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ABSTRACT

Current health monitoring descriptions often base on assumptions on how a degraded component behaves. Bearing and gear frequencies quite often play a role in this classic health monitoring. Even with a perfect monitoring, a positive result can only be given as soon as damage has occurred. The presented method detects the availability of oil in the actuator and can therefore predict upcoming damages that are caused by a lack of oil.

KEYWORDS

Bearing, EMA, Gear, Hardware testing, Health Monitoring, Pressure,

I INTRODUCTION

The monitoring of electromechanical actuators is well-researched. Most of the methods for the monitoring of such actuators are based on vibration analysis (Balaban, et al., 2015) or the detection of faults using a combination of the on-board sensors (van der Linden & Dorkel, 2017). Both methods have proven to be able to detect artificial faults on a test bench (Van der Linden, et al., 2016).

Furthermore, methods exist that observe the total behavior of the actuator that trigger when a fault is detected that influence the actuator-performance (Ossmann & Van der Linden, 2015). Such methods can be used for reconfiguration of aircraft control and actuator control algorithms.

However, since the detection of faults in these methods is based on a known fault signature, different faults cannot be detected. Especially for ballscrews, the high complexity of ballscrews could easily lead to an omission leading to undetected faults.

To detect known, but also unknown methods of failure, the cause of the development of these faults must be assed. As most of the faults start with either a bad lubrication or even corrosion of the parts, it seems to be obvious to monitor the state of the seals and the oil level. (Chan, et al., 1990) identified for the screwjack type actuators water ingress and ineffective lubrication as common causes of failure. Monitoring the state of the seals using torque or motor current monitoring has not been successful to the knowledge of the author for flight systems. Furthermore, by analyzing the FMEA of a candidate EMA, it has been shown that the loss of oil accounts has a high impact on the reliability.

Therefore, a new type of EMA monitoring is proposed that can detect the effectivity of the seals and the amount of lubricant in an actuator based on the pressure and temperature in the actuator. The algorithms as presented in this report are patent under DE10 2016 111 639 and EP 3115763 A1.

II DETECTION METHOD

Three detection methods will be presented, one that identifies the amount of lubricant in an actuator, and a second method that analyzes the leaks through the seals of an actuator. To initialize these methods, an automated initialization routine has been implemented which can be used itself for the detection of a loss of lubricant.

To be able to use this method, the actuator volume should be sealed and a piston rod that changes the volume inside the actuator must be used.

2.1 Initialisation and estimate of the gas and oil volume

For the initialization of the routines, the volume, pressure and temperature of the actuator at x = 0 must be known. It is possible to obtain these initial values by using following initialization routines:

Gas volume at ram position = 0

The air volume of the actuator can be obtained by using the pressure, temperature and position measurements at three positions: the zero position of the actuator, and two positions, each on one end of the stroke. Now using the ideal gas law, it is possible to calculate the volume of the gas at the stroke x = 0 (V_0):

$$\frac{p_1(V_0 + \Delta V_1)}{T_1} = \frac{p_2(V_0 + \Delta V_2)}{T_2} \tag{1}$$

p_1 and p_2 are the pressures at the end of the stroke, V_1 and V_2 the corresponding volumes calculated using Equation (6) and T_1 and T_2 the corresponding temperatures of the gas. Rewriting this equation gives:

$$V_0 = \frac{p_1 T_2 \Delta V_1 - p_2 T_1 \Delta V_2}{p_1 T_2 - p_2 T_1} \tag{2}$$

Assumption 1

The actuator is moved sufficiently slow so that an isotherm compression can be assumed

Assuming $T_1 = T_2$, can simplify this equation further. This assumption holds true when the actuator is moved sufficiently slow so that an isotherm compression can be assumed. As often the response of the used temperature sensor relatively slow, the movement of the actuator must be slow enough to either fit in the dynamics of the temperature sensor, or be slow enough that the temperature between both measurements can be assumed to be constant.

It has to be further investigated if the temperature changes for fast position dynamics might be low enough to be neglected (10K change in temperature at 273K is only 2.6% difference). This reduces Equation (2) to:

$$V_0 = \frac{p_1 V_1 - p_2 V_2}{p_1 - p_2} \tag{3}$$

This air volume at the x = 0 (V_0) can be used as the first method to check the oil volume of the actuator, as

$$V_{lubricant} = V_{actuator,0} - V_0 \tag{4}$$

2.2 Lubricant volume and leak detection

If the amount of lubricant in an actuator is too low, the lubrication of all parts cannot be guaranteed and a warning should be issued. The detection of the lubricant volume is based on the detection of the air mass inside the actuator and the change of the inside volume the actuator during the movement of the cylinder. This method can be operated continuously during flight.

Estimation of the amount of lubrication

By measuring the temperature and the pressure in the actuator, it is possible to predict the volume of the gas inside the actuator.

$$V_{Gas} = \frac{m_{gas,0} \cdot R_{gas} \cdot T_{gas}}{p_{gas}} \tag{5}$$

In this equation, $m_{gas,0}$ is a constant set in the factory (calculated by the air volume in the actuator, the actual temperature and actual pressure), or a constant estimated by the initialization routine (see Section 0) before each flight.

Assumption 2

The air mass $m_{Gas,0}$ is constant over the measurements

Assumption 2 does not hold when a leak is present. If the used algorithms are used, this leak will lead to a deviation in the volume of the calculated lubricant which can be detected.

The volume change due to the ram movement is defined by the position of the ram.

$$\Delta V_{ram} = \pi \cdot r_{ram}{}^2 \cdot \Delta x_{ram} \tag{6}$$

Since the total volume of the actuator is defined by the sum volume of the ram-cylinder, air and lubricant, the lubricant volume can be estimated by:

$$V_{lubricant} = V_{actuator,0} - \Delta V_{ram} - V_{gas} \tag{7}$$

In this equation, $V_{actuator,0}$ defines the internal actuator volume with the ram at the position x = 0.

This lubricant volume is an estimation when non-ideal Sensors are used or when Assumption 1 or Assumption 2 only hald partially. Therefore the calculated lubricant volume is called the Estimated Lubricant Volume (ELV). This ELV can be used to trigger an alarm if the amount of lubricant is deviating from the needed amount of lubricant.

Estimation of a lubricant leak velocity

For the monitoring of the health of the actuator, it is further possible to estimate the leakage through the seals. This is mainly a good indication to assess the quality of the seals. First of all, the volume changes during time can be calculated for a hermetically sealed actuator by differentiating Equation (7)

$$\dot{V}_{lubricant} = \dot{V}_{actuator,0} - \dot{V}_{ram} - \dot{V}_{gas} \tag{8}$$

This leakage monitor can also be used to estimate the leakage in not 100% hermetic closed actuators, (when Assumption 2 does not hold). Since the internal actuator volume $V_{actuator,0}$ is a constant, its derivative is zero by definition. As in case of a leak, the mass balance inside the actuator is violated. To take care of this violation, a new term $\dot{V}_{leak}$ is introduced for all leaks form or to the actuator, these volume flows can be can be air or lubricant leaks.

$$\dot{V}_{leak} = \dot{V}_{gas} + \dot{V}_{lubricant} + \dot{V}_{ram} \qquad (9)$$

As $V_{lubricant}$ is the amount of lubricant in the actuator at initialization, also its derivative over the measurement is assumed to be negligible due to incompressibility.

Therefore, following assumption is posed to simplify the calculations:

Assumption 3

The lubricant is assumed to be incompressible.

Using this assumption that, the used leakage indication is

$$ELS = \dot{V}_{ram} + \dot{V}_{gas} \qquad (10)$$

This indicator is called Estimated Leak Speed (ELS) and will be normalized further on. The change of the air volume V_{gas}can be calculated by the differentiation of Equation (5)

$$\dot{V}_{gas} = R \cdot \frac{p(t) \cdot \left(\dot{m}_{gas,0} \cdot T_{gas}(t) + m_{gas} \cdot \dot{T}_{gas}\right) - \dot{p}(t) \cdot m_{gas,0} \cdot T_{gas(t)}}{p^2} \qquad (11)$$

The change of the cylinder volume can be obtained by

$$\dot{V}_{ram} = \pi \cdot {r_{ram}}^2 \cdot \dot{x}_{ram} \qquad (12)$$

By substituting Equations (11) and (12) into Equation (10) and with the assumption that the mass-flow of air is negligible during the measurement, the leak indication becomes

$$ELV = \pi \cdot {r_{ram}}^2 \cdot \dot{x}_{ram} + R \cdot \frac{p \cdot m_{gas,0} \cdot \dot{T}_{gas} - \dot{p} \cdot m_{gas,0} \cdot T_{gas}}{p^2} \qquad (13)$$

This leak indicator can be compared with a threshold to give a waring if the actuator should be inspected. This threshold is needed to allow for model-uncertainties and eventual allowed leak flows.

III HEALTH MONITORING TESTING

To test and validate the working of the developed algorithms, tests have been carried out on a modified testrig.

3.1 Testrig setup

Using the test rig at Liebherr that is presented in (Van der Linden, et al., 2016), measurements have been carried out on a healthy actuator as well as an actuator with a leak. For the tests of a "healthy" actuator, the original actuator has been used without any artificially introduced leaks. For the tests with a "leaky" actuator, a small leak was introduced in the form of a hollow needle with a diameter of 0.33mm and a length of 19mm in the actuator. In Figure 1, an overview of the cannula is given. The cannula is cemented in an oil filler screw, which is positioned at the top of the actuator. During the conditions on the testrig, only air will leave or enter the actuator through this needle.

In Figure 2, the position of the oil temperature and pressure sensor is given.

Figure 1. Cemented Blunt cannula in an oil filler screw

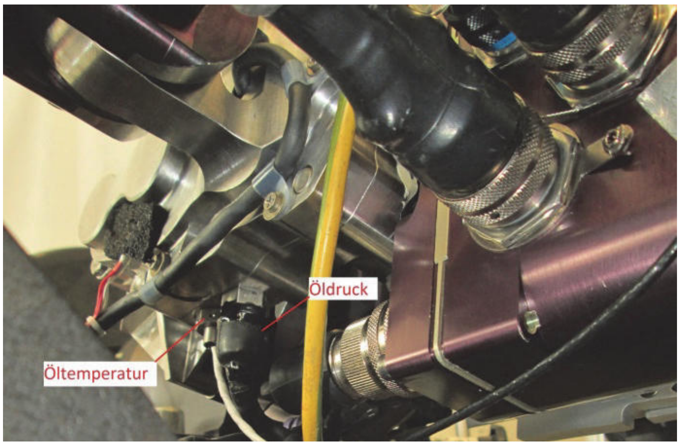

Figure 2. Position of the oil pressure (Öldruck) and temperature (Öltemperatur) sensors in the actuator. View from below.

3.2 Results of the initialization routines

Using the initialization routines, the lubricant amount can be estimated on the initialization. The estimated lubricant amount is given in Table 1. In this table, the measurements 1 to 4 are measurements with the pre-damaged actuator with a leak as defined in Section 0. The measurements 5 to 11 use a heathy actuator without leak.

The large (sometimes even negative), estimated volumes of the lubricant are caused by the fact that for the initialization a constant gas and lubricant mass is assumed. When a leak occurs, this indicator does no more represent a volumetric flow, and the estimation will not yield the real amount of lubricant in the actuator. The estimated actuator status is set from "*healthy*" to "*damaged*" if the lubricant amount has a deviation of more than a certain portion of the initial volume.

Table 1. Estimated lubricant volume using the initialization routine from Section 0 for different measurements. A normalized volume estimation of 1 represents the expected amount of filled oil. This can differ slightly from the final filled amount in the actuator due to rest- oil after dismantling.

Measurement description	Real Actuator status	Normalized estimated lubricant volume	Estimated Actuator status
Slow full stroke extension	Damaged (leak)	-948.8922	Damaged
Slow full stroke retraction	Damaged (leak)	-809.2797	Damaged
High speed, short stroke	Damaged (leak)	3.7518	Damaged
High speed, full stroke	Damaged (leak)	2.5222	Damaged
Full stroke, high speed, no load, State 1	Healthy	0.9165	Healthy
Full stroke, high speed, no load, State 2	Healthy	1.0379	Healthy
Full stroke, high speed, no load, State 3	Healthy	1.0329	Healthy
Full stroke, high speed, max load, State 1	Healthy	0.9314	Healthy
Full stroke, high speed, max load, State 2	Healthy	1.0391	Healthy
Full stroke, high speed, max load, State 3	Healthy	1.0422	Healthy

3.3 Results of the volume- and leak detection

To test the algorithms, the actuator is commanded to move in both directions to trigger an increase in pressure. As also seen in

Table 1, multiple speeds have been used, and the tests have been performed multiple times during the endurance tests.

Healthy Actuator

The position profile can be seen in Figure 3 and the actuator is in the state “Full stroke, high speed, no load, State 2” as indicated in Table 1. The results of the detection algorithms while moving the actuator as shown before are shown in Figure 4 and Figure 5. The measurements have been initialized with the results of the initialization routines (Section 0). The monitoring algorithms are only activated after a successful initialization. This takes place after the initialization algorithm found the minimum and maximum offset position as well as the zero position.

As can be seen, the results stay in the prescribed bandwidth, and therefore no alarms are triggered. Small deviations of the estimated lubricant volume are probably caused by the fact the Assumption 1 does not hold perfectly and the temperature sensors are not fast enough to measure fast temperature changes.

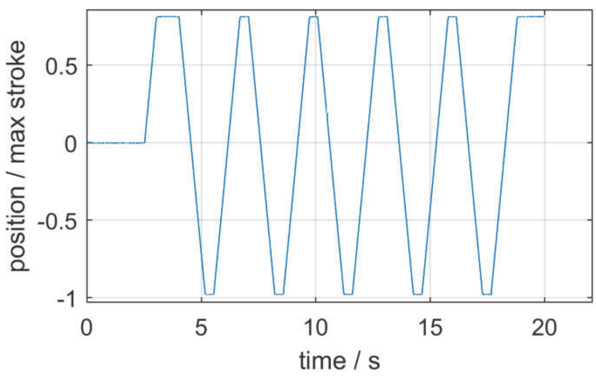

Figure 3. Position change of healthy actuator.

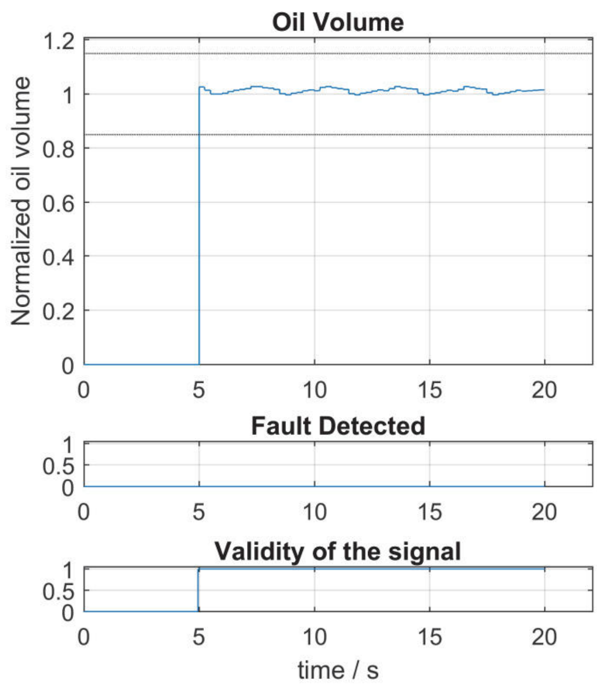

Figure 4. Estimated oil volume (ELV). The dotted lines are the prescribed volume tolerance.

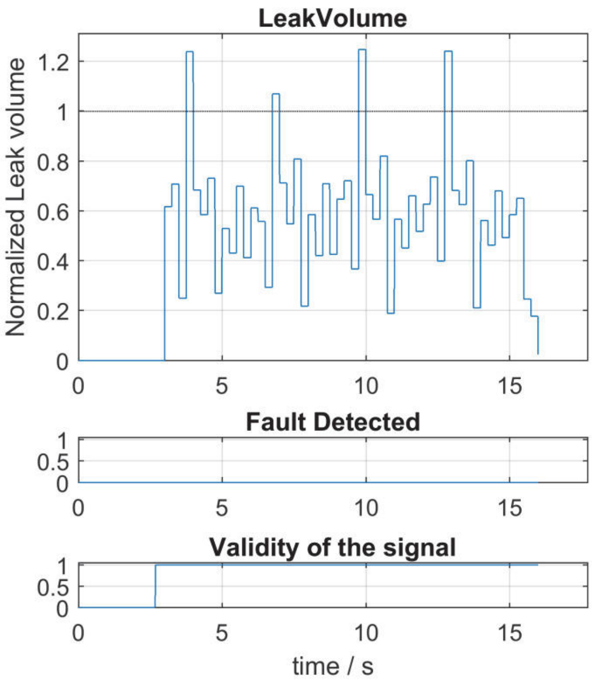

Figure 5. Estimated leak speed (ELS). The dotted line is the maximal allowed leak velocity.

Damaged Actuator

The results of a single measurement with a leak in the actuator can be seen from Figure 6 to Figure 8 (Using measurement "High speed, full stroke"). For the monitoring of the leak, the same algorithms as for the healthy actuator are used, including the automatic initialization routines. As can be seen from Figure 7, the estimated oil volume is out of the specifications. Furthermore, the large variation of the estimated oil volume indicated that a leakage is available. By studying Figure 8, the estimated leak is also much higher than the maximal allowed leakage, leading to an alarm.

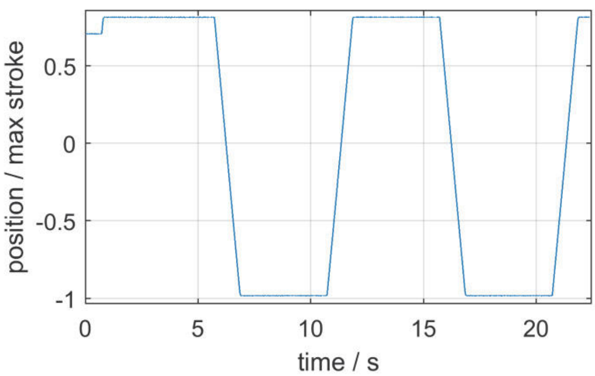

Figure 6. Position change of healthy actuator.

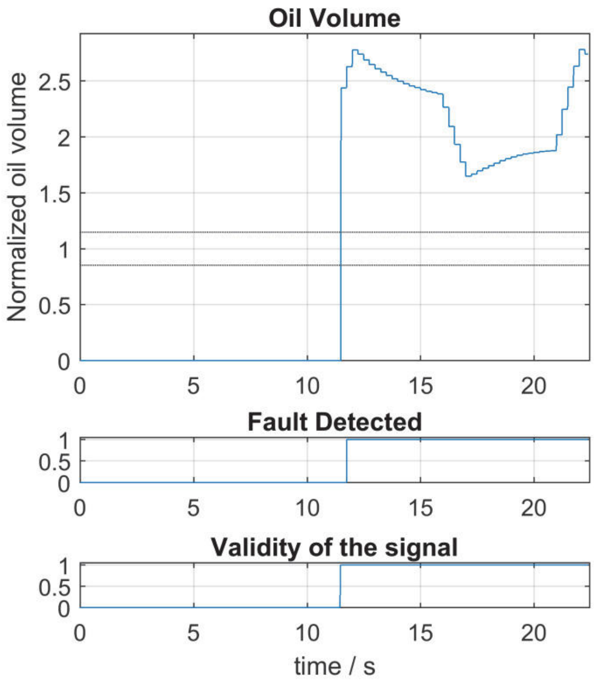

Figure 7. Estimated oil volume (ELV). The dotted lines are the prescribed volume tolerance.

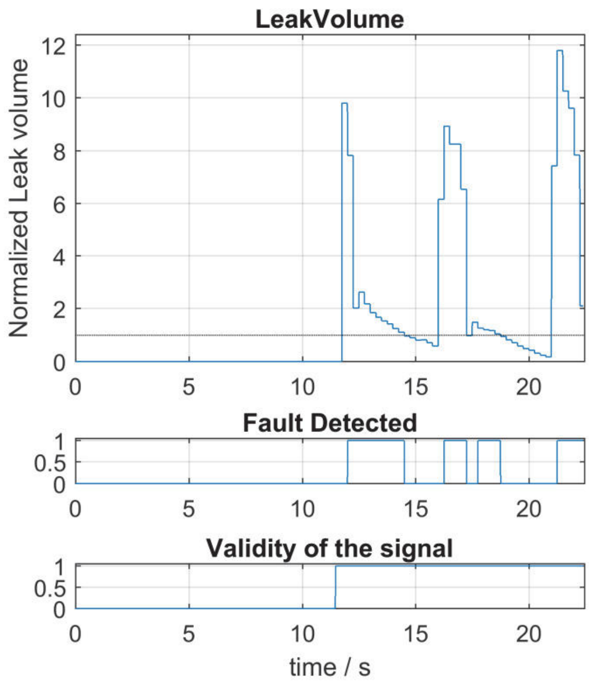

Figure 8. Estimated leak speed (ELS). The dotted line is the maximal allowed leak velocity.

IV CONCLUSION

The proposed pressure-based health monitoring algorithm can detect very early faults that can be caused by insufficient lubrication of the actuator.

In case of a sensor failure, the method is fail-safe as a sensor failure will directly lead to the triggering of an alarm (not proved in this paper). To use the proposed method, an extra pressure and temperature sensor must be included in the actuator. For low failure rates, an integrated pressure-temperature sensor is advised.

The proposed methods can self-initialize, thereby a precise documentation of the lubricant volume, as well as temperature and pressure during fabrication of the actuator can be avoided. Furthermore, the proposed method has alow computational load. The largest part of the algorithms can run on low sample time calculation frames.

The experimental validation of the method shows a 100% detection rate without false positives. Further experiments are needed to prove the reliability of the methods in low temperature environments.

V DISCUSSION

Measuring the air temperature inside the actuator is difficult, as it can change fast due to the compression of the air and most sensors are not capable to measure these fast changes. Furthermore, it is not possible for an inside sensor to be able to avoid measuring errors caused by oil contamination due to oil droplets. Therefore, the temperature that is measured is used as a mixed temperature of air and oil. It is assumed that these temperatures are the same. For slow movements, this will be correct, and for fast movements, the oil is expected to be splattered around by the gears so that a good heat transfer should be possible.

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