is important to helicopter safety because helicopters depend on the power train for propulsion, lift, and flight maneuvering. In order to detect impending transmission failures, the ideal diagnostic tools used in the health monitoring system would provide real-time health monitoring of the transmission and would demonstrate a high level of reliable detection to minimize false alarms. Today’s helicopter health monitoring systems (HUMS) are not yet capable of real-time, on-line, health monitoring. Current data collected by HUMS is processed after the flight, and the health status reported is often plagued with high false alarm rates and undetected faults. The current fault detection rate of commercially available HUMS through vibration analysis is 70 percent [1]. False warning rates average 1 per hundred flight hours [2]. Often these systems are complex and require extensive interpretation by trained diagnosticians [3].

The objective of this research is to integrate oil debris and vibration based gear damage detection techniques into a health monitoring system capable of detecting gear pitting damage with improved detection and decision-making capabilities as compared to existing individual diagnostic tools. This hypothesis will be evaluated experimentally with vibration and oil debris data collected from fatigue tests performed in the NASA Glenn Spiral Bevel Gear Test Facility. Spiral bevel gears are used in helicopter transmissions to transfer power between nonparallel intersecting shafts.

Vibration data will be collected from accelerometers and used to calculate previously validated gear vibration diagnostic algorithms. Oil debris data will be collected using a commercially available in-line oil debris sensor. Oil debris and vibration data will be integrated using fuzzy logic and decision fusion analysis techniques. The goal of this research is to provide the end user with clear information on the health of the gears.

2 Experimental Investigation

Experimental data was recorded from tests performed in the Spiral Bevel Gear Test facility at NASA Glenn Research Center. A detailed analysis of this test facility can be found in the references [4], [5]. The Spiral Bevel Gear Test Facility is illustrated in Figure 1. The test rig is used to study the effects of gear material, gear tooth design, and lubrication on the fatigue strength of gears. The facility
Vibration data was measured by two accelerometers and an oil debris sensor. Multisensor data fusion analysis techniques were chosen to be applied to gear damage data collected from the two accelerometers and an oil debris sensor. Multisensor data fusion is a process similar to methods humans use to integrate data from multiple sources and senses to make decisions. In this process, data from multiple sensors are combined to perform inferences that are not possible from a single sensor. Commercially available software was used to perform the analysis [13].

Sensor data can be fused from the raw data level, feature level, or decision level. Decision level fusion was chosen to integrate these features because this does not limit the fusion process to a specific feature. By performing fusion at the decision level, new features can be added to

Figure 1. Spiral Bevel Gear Fatigue Rig.
the system or different features can be used without changing the entire analysis. This allows the most flexibility when applying this process to other condition based systems since, in most cases, different sensors and post-processing methods are used.

Features are extracted from the vibration and oil debris data for input into the data fusion system. Vibration algorithms FM4 and NA4 Reset are calculated for the two accelerometers, but only one feature for FM4 and NA4 Reset is input into the model. FM4 and NA4 Reset with the higher value is input into the model. The larger value of FM4 and NA4 was chosen to indicate the side with the most damage and to limit the features to 3. A more complex model can be developed with additional features but is outside the scope of this paper. The accumulated mass measured is used as the feature for the oil debris sensor [14].

Fuzzy logic membership functions were defined for the identity declaration step. Fuzzy logic was chosen because it is tolerant of imprecise data, flexible and can incorporate the experience of experts. Fuzzy logic starts with a fuzzy set, extending boolean set theory to a continuous valued logic via the concept of membership functions valued between 0 and 1. The truth of any statement becomes a matter of degree. The fuzzy logic membership functions identify the damage level on each feature. Levels of damage are indicated by the oil debris and vibration features oil debris mass, FM4, and NA4 Reset. Figure 2 shows the data fusion model used for this application.

Fuzzy logic is used to identify the damage level on each feature and to perform the decision level fusion process on the features. Although other data fusion techniques are available, fuzzy logic was chosen based on the results of several studies to compare production rules, fuzzy logic and neural nets. One study found fuzzy logic the most robust when monitoring transitional failure data on a gearbox [15]. Another study comparing automated reasoning techniques for condition-based maintenance found fuzzy logic more flexible than standard logic by making allowances for unanticipated behavior [16]. The fuzzy logic process consists of converting each piece of input data to degrees of membership, aggregating all outputs into a single fuzzy set, then converting fuzzy membership information into a single output.

Membership functions for the features are defined as levels of damage. Levels of damage are damage low (DL), damage medium (DM), and damage high (DH). The levels of damage for each feature are as follows: oil debris mass (DL, DM, DH), NA4 Reset (DL, DH), and FM4 (DL, DH). Membership functions and rules for the membership functions were developed based on analysis of this experimental data and the experience of the diagnostician. A detailed description of the process used to define the membership functions is referenced [17]. The membership functions and rules used for this analysis are shown in Table 1 and Figure 3. Triangular membership functions were used because of the ease of modifying the membership functions for other geared applications. The only parameters that need to be changed are the input/output scaling factors on the membership functions.

Table 1. Rules for Bevel Rig Data Fusion Model

<table>
<thead>
<tr>
<th>Rule Description</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>If (FM4 is DL) and (NA4 is DL) and (debris is DL) then (output is O.K)</td>
<td>O.K.</td>
</tr>
<tr>
<td>If (FM4 is DL) and (NA4 is DL) and (debris is DM) then (output is INSPECT)</td>
<td>INSPECT</td>
</tr>
<tr>
<td>If (FM4 is DL) and (NA4 is DL) and (debris is DH) then (output is SHUTDOWN)</td>
<td>SHUTDOWN</td>
</tr>
<tr>
<td>If (FM4 is DL) and (NA4 is DL) and (debris is DM) then (output is INSPECT)</td>
<td>INSPECT</td>
</tr>
<tr>
<td>If (FM4 is DL) and (NA4 is DL) and (debris is DH) then (output is SHUTDOWN)</td>
<td>SHUTDOWN</td>
</tr>
<tr>
<td>If (FM4 is DL) and (NA4 is DL) and (debris is DM) then (output is INSPECT)</td>
<td>INSPECT</td>
</tr>
<tr>
<td>If (FM4 is DL) and (NA4 is DL) and (debris is DH) then (output is SHUTDOWN)</td>
<td>SHUTDOWN</td>
</tr>
<tr>
<td>If (FM4 is DL) and (NA4 is DL) and (debris is DM) then (output is INSPECT)</td>
<td>INSPECT</td>
</tr>
</tbody>
</table>

Decision level fusion is then performed integrating membership functions with fuzzy logic rules. The output is the state of the gear. The output of the system is defined as the state of the gear and possible action by the end user. The three states of the gear are O.K. (no gear damage), inspect (initial pitting), and shutdown due to damage (severe destructive pitting).
The right side vibration features and oil debris features for experiment 3 are plotted on Figure 4. Although vibration data was collected on both sides of the gearbox, the vibration feature on the right side began to substantially increase during the test, indicating damage was beginning to occur on the right side of the test rig. The gears were inspected at test completion and damage to two teeth on the right side pinion is shown in Figure 4. Figure 4 also shows the output of the decision fusion model for this experiment. The output of the model indicates three states of the gear based on 3 shades of gray: O.K; inspect; and shutdown. The x-axis, labeled reading number, is the same on both the feature plot and the output plot. The reading number is also the run time in minutes since data was collected once per minute. If the model was available on-line during testing, the gears would have been shutdown for inspection at approximately reading 1500, since the output indicates to inspect the gears due to damage. If initial pitting was of interest to the end-user of the diagnostic tool, the oil debris membership function or rules could be adjusted to be more sensitive to this type of failure.

4 Discussion of Results

The results discussed in this section are based on data collected during 6 experiments. During experiments 1 and 2, only oil debris data was collected. And, during experiment 2, only the total debris at test completion was measured. At test completion of experiment 1, initial pitting was observed on one pinion tooth. At test completion of experiment 2, destructive pitting occurred on 2 teeth on the right pinion and initial pitting occurred on one tooth on the left pinion. This data was used to define the oil debris feature membership functions. Oil debris and vibration data was collected for experiments 3 through 6 and is discussed in the following paragraphs. The amount of debris measured at test completion for all 6 experiments is shown in Table 2.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Readings</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29496</td>
<td>42</td>
</tr>
<tr>
<td>2</td>
<td>NA</td>
<td>104.3</td>
</tr>
<tr>
<td>3</td>
<td>1835</td>
<td>42.4</td>
</tr>
<tr>
<td>4</td>
<td>6073</td>
<td>26.5</td>
</tr>
<tr>
<td>5</td>
<td>10569</td>
<td>41.2</td>
</tr>
<tr>
<td>6</td>
<td>4840</td>
<td>137.7</td>
</tr>
</tbody>
</table>

Figure 3. Feature Membership Functions.

Figure 4. Vibration oil debris features and damage to right pinion teeth for bevel test 3.
The left side vibration features and oil debris features for experiment 4 are plotted on Figure 5. For this experiment, the vibration feature calculated from the left accelerometer began to substantially increase indicating damage was beginning to occur to the gears on the left side of the test rig. The gears were inspected at reading 5742 and pitting began on one tooth on the left pinion. The gears were inspected at test completion and the damage to the one tooth on the left side pinion is shown in Figure 5. Figure 5 also shows the output of the decision fusion model for this experiment, indicating to inspect the rig due to damage.

The left side vibration features and oil debris features for experiment 5 are plotted on Figure 6. For this experiment, the vibration feature calculated from the left accelerometer began to substantially increase indicating damage was beginning to occur to the gears on the left side of the test rig. The gears were inspected at test completion and damage to one tooth on the left side pinion is shown in Figure 6. Figure 6 also shows the output of the decision fusion model for this experiment. The output indicates to inspect the gears due to damage at approximately reading 9200.

The right side vibration features and oil debris features for experiment 6 are plotted on Figure 7. Although vibration data was collected on both sides of the gearbox, the vibration feature on the right side began to substantially increase early on in the test. The gears were inspected at reading 99 and initial pitting was beginning to occur on the right side of the test rig. Initial pitting was triggered by vibration algorithm NA4, since debris membership functions were not as sensitive to initial pitting. The gears were inspected at test completion and destructive pitting to one tooth on the right side pinion is shown in Figure 7. Figure 7 also shows the output of the decision fusion model for this experiment. Inspect was indicated early on in the...
test and shutdown was indicated at approximately reading 2600. At test completion, it was found that damage also occurred on the pinion bearing. The damage is shown in Figure 8. Although the sensitivity of the parameter can be adjusted to be more sensitive to different levels of damage, the parameter must be defined on the type of failure the end user is trying to detect. The vibration features are specific to gear damage detection. Additional features and logic must be programmed into the model to differentiate between gear and bearing failures.

Figure 7. Vibration oil debris features and damage to right pinion teeth for bevel test 6.

Additional vibration diagnostics for bearing damage detection can be added to the model to predict future failures. As more data is acquired on different types of

failures, the model can be modified to recognize unanticipated failures. The bearing failure also reinforces the importance of fusing different measurement technologies for damage detection since each have strengths and weaknesses for different applications.

5 Conclusions

After review of the data from these experiments, the advantage of fusing the features of different measurement technologies is evident. The output gives clear information to the end user when making a decision based on the data. As a diagnostician, it is important to identify the end user of the diagnostic tool early on in the process. The end user of most helicopter transmission diagnostic tools is the technician that determines if maintenance is required on the transmission. If the tool being developed requires hours of analysis and large amounts of stored data to determine the health of the system, it is probably not feasible for this application. It is thus important to keep the man-machine interface in mind when designing diagnostic tools.

The model developed can incorporate the knowledge of the diagnostician into a system that can be used to make clear decisions on the status of the geared system relieving the end user of interpreting large amounts of sensor data. This research demonstrated integration of two measurement technologies, oil debris analysis and vibration, results in a system with improved damage detection and decision-making capabilities. Understanding the strengths, weaknesses and constraints of each measurement technology, then capitalizing on these strengths via data fusion, is key to the development of future health monitoring systems.

6 References


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**Supplementary Notes**

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**Subject Terms**
Gears; Damage detection; Vibration; Wear debris; Data fusion; Fuzzy logic