Advance method of Leakage Detection in Aircraft Hydraulic System

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ABSTRACT

Aircraft hydraulic systems are composed of several components connected and distributed along the aircraft. Monitoring leakage of these components are time consuming tasks, and often cover only some parts of the system. The objective of this work is to present a method to estimate hydraulic leakage and recommend maintenance and servicing tasks using aircraft standard sensors such as fluid temperature and reservoir level.

The proposed method was tested using several aircraft operating data with different levels of degradation (external leakages) and the results were analyzed in order to evaluate its precision on estimating leakage. Results showed the capability to detect leakage although uncertainties must be considered when evaluating maintenance interventions.

1. INTRODUCTION

Increased aircraft availability is one of the most desirable fleet characteristics to an airliner. Delays due to unanticipated system components failures cause prohibitive expenses, especially when these events occur on sites without proper maintenance staff and equipments. In recent years researches have focused on providing new technologies which could detect incipient failures and notify maintenance staff in advance when any component is about to fail. On the other hand these technologies requires several sensors that sometimes are not available on the aircraft which limits their application and consequently operational savings.

Hydraulic systems are found on most of the aircrafts nowadays and contain several components with significant failure rates. Some sensors are available to monitor them, but due to the number of components and their distributed localization along the aircraft, several faults are not monitored. Hydraulic fluid leakage is one example.

Hydraulic leakage detection systems major applications are in the oil and gas industries (Stavenes, 2010) focusing most on pipelines such as "American Petroleum Institute Publ 1149" and (Beushausen, 2004). Aircraft applications are most of the times limited to visual inspections of some components with higher failure rates or some internal leakage monitoring such as pumps case drain flow monitoring as presented in (Copsey, 2006) and (Byington et al. 2003). The main issue related to aircraft applications is the sensors availability. Most of the aircraft hydraulic systems do not contain the proper set of sensors to monitor leakage although dispatch recommendations are made for leakage limits.

The method presented in this article describes a method to detect total system leakage using only a set of sensors available on most of aircrafts.

2. SYSTEM DESCRIPTION

A simplified architecture of aircraft hydraulic systems can be summarized as Figure 1.

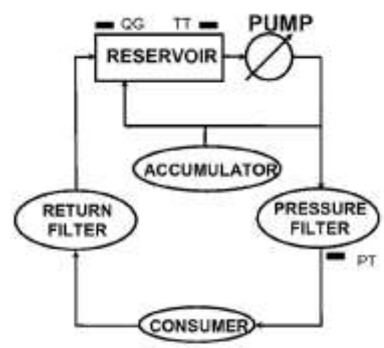

Figure 1 General Schematic of a Hydraulic System

The system contains one or more variable displacement pumps, accumulators, filters, and consumers, that include all the actuators connected to the hydraulic power such as flight controls, brake and landing gear. Also the system contains a bootstrap reservoir. The basic set of sensors available are pressure transducers (PT) at the pressure line, fluid temperature transducers (TT) at the reservoir and a quantity gauge (QG) indicating the reservoir level.

3. Leakage Detection Method

The method here described was created for the EMBRAER Regional jets (E-Jets). On this platform the three sensors listed in Figure 1 were available and recorded on the Flight Data Recorder (FDR). Figure 2 illustrates some flight records for the reservoir level and fluid temperature under nominal behavior.

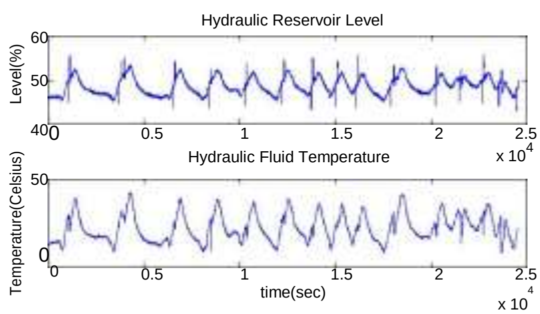

Figure 2 Hydraulic system flight record example.

From Figure 2 it is possible to conclude that direct measurement of the reservoir level is not enough to estimate the system total leakage since the fluid is submitted to a significant variance of temperature. Also some actuators (landing gear specially) interfere on the measured reservoir level as observed by the spikes in the first curve in Figure 1 when the landing gear is actuated.

The first step is to eliminate the influence of these parameters on the level measurement and to accomplish that a model was proposed considering fluid physical properties. According to (Merrit, 1967), a linear approximation for the fluid density is:

$$\rho = \rho_0 \left[1 + \frac{1}{\beta}(P - P_0) - \alpha(T - T_0)\right] \quad (1)$$

where:

β is the Bulk Modulus

α is the Coefficient of Expansion

ρ_0 is the initial density (ISA Condition)

P_0 is the initial pressure of 1 atm (ISA Condition)

T_0 is the initial temperature of 15 ^{o}C (ISA Condition)

ρ is the actual density

P is the actual pressure

T is the actual temperature

For the elimination of temperature variation on the reservoir level, the volume was estimated for constant fluid density at ISA (International Standard Atmosphere) conditions. By manipulating Eq. (1), the hydraulic system fluid volume at ISA conditions is:

$$V_0 = V\left[1 + \frac{1}{\beta}(P - P_0) - \alpha(T - T_0)\right] \quad (2)$$

where:

V_0 is the hydraulic system fluid volume at ISA conditions

V is the hydraulic system fluid volume

The relation between V and the reservoir level indication is

$$V = V_{QG} + V_{sys} \quad (3)$$

where:

V_{QG} is the sensor indication

V_{sys} is the system volume excluding reservoir. It contains all volumes specified in “SAE Aerospace Standard AS5586”

To estimate V and consequently V_0, it is necessary to estimate V_{sys} first. Two methods could be used for that. The first one is to measure the volume of fluid necessary to fill the entire hydraulic system, and the second is to estimate V_{sys} by minimizing Eq. (4) using aircraft operating data (for example those in Figure 2) in a healthy condition. A gradient descent method was used to solve this equation.

$$ArgMin[\mathrm{var}(V_0), V_{sys}] \quad (4)$$

which is the same as:

$$ArgMin \ \mathrm{var}\ V\left(1 + \frac{1}{\beta}(P - P_0) - \alpha(T - T_0)\right), V_{sys} \quad (5)$$

It was assumed V_{sys} constant, which in other words means that variances in actuators, piping, accumulators and any other components volumes were not considered . To minimize these variations only data with similar operating conditions (for example cruise) were used and with no observed leakage.

After estimating V_{sys}, the value of the estimated quantity gauge sensor indication at ISA condition (V_{est}) was estimated with Eq. (6) representing the mass estimation (density multiplied by volume) for both temperatures: ISA and actual temperature.

$$\rho_0 (V_{sys}+V_{est})=\rho(V_{sys}+V_{QG}) \tag{6}$$

For illustration purposes, the same data of Figure 2 was used to estimate the values of V_{est} (using Eq. 6) illustrated in Figure 3.

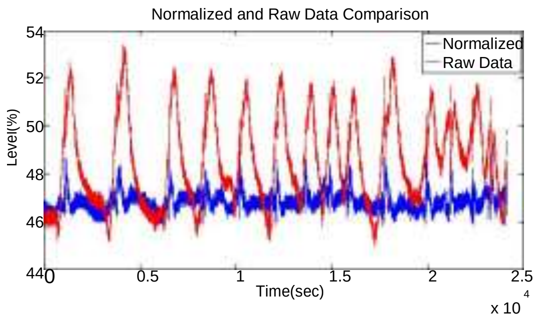

Figure 3 Normalized level indication (V_{est}) Vs Raw data level indication.

The variance of the raw data from Figure 3 was 3.41 and the variance of the normalized data was 0.157. Although reservoir level variance decreased significantly, some variations still persisted probably caused by non uniform fluid properties in the system and consumers' variations (accumulators for example).

If no data is available for fluid properties (β and α), a principal component analysis (PCA) could be used to eliminate the temperature influence (1^{st} component). Figure 4 illustrate the relation between temperature and reservoir level for the same data in figure 2

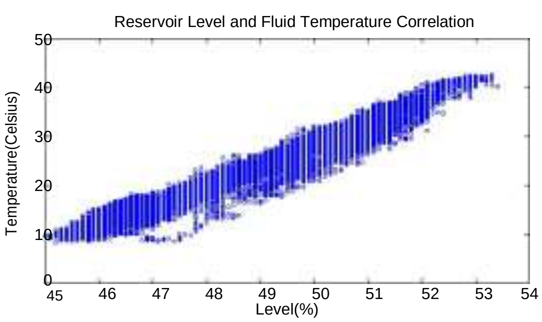

Figure 4 Relation between temperature and reservoir level.

The coefficients (loadings) of the two components are given by the following matrix:

$$\begin{bmatrix} 0.230 & 0.973 \\ 0.973 & -0.230 \end{bmatrix}$$

and the components variances:

$$\begin{bmatrix} 62.1 \\ 0.148 \end{bmatrix}$$

The much larger value of the first component variance indicates the strong correlation of level and temperature as expected.

The expected hydraulic system leakage can be determined through the angular coefficient of a linear interpolation of the normalized levels over the time. A least square method was used with data collected from the last 5 flights. Eq. (7) represents the equation variables estimated from the least square method.

$$Level(t)=(\_Leakage)t+InitialLevel \quad (7)$$

4. Servicing and Maintenance Recommendation

The current method triggers two possible maintenance actions. The first one is the inspection of the system and repair of leaking components when leakage estimation reaches a predetermined threshold. This task could be an improvement of the traditional periodical visual inspection. The next one is the reservoir hydraulic fluid filling service. This task can be trigged when for example the estimated future level for 5 days from now will reach the minimum allowed level to operate the system. This expected future level can be obtained from Eq. (7).

By using both of these alerts, maintenance could improve leakage inspections and optimize filling services, reducing non-schedule maintenance activities and AOG (Aircraft On Ground) events.

5. Results

To validate the method operational data were used. Several flights from different aircrafts were collected and analyzed under several different health conditions. Figure 5 illustrates the three main different situations observed from all those data. Each sample represents the average level for 1 flight.

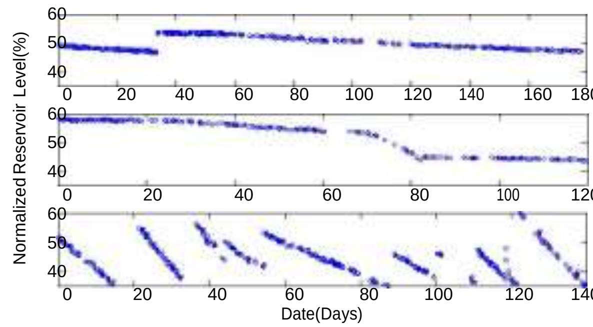

Figure 5 Examples of normalized level estimations.

The upper example shows an aircraft with no significant leakage as the reservoir level decreasing rate (leakage) is low. Also it was possible to observe a filling task around day 35 (abrupt increase in level).

The middle example shows a failure around day 70 and its repair around day 81, probably detected from visual inspection.

The lower example shows a system with increased leakage requiring several hydraulic filling tasks in order to keep the system within the required levels. Probably the visual inspections executed for this example could not detect the excessive leakage.

For the same examples the leakage was plotted and displayed in Figure 6.

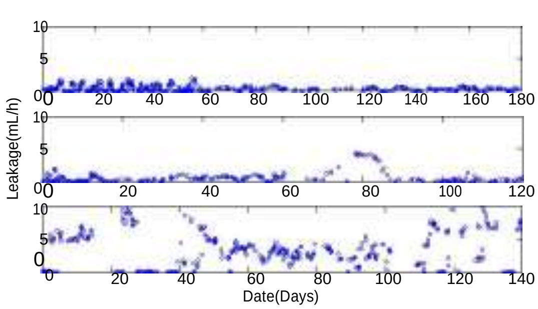

Figure 6 Examples of leakage estimations.

It is possible to observe that leakage estimations are noisier than levels estimations, especially with the presence of higher levels of leakage as seen in the third example of figure 6. This behavior is caused by the derivative nature of leakage estimation when few errors in level estimation generate increased errors in the leakage (derivate). One possible solution to minimize this error is to increase the interpolation window, here established in 5 flights. Although it softens the results, it increases the time response of leakage detection.

From all flights analyzed, 1202 filling tasks were executed in which 541 could be eliminated if the proposed method were used. Also a histogram is plotted in Figure 7 showing the leakage estimation for all flights analyzed.

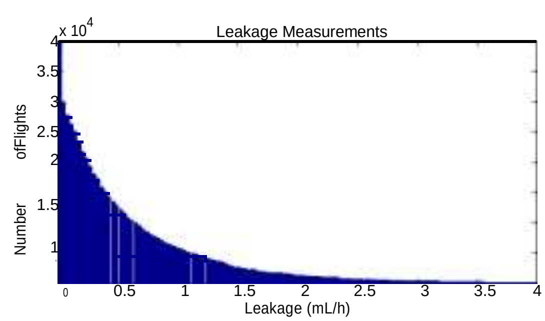

Figure 7 Fleet leakage estimation histogram.

From this plot, it is possible to perform several statistical analysis for the entire fleet and each individual aircraft such as an estimative of the number of flights with leakage levels above the recommended limit and how each aircraft is positioned compared to the entire fleet.

6. CONCLUSION

Aircraft hydraulic leakage detection maintenance tasks are time consuming and often do not bring an estimation of the leakage of the entire system. Also the lack of dedicated sensors makes this estimation more difficult. This paper presented a method to estimate total leakage and future reservoir levels from a hydraulic system considering only reservoir quantity gauge, fluid temperature and fluid pressure sensors. Also servicing and maintenance recommendations were proposed for these estimations in order to increase fleet leakage detection and reduce AOG (Aircraft On Ground) events.

Several aircraft data were used to validate the method. Although some estimations were less precise (leakage estimation), the method showed to be promising.

ACKNOWLEDGEMENT

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