Failure Prognostics of a Hydraulic Pump Using Kalman Filter

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ABSTRACT

Hydraulic systems are an important power source in modern aircraft. Most aircraft employ hydraulic power for flight control systems and landing gears actuation. Pumps are a critical component in hydraulic system and monitoring the health of such components may provide economic and operational benefits to aircraft operators. This work describes the use of Kalman Filter techniques for the estimation of remaining useful life of aircraft hydraulic pumps. An empirical model of degradation evolution is employed for this purpose. Low sampling rate measurements of the hydraulic pressure of the aircraft hydraulic systems are the only measurements employed. In order to illustrate and validate the method, two time series of actual run to failure data are analyzed. Results provide evidence that the method can be successfully employed for actual aircraft hydraulic pump failure prognosis.

1. INTRODUCTION

Hydraulic power is widely employed in aircraft systems, mainly in the actuation of flight control surfaces and landing gears. One important reason for this is the fact that hydraulic actuators present a high power density, i.e. compact and light actuators may withstand large loads (Merrit, 1976). This makes hydraulic power very suitable for aircraft systems applications. Therefore, hydraulic systems comprise an important power source in modern aircraft.

Although redundancies are employed in the design of aircraft systems in order to guarantee high airworthiness levels, the failure of a hydraulic system commonly represents adverse economic and operational consequences. Therefore, the application of prognosis techniques to avoid failures in hydraulic system components can potentially provide benefits to aircraft operators. Pumps are the heart of a hydraulic system, since they are the components which transform mechanical power from the engine gearbox or from an electric motor into hydraulic power. This work describes an innovative application of PHM techniques in the estimation of remaining useful life (RUL) of hydraulic pumps in aircraft hydraulic systems. In the proposed solution, low sampling rate measurements of the hydraulic pressure of the hydraulic system fed by the hydraulic pump are the only source of information for the estimation of component health. This kind of measurement is commonly available in modern aircraft. The Kalman Filter (KF) technique (Kalman, 1960) is employed for estimating current degradation and its trend, based on an empirical model of degradation evolution. Such estimates are then extrapolated for performing failure prognosis.

There are previous works in the literature which deal with failure prognosis of hydraulic pumps. For industrial pumps, various works such as (Hancock and Zhang, 2006) present solution. This specific solution is based on vibration measurements which are analyzed using wavelet and neuro-fuzzy techniques. Concerning aircraft hydraulic pumps, (Byington, Watson, Edwards, and Dunkin, 2003) describe the application of neuro-fuzzy classifiers and a Bayesian belief formulation in order to obtain failure prognosis. In this case, measurements of pump pressure, case drain flow and case drain temperature were employed. (Bechhoefer, Clark and He, 2010) presents the use of Kalman Filter for performing prognosis of this kind of component. However, in such work, the condition indicator (CI) is based on vibration measurements, taken from dedicated sensors. The proposed method differs from such technique due to the fact that in the former only system hydraulic pressure measurements are employed, with low sampling rates. Such measurement are used for control and safety purposes and are therefore usually available in modern aircraft with no need for additional sensors or recording capability.

The remaining sections are organized as follows: section 2 describes the hydraulic pump considered in this work;

section 3 presents the failure prognosis technique employed; section 4 presents the results and section 5 is the conclusion.

2. Component Description

The component under study is a variable displacement axial piston pump with pressure compensation system to deliver constant discharge pressure of 3.000 psi.

The pressure compensation system comprises a piston and valve that controls the swash plate angle. Increased angles provide higher flows while lower angles provide lower flows. If discharge pressure decreases, the compensation piston actuates decreasing the swash plate angle and the discharge flow. This brings the discharge pressure back to nominal values. The compensation system is illustrated in Figure 1.

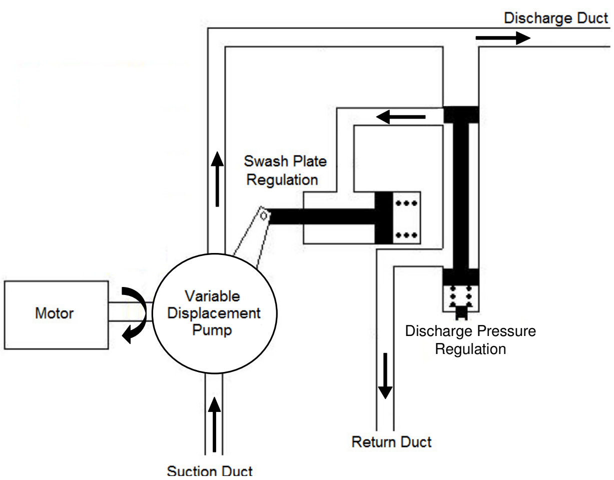

Figure 1. Pressure compensation system schematic

This component contains a spring actuated hydraulic cylinder controlled by a pressure regulator valve. This valve contains a spring whose pre load calibration defines the pump discharge pressure.

One common failure of this type of pump is the looseness of the regulator valve spring which decreases the pump discharge pressure. This failure mode can be sensed by pressure transducer data acquired at the pump discharge duct at no load condition. For the analysis presented in this paper, hydraulic discharge pressure data was acquired for different aircraft operating at different conditions for several flights.

3. Failure Prognostics Methodology

As presented in section 2 the failure mode considered in this work can lead to a reduction in the pressure delivered by the pump. This fact is well known and a failure monitor is commonly available to detect when pressure drops below a given threshold for a certain period of time. Although this failure detection system is usually available for aircraft hydraulic systems, failure prognosis is not currently found in commercial systems.

The proposed failure prognostics system uses the average of measured system pressure as a CI. The idea is to track this average pressure and to predict when it will reach a level that triggers the designed failure monitor.

Data employed in the present analysis correspond to field data collected from two aircraft that presented pump failures. Data ranging from pumps in normal condition up to failure monitor triggering are available for both aircraft. Figure 2 and Figure 3 show normalized hydraulic pump CIs calculated for these two aircrafts.

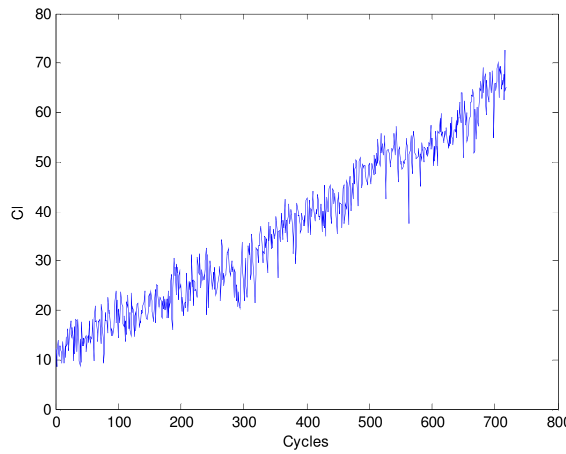

Figure 2. CI for Pump 1

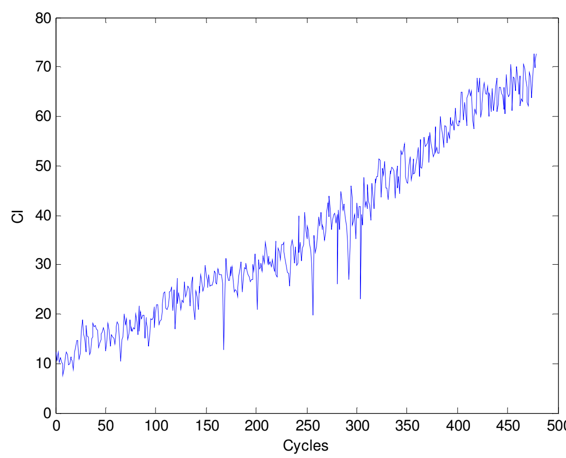

Figure 3. CI for Pump 2

For failure prognostics implementation, a Kalman filter was employed. Concerning the dynamic model necessary for filtering and extrapolation, no first principles model was used. The state space representation of a linear degradation evolution with unknown slope was used for this purpose.

This model was empirically chosen based on the aspect of the CI plots. It may be noticed that the degradation rate is not constant for different pumps. This may be the case even for the same pump under different operating conditions. Therefore, it is necessary to estimate the slope – which describes the degradation evolution trend – along with the degradation estimation itself. The resulting model may be defined as follows:

$$\begin{aligned} d_{k+1} &= a_k + d_k + v_{1_k} \\ a_{k+1} &= a_k + v_{2_k} \\ CI_k &= d_k + w_k \end{aligned} \qquad (1)$$

where d is the estimated degradation, a is the slope, v_1, v_2 and w are gaussian noises, CI is the condition indicator and k is the discrete time instant. In this case, k represents aircraft cycles. State noise v_1 and observation noise w represent actual state and observation noises present in the data, while v_2 is an artificial noise added for the estimation of the fixed parameter a. A noise adaptation scheme to adapt v_2 variance during filtering (Leão, 2011). In Kalman filter, the information concerning the variance of the parameter estimates at instant k is contained in the covariance matrix P_k. Using this information, the variance σ^2_{v2k} is obtained by :

$$\sigma^2_{v_2 k} = \left(-1 + \frac{1}{\lambda}\right) P_k \qquad (2)$$

Using the d and a distributions estimated at a given instant and the model presented in Eq. (1), Monte Carlo simulations were performed until d reaches a failure threshold. Failure thresholds were chosen according to the concept of Hazard Zone (HZ) (Orchard and Vachtsevanos, 2009).

The HZ defines a region, modeled by a bounded distribution, with high probability of failure occurrence. In this work, failure thresholds were sampled according to the chosen HZ distribution. The HZ was defined as a normal distribution with mean of 70 and standard deviation of 3.

The HZ definition was performed empirically. A more systematic approach to choose it could only be developed as more run-to-failure time series are available.

4. RESULTS

The proposed method was tested using the two run-to-failure datasets corresponding to the two mentioned hydraulic pumps. For each pump, five predictions were made in different time-to-failure (TTF) situations. Chosen instants were 250, 200, 150, 100 and 50 cycles before failure. Figure 4 and Figure 5 show the result for each pump. The plots present the real and estimated remaining useful life (RUL) for each pump. Bars indicating the uncertainty of the corresponding RUL estimate were also presented.

In both cases, uncertainty bars were defined as an interval corresponding to 95% of the predicted distribution

Figures 4 and 5 show promising results: in all prognostics attempts, the TTF value was inside the predicted distribution. Another desirable characteristic is the fact that uncertainty in RUL estimates was reduced as TTF reduces.

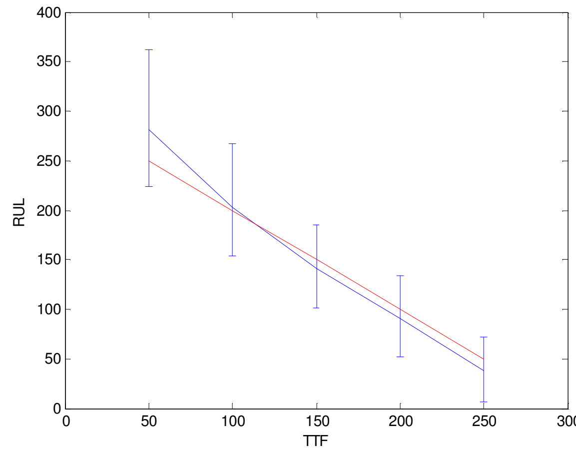

Figure 4. Prognostics for Pump 1

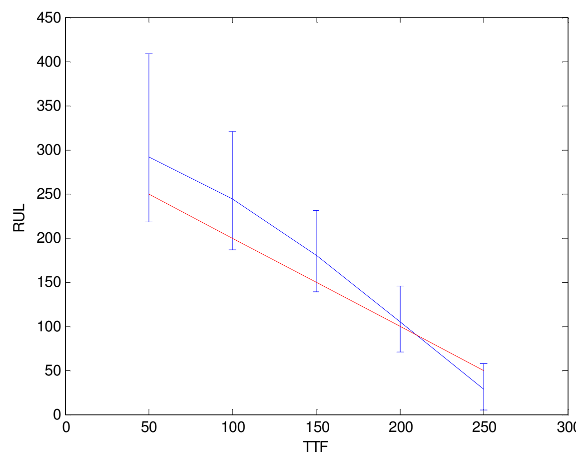

Figure 5. Prognostics for Pump 2

5. CONCLUSIONS

The present work showed a method for aircraft hydraulic pump failure prognostics using Kalman Filter. First principles were not used to model the degradation evolution. A linear model with uncertain slope was empirically employed for this purpose. All calculations were based on a low bandwidth measurement of the hydraulic pressure in the system fed by the hydraulic pump.

Despite the simplicity and wide applicability of the method, results obtained from its application to two run-to-failure time series of actual aircraft hydraulic pumps showed to be promising. More conclusive results may be obtained as long as more run-to-failure time series for hydraulic pumps become available.

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BIOGRAPHIES

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