Online Flow Estimation for Condition Monitoring of Pumps in Aircraft Hydraulics

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Abstract

Hydraulic systems in conventional civil aviation are currently monitored in a very rudimentary way. Normally, measured values are compared with a fixed threshold. If these measured values are outside the predefined limits, the entire hydraulic system is usually shut down. To overcome this deficit, a study regarding a novel prognostic health management method for aircraft hydraulic pumps, which allows a statement about the pump condition, is presented in this paper. The method is based on measuring differential pressure and temperature at a suitable resistance. In the first part of the study, the overall concept for monitoring the motor pump unit is analyzed. This is followed by a discussion of possible measurement methods and suitable resistors to determine the condition of the pump. In the second part of the study, the implementation for online monitoring of the pump is discussed. After a suitable approximation is found, the quality of the proposed method is evaluated with real hydraulic power generation and consumers.

1. Introduction

Hydraulics play an essential role as a power supply in today's (modern) civil aviation. It can be assumed that due to increasing electrification, new electrohydraulic (eH) systems with high availability will be responsible for the actuation of various aircraft actuators, in form of highly efficient power packages (eHEPP). A simplified illustration of an eHEPP is presented in Figure 1. The eHEPP consists basically of two redundant Electric Motor Pumps (EMPs) and all other relevant components for hydraulic power generation e.g. filters, check valves and manifold (not depicted). A description gives (Trochelmann, Rave, Thielecke, & Metzler, 2017). Each EMP includes a Motor Control Electronics Unit (MCE) and a Motor Pump Unit (MPU).

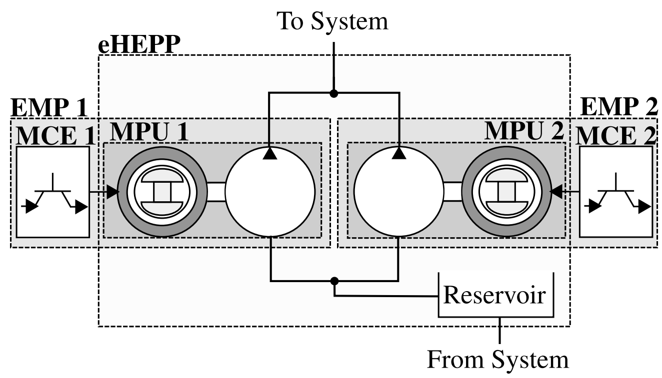

Figure 1. Simplified representation of the eHEPP

As the hydraulic energy generator, the pump is one of the most important components in the system and thus has a significant influence on the availability of the eHEPP, the entire hydraulic system and the flight controls. Current monitoring of EMPs in commercial aircraft is usually carried out by comparing actual values with limit values and does not allow any statement to be made about the condition of the pump. For example, the system pressure or the output pressure of the EMP is monitored by means of a pressure sensor or pressure switch (Poole, 2015). If a fault is detected, usually the entire hydraulic circuit is shut down, which can lead to flight cancellations and higher costs for the airline. To achieve an improvement in reliability, availability and ultimately a reduction in operating costs, it is necessary to implement an enhancement in monitoring of this critical element via Prognostic Health Monitoring (PHM). A possible PHM for aircraft hydraulic pumps is presented in this paper, which is structured as follows.

Section 2 introduces the considered MPU and its overall PHM concept. A brief introduction, assessment and selection of volumetric flow measurement methods is presented in Section 3. The theory behind the selected method is shown in Section 4. The implementation of the method follows in Section 5. Section 6 includes some lessons learned and the conclusion of this study is found in Section 7.

2. HEALTH MONITORING OF THE MPU

The following section discusses the EMP of the eHEPP in more detail. The operating principle of this device will also be explained. In addition, the basic concept for the prognostics and health monitoring of the hydraulic pump is described.

2.1. The Motor-Pump-Unit

Constant pressure hydraulic systems are state of the art in aircraft hydraulics. Typically, hydraulic power is supplied by a pressure compensated axial piston pump (AKP). The pump is driven by the aircraft engine (Engine Driven Pump - EDP) or an electric motor (EMP). The motor of this state of the art EMP (e.g. in the Airbus A320) is supplied with constant frequency current, thus the pump rotates with constant speed. The pressure is then regulated to the desired level with the swashplate of the AKP. This EMP is usually called the fixed speed variable displacement - EMP (FSVD-EMP). In comparison, the EMP presented in this study controls the system pressure by changing the pump speed. Figure 2 shows a simplified representation of the electric motor driven pump prototype.

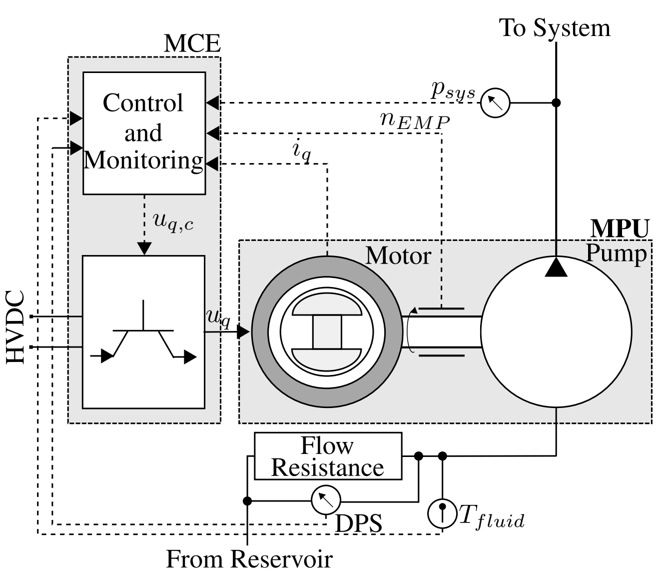

Figure 2. Simplified representation of the VSFD-EMP

The prototype is a variable speed fixed displacement (VSFD)-EMP and essentially consists of three main components. The first component is the motor control electronics (MCE), which in turn consists of a control and monitoring unit and an inverter. The second component is the electric motor, in this case a permanent magnet synchronous motor (PMSM). Finally, the last component is the hydraulic pump, more specifically an internal gear pump (IGP).

As already described the system pressure is regulated by adjusting the pump speed. A baseline pressure control concept is described in (Trochelmann, Bischof, Thielecke, Metzler, & Bassett, 2018). It is a common cascade control concept. In the innermost loop of the control system current is controlled. The speed controller is located in the middle loop. Lastly, the system pressure is controlled in the outer loop. The main measurements and signals needed for pressure control with the EMP prototype are also depicted in Figure 2.

Since the VSFD-EMP must be controlled digitally, the current, speed, and pressure of the system are known. Compared to the state of the art EMP, the Fixed Speed Variable Displacement (FSVD)-EMP, the new concept provides substantially more information than the FSVD-EMP type, especially the MPU speed and its known fixed displacement. Therefore, the new EMP prototype enables new concepts for monitoring the pump condition. This concept is presented next.

2.2. PHM Concept for Motor-Pump-Unit

As previously shown, the HePP includes two redundant MPUs so that the required availability can be met. This does not always mean that both EMPs are active at the same time. At this stage of development, the proposed health monitoring concept assumes that only one EMP is active, though this consideration is heavily dependent of the design of the system. This postulation does not lead to the notion that it is always the same EMP that is active. The active EMP should be changed continuously, e.g., after each flight. This not only reduces the possibility of highly uneven degradation of the MPUs, but also allows health monitoring each second flight which minimizes dormant times.

In general, degradation, which affects performance, of MPUs can be divided into two main categories, (hydro-)mechanical and volumetric degradation, however it has been experimentally proven and it is well known that volumetric degradation is the main failure mode of a hydraulic pump, hence a novel concept for measuring volumetric pump wear is presented in study.

Pump Health Monitoring

Most of the failure cases in the IGP, and in fact in all types of pumps, are reflected in the volumetric efficiency. Due to mechanical wear gaps between the different pump elements become larger, increasing the internal leakage of the pump and consequently decreasing the volumetric efficiency of the MPU. (Rundo & Corvaglia, 2016) present an overview of possible gaps in IGP.

Volumetric efficiency is defined as the quotient of effective flow rate $Q_{\text{effective}}$ and theoretical flow rate $Q_{\text{theoretical}}$

$$\eta_{vol} = \frac{Q_{\text{effective}}}{Q_{\text{theoretical}}}. \quad (1)$$

The theoretical flow is calculated with the MPU-Speed n_{MPU} and the fixed known displacement of the pump V_{pump}

$$Q_{\text{theoretical}} = n_{\text{MPU}} \cdot V_{\text{pump}}. \quad (2)$$

As shown in Figure 2 and with Eq. (2), the theoretical volumetric flow for the VSFD-EMP can be calculated because of the known pump speed and the fixed displacement. By continuously determining the volumetric efficiency, e.g. for predefined operating points (OP), the (volumetric) state of the pump can be compared to the previously defined volumetric efficiency limit $\eta_{vol,lim}$, as seen in Figure 3.

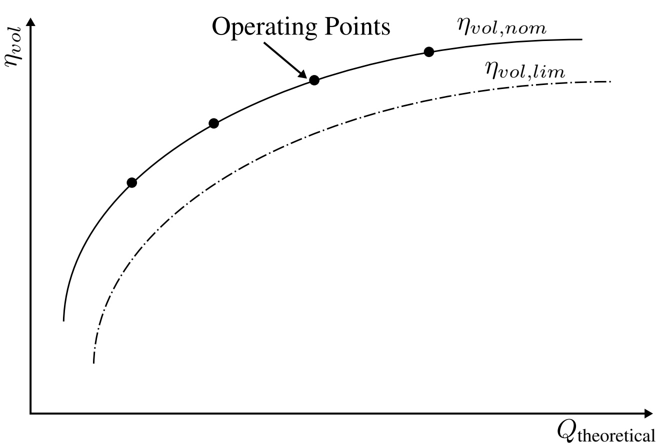

Figure 3. Volumetric efficiency

If the predefined limit is reached the MPU is replaced. Because it is assumed that the EMP is designed as a Line Replacement Unit (LRU), the specific reason for the deterioration in volumetric performance is not determined insitu. The MPU, as an LRU, will be disassembled and examined in more detail offboard in a second step. By checking similar OPs regularly even a prognostic about the pumps remaining remaining safe operating time ($\Delta\tau$), based on the distance between the computed volumetric degradation trend and the volumetric efficiency limit, can be computed. This is shown qualitatively in Figure 4.

The determined efficiency degradation trend of the pump is plotted over the flight cycles. A η_{vol} trend, in form of a (linear-) regression (LR) is then defined. By extrapolating the computed trend, the remaining operating life within safe limits $\Delta\tau$ is computed.

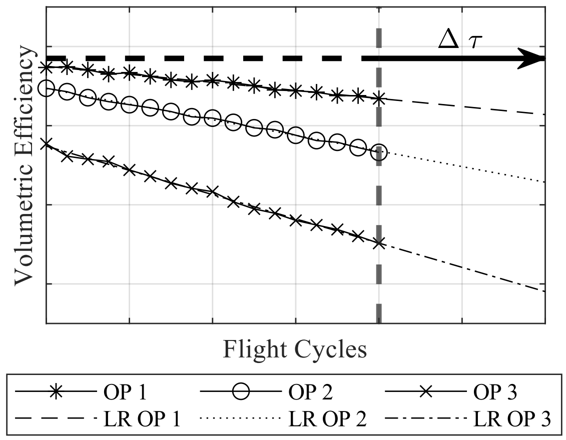

Figure 4. Volumetric efficiency trend for PHM

Furthermore, it should be noted that the theoretical flow can also be determined for an FSVD-EMP, however the position of the swashplate must be known. Consequently, for a FSVD-EMP, an additional sensor with very high accuracy would need to be installed to measure the position of the swashplate. This would increase the overall cost and complexity of the device. Therefore, the introduction of the VSFD-EMP enables a new approach to pump health monitoring.

In contrast to the determination of the theoretical volumetric flow, the determination of the effective volumetric flow is independent of the fixed displacement pump type.

3. Measurement of the Effective Volumetric Flow

As mentioned in the section before, the determination of the effective volumetric flow is critical for pump monitoring. This section gives a brief review of measuring methods. This is followed by an evaluation of the methods for use in aircraft hydraulics. Lastly, the most promising method is presented.

There are many ways to classify flow measurement devices. The classification shown in this study is presented in (Hardy, Hylton, McKnight, Remenyik, & R., 1999) and is based on the method used to extract the information from the fluid system. An overview of the classification and some examples of flowmeters can be seen in Figure 5.

Inferential flowmeters measure a physical quantity other than flow or velocity, whereupon the volumetric flow rate is then calculated. Energy-additive flowmeters transfer energy into the fluid. The effects of the flow on this energy are then used for the flow calculation. The volumetric flow is directly measured with Direct-measurement flowmeters.

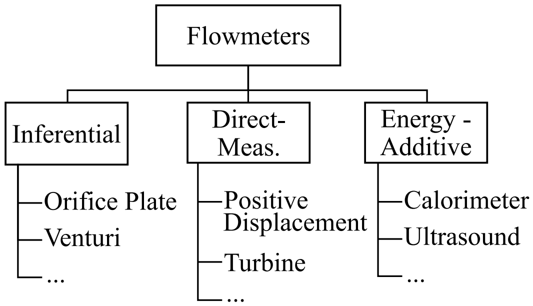

Figure 5. Flowmeter classification acc. (Hardy et al., 1999)

Insitu Measurement

The selection of a volumetric flow sensor for aircraft use is more stringent than for common industrial applications.
There are many possible considerations that must be taken into account, such as price, weight, complexity, and reliability. This study focuses mainly on two aspects. The first is that the chosen method should be approved for onboard use (Insitu Measurement). The second is the suitability of the measurement me-thod within the hydraulic system. This means that under no circumstances should the chosen method interfere with the operation of the hydraulic system itself.

Ultrasonic-based flowmeters, have been successfully tested at the Institute of Aircraft Systems Engineering under laboratory conditions. They do not interfere with the operation of the hydraulic system as they are a non-invasive method of flow measurement, but they are not approved for onboard use. All in all, energy-additive flowmeters require complex electronics which are costly and reduce the overall reliability of the measurement method.

Direct-measure flow meters, such as gear flow meters, are not approved for onboard use and will affect hydraulic fluid operation. Taking a gear flow meter as an example, when the gears fail and can no longer turn, additional resistance is created in the hydraulic system. This results in massive pressure losses that ultimately lead to a system shutdown. To solve this problem, an additional bypass is required, which increases the weight and overall complexity of the system.

Inferential flow meters, such as orifice or venturi flow meters, use a pressure differential to calculate volumetric flow. For example, an orifice plate creates a pressure drop between the upstream and downstream of the orifice plate. By measuring the pressure drop, temperature, and knowing the properties of the fluid under operating conditions, the flow rate is then calculated. The differential pressure sensor (DPS) and temperature sensor have no failure effect on the hydraulic system, as they are not invasive and have no moving parts which can fail. Differential pressure sensors are already used in aerospace to monitor filters and for force fight compensation on Primary Flight Control Actuators for active-active control of surfaces such as the rudder for example (Lauckner & Baumbach, 2010; Spitzer, 2018). Temperature sensors have long been used in aircraft hydraulics. Therefore, inferential flowmeters are theoretically approved for onboard use but installing orifice plates in the hydraulic system is also non-practical because they cause unwanted pressure losses.

Therefore, the choice of a resistance to create a pressure differential and use of this principle to monitor pump condition must be made carefully.

Possible Resistances for Flow Estimation

As mentioned previously, pressure losses on the high pressure side of the system are not desirable. This is true for any aircraft hydraulic system, but the choice of resistance is system dependent. This study considers the scenario of a More Electric Aircraft (MEA) with a distributed eH-system architecture as introduced in (Trochelmann, 2020). A short description of the systems is given.

A center-zone system supplies hydraulic power to the main landing gear (MLG) and the power control unit (PCU), which are the consumers of the hydraulic system. Since the system is active only during short periods before takeoff (slats, flaps extension), after takeoff (MLG and slats/flaps retraction, before landing (MLG and slats/flaps extension), and after landing (slats/flaps retraction), a selector valve with a heating restrictor (Heating Valve) is installed to isolate the loads from the MPU, cf. Figure 6. The heating restrictor generates throttle losses and heats the fluid, e.g. before landing. The heating valve provides a resistance in the system that does not cause pressure losses when hydraulic fluid is directed to the consumers, thus enabling flow measurement. It has to be noted, that this principle can be basically used for every hydraulic system, as long as a valve decouples the consumers from the HePP.

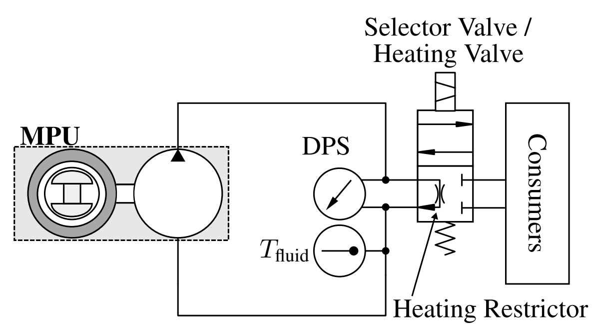

Figure 6. Simplified representation of a center-zone system with heating valve

The tail system consists of an eHEPP that supplies hydraulic fluid to the elevators and a rudder actuator. These consumers are always active and do not require a heating valve. There are no resistances in the hydraulic system that can be used to determine the effective volumetric flow rate. Therefore, as an alternative to the heating valve, a flow resistance is built into the eHEPP itself. The flow resistance can be placed, for example, between the reservoir and the suction port of the pump. This is shown in Figure 2 as a generic flow resistance. The resistance creates the necessary pressure drop to be able to estimate the effective volumetric flow.

Comparison of Resistances

There are two main differences between the two possible presented resistances. The first difference is the method of calculating the flow rate. On the one hand, the heating valve has known characteristics, so the calculation is simple. The calculation can be done with the usual orifice equation

$$Q_{HV} = \alpha \cdot A \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho(p, T_{\text{fluid}})}}, \quad (3)$$

where α is the flow coefficient, A is the orifice area, Δp is the pressure difference, and ρ is the density of the fluid. On the other hand, it is assumed that the flow resistance has a complex geometry, which makes the calculation of the volumetric flow cumbersome. The second difference is that the heating valve is part of the hydraulic system, while the generic flow resistance is part of the eHEPP. This makes the flow resistance system independent, which is a significant advantage over the heating valve. Therefore, the flow resistance within the eHEPP is chosen for flow estimation. In order to overcome the challenge regarding the computation of the volumetric flow, a different approach is taken, which will be discussed in the next section.

4. Volumetric Flow Estimation with the Flow Resistance

The characterization of the flow resistance is one of the most relevant steps for the flow estimation. Because the characterization is performed experimentally, the test rig at the Institute of Aircraft Systems Engineering (FST) of the Hamburg University of Technology (TUHH) is introduced. This is followed by the actual characterization.

4.1. System-Test Rig

The system test rig is shown in Figure 7. It consists of two separate component test rigs. On the first test rig (eHEPP test rig), two parallel VSFD MPUs are installed. Each pump has a separate high pressure and suction line. This test rig also has other relevant power generation components such as reservoir, check valves, relief valves and filters. As described in the previous section, a servo valve for load emulation is also present in this test rig. The second test rig represents the hydraulic consumers of the tail section of the aircraft. It includes two elevators and one rudder of the aircraft. These are supplied with hydraulic fluid from the eHEPP test rig.

Each test stand has its own control unit. For data exchange and synchronization, the control models are connected via a CAN bus system. The data is then recorded centrally in the control unit of the eHEPP test rig.

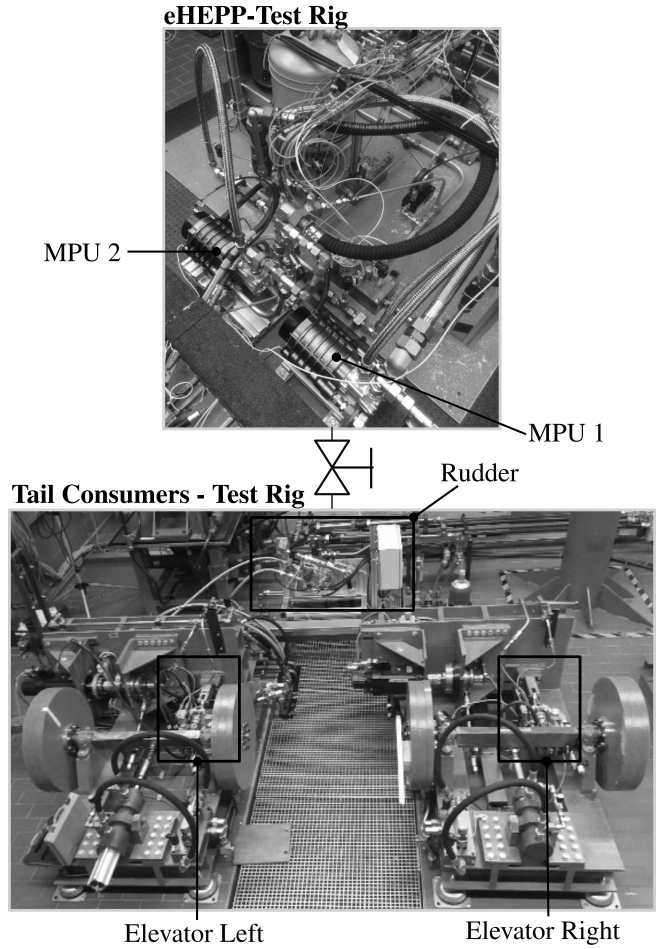

Figure 7. System-test rig at FST

4.2. Characteristic Map of the Flow Resistance

Similar to the heating valve, it can be assumed that the pressure losses in the flow resistance depend on the viscosity and density of the fluid. Both properties depend on the pressure and temperature of the fluid itself. Therefore, a flow calculation with a known analytical solution is not straightforward. The chosen solution to this problem is to measure the characteristic map of the flow resistance. This approach implicitly takes into account the properties of the fluid and their effect on the pressure difference.

The determination of the characteristic map is carried out with the eHEPP test rig at the FST with a MPU. Several operating points of the EMP are set with the load servo valve.

The aim is to achieve a homogeneous distribution of the calibration points in form of

$$Q_{\text{effective}} = f(\Delta p, T_{\text{fluid}}). \tag{4}$$

The differential pressure Δp, fluid temperature T_{fluid} and volumetric flow rate $Q_{\text{effective}}$ are measured over a period of approximately five seconds. Table 1 shows the properties of the used sensors.

Table 1. Accuracy of sensors

Measurement	Sensor	Accuracy
Differential Pressure Sensor	Δp	$\pm 0.2\%$ FS
Temperature Sensor	T_{fluid}	$0.5°C$
Volumetric Flow Sensor	$Q_{\text{effective}}$	0.3% of meas. value

It should be noted that the volumetric flow is measured with a gear flowmeter mounted on the high pressure side of the system. For each operating point, the average value of pressure, temperature and volumetric flow is calculated. This results in a characteristic map of the chosen flow resistance, as shown in Figure 8.

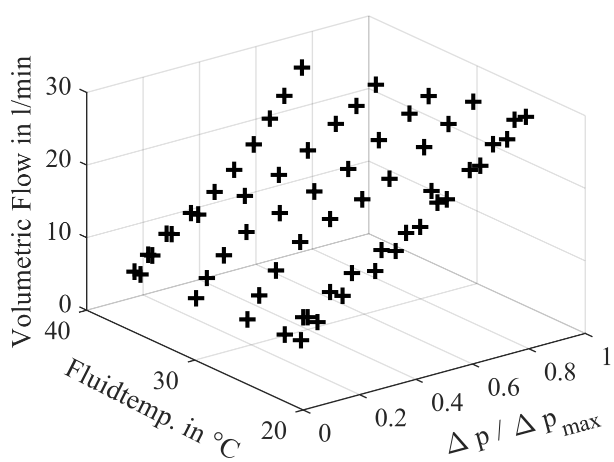

Figure 8. Calibration data

The temperature dependence of the pressure losses can be clearly seen. Especially at higher flow rates, the pressure drop is lower at higher temperatures. This is to be expected due to the lower viscosity and density of SKYDROL at higher fluid temperatures.

An initial assessment of the chosen method for determining the effective volumetric flow is the total measurement uncertainty for each measurement $\sigma_{total,x}$, where x stands for the differential pressure measurement, the fluid temperature or the volumetric flow. This is composed of the standard deviation of the mean $\sigma_{\bar{mw}}$ and the sensor uncertainty σ_S

$$\sigma_{total,x} = \sqrt{\sigma^2_{\bar{mw}} \cdot \sigma^2_s}. \tag{5}$$

Low total uncertainty values are achieved for all calibration points and all measurements. Therefore, the calibration points can be used for the calculation of the volume flow. However, using individual measurements as a map to determine the flow rate can lead to inaccuracies (e.g., interpolation and extrapolation). A suitable method to approximate the points, reduce the inaccuracy and avoid large computational capacities is still necessary. This would also enable the online implementation of the monitoring concept.

4.3. Approximation of the Characteristic Map

There are several methods to approximate the calibration data for online flow estimation. The various approximation methods are examined using the *Matlab Curve Fitting Toolbox*. Many options are available to evaluate the goodness of fit, e.g. statistics, residual analysis, confidence and prediction bounds. On the one hand, statistical analysis and confidence bounds are numerical methods for determining the goodness of fit. On the other hand, residual analysis and prediction bounds are graphical methods. Depending on the data and the fitting requirements, a suitable method of approximation and evaluation is chosen.

In this case, a simple, easy-to-understand model is desired. Since it does need not have physical meaning, a polynomial approximation is chosen. For the evaluation, a simple residual analysis is performed. The reason for this selection is that this method makes it simple to evaluate the effects of the approximation on the monitor. For example, a deviation between calibration data and approximation at low volumetric flows leads to a large relative error. The same deviation leads to small errors at high volumetric flows. A residual analysis is therefore used for an initial evaluation of the chosen polynomial. Figure 9 shows the calibration data with the selected area fits.

As can be seen in the figure, the calibration data were approximated using two surface fits. The reason for this is that the approximation of all calibration points with one surface (one fit) did not meet the main requirement, particularly large errors were obtained for small volumetric flow rates. A better overall approximation is achieved with two separate approximations. For this purpose, the calibration data is divided into two sets. The first set contains all calibration points with a normalized pressure drop of approx. 0.25 or less. The second set contains all other values. It has been shown that a bivariate polynomial with a total degree of three is a good approximation for the available low and high volume flow data. The two variables are the pressure difference Δp and the outlet temperature T_{fluid}. However, the coefficients of the polynomials differ.

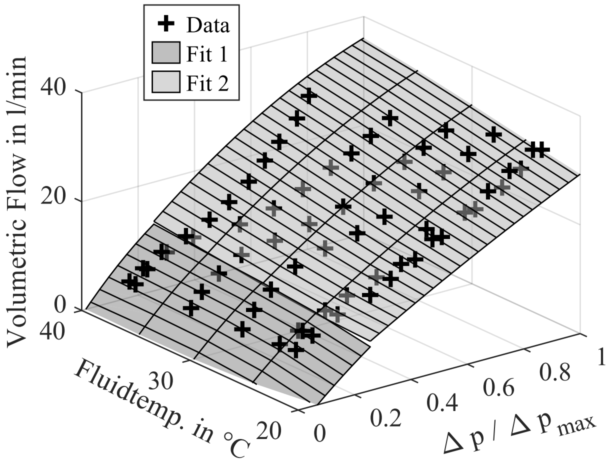

Figure 9. Characteristic map of the flow resistance

The residual analysis for all fluid temperatures is shown in Figure 10.

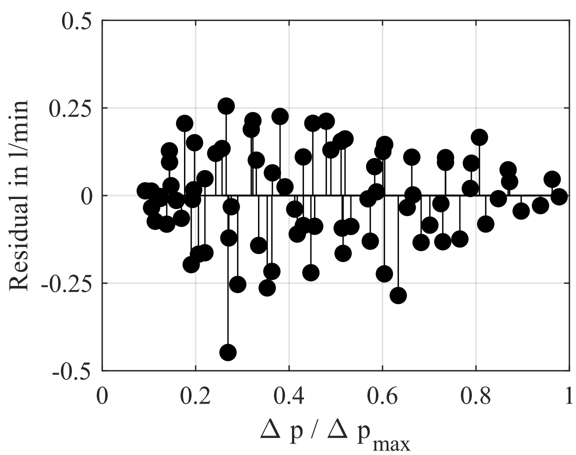

Figure 10. Absolute error calibration data-polynomial

For low pressure drops, the maximum residual value is less than $0.25\frac{l}{min}$, resulting in a relative error of less than 5%. For higher flow rates and higher pressure drops, a similar residual value can be found, resulting in a much smaller calculated error approx. 1% . The created characteristic map of the flow resistance is then implemented.

5. Online Flow Estimation

The approximation chosen in Section 4 is implemented in the control model of the eHEPP test rig, allowing the online computation of the volumetric efficiency of the MPU 2. The results of a test campaign with the real consumers are shown in this section.

5.1. Pump PHM with Real Consumers

In a system with real consumers, the operating points with low dynamics, which is expected to deliver a more accurate estimation of the volumetric flow, depend on the system. For example, in the blue hydraulic system of the A320, the extension of the slats before takeoff and the compensation of leakage during cruise are suitable operating points for volumetric flow estimation. In contrast, for the tail system, only the compensation of leakage during cruise is suitable. To be able to set other operating points, a targeted procedure of the actuators is an alternative. This could be implemented as an automatic pre-flight test. Now it has to be checked up to which actuator speeds, suitable operating points for volume flow estimation are reached (quasi-stationary states). This is checked on the FST System test rig.

Table 2 shows the selected profiles of the actuators for the investigation of estimation based on the pressure drop across the selected flow resistance. The operating points cover different load flow rates by varying both the combination of actuators and the rate of change. This can be changed depending on the OP to be monitored.

Table 2. Possible operating points for pump condition monitoring

Time	**OP 1**	**OP 2**	**OP 3**	**OP 4**	**OP 5**
$x_{\text{cmd,elevators}}$ in mm	20	-40	20	-40	20
$v_{\text{elevators}}$ in mm/s	15	30	40	40	40
$x_{\text{cmd,rudder}}$ in mm	11	11	11	55	-35
v_{rudder} in mm/s	0	0	0	30	88

The profiles are selected so that the movement of the consumers (elevators and rudder) ends simultaneously. This reduces dynamic effects and achieves homogeneous curves. OP 5 corresponds to the operating point where the maximum volumetric flow due to movement of the actuators is achieved.

For the evaluation of the flow estimation, the measurement data is first filtered with a low pass filter

$$H(s) = \frac{1}{1 + \frac{s}{w_c}} \tag{6}$$

where ω_c represents the cutoff frequency. The cut off frequency is chosen so that measurement noise is suppressed but the dynamics of the system are not. The characteristic map is implemented in the test rig control model. Similar to Figure 2 the differential pressure, fluid temperature and pump speed is used to compute the volumetric efficiency.

The results of the investigation are shown in Figure 11. The figure shows the position of the actuators, the online volumetric flow estimation and the calculated volumetric efficiency. For the volumetric flow rate and volumetric efficiency, the estimate is compared with the gear flow meter.

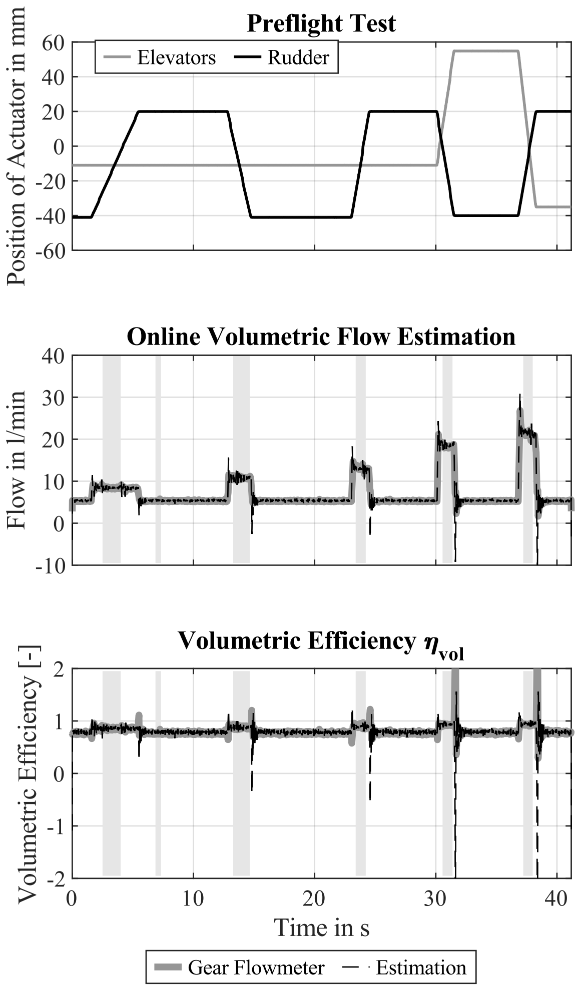

Figure 11. Comparison flow estimation vs. flowmeter with real consumers

The chosen approximation with the two polynomials shows the desired behavior. For small and large volume flows, the approximation achieves high accuracy. This is particularly evident for quasi-stationary and less dynamic operating points and are marked by a light gray background.

Large differences between the estimated and the measured flow are observed when much higher dynamics are present. The main reason for this is the different installation position of the DPS and the gear flow meter. While the DPS is located in the suction line, the gear flow meter is installed on the high pressure side of the system. The effects of the inertia of the fluid becomes particularly apparent when the pump speed is drastically reduced (the actuators reach the desired set position). Because negative pressure differentials are achieved, the results are to negative flow rate estimates. A similar effect also occurs when the pump is accelerated (the actuators start to move). In this case, high pressure differences are measured and higher volume flow rates are estimated. Nevertheless, this is not an indication of an erroneous estimate. The errors that occur in highly dynamic processes are caused by the position of the DPS and the working principle. To be noted here is, that the tracking of volumetric pump efficiencies is not required in all states including transients. The tracking is essential in the quasi stationary main operating points of the hydraulic system, which indicates the pump wear sufficiently.

Lastly, similar to the section 2.2, the volumetric efficiency for the different OPs are calculated. For this purpose, the mean value of the volumetric efficiency during (mostly) quasistationary phases is computed. The result are shown in Figure 12.

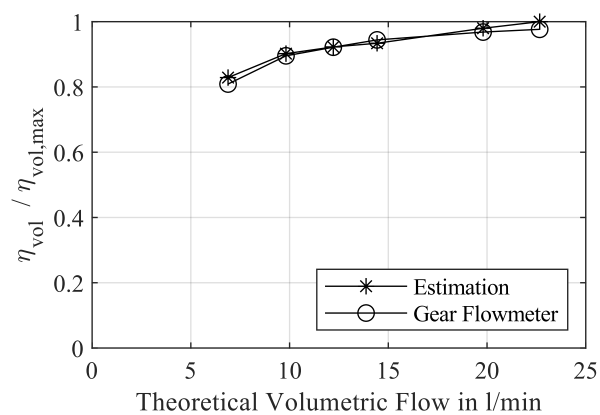

Figure 12. Comparison of pump efficiency: estimation vs. gear flowmeter

The figure shows the results for the gear flowmeter and for the estimation. As it can be seen the characteristic curves match well. This means that the chosen method for the estimation of the volumetric flow can be used for the monitoring of the condition of the hydraulic pump in aircraft hydraulics.

6. Lessons Learned

In this section some of the lessons learned during this study are summarized.

Integration of DPS: The sensitivity of the integration of the DPS was also investigated in this study because there are two MPUs in the EMP test rig. Some small changes in the integration of the DPS between two MPUs lead to large differences in the estimated volumetric flows. Therefore, an optimal integration of the DPS is strongly recommended.

Inaccuracy for low volumetric flows: Depending on the objective for determining the efficiency (low or high volume flows), the quality of the approximation must be taken into account. As already described, an approximation with high residuals leads to significantly higher errors at low volumetric flows.

Measurement of Actuator Leakage: The proposed method allows not only to determine the volumetric efficiency of the pump, but also to determine the internal leakage of the Control Servo Actuators (CSA). Depending on the mode (active or inactive) of the actuators, the internal leakage of all active actuators can be determined. Even if the CSA with higher leakage cannot be isolated, the process of isolation can be accelerated.

7. Conclusion

In this paper, a new concept for pump health monitoring is proposed. The concept is based on the insitu estimation of the effective volumetric flow. The estimation leads to the calculation of the volumetric efficiency, which is then used to determine the volumetric pump efficiency with the known speed and displacement. In the first section, various options for determining the effective volumetric flow rate were analyzed with respect to their application in an aircraft hydraulic system. It was found that none of the conventional methods can be used in aircraft hydraulics, but the rugged and well mature principle with high reliability of measuring differential pressure and fluid temperature in aerospace may be employed. The main challenge in this instance is to find the appropriate resistance. In this case, a generic flow resistance was used. The main advantage of such a resistance is the system independence. Depending on the resistance, the corresponding pressure drop and desired accuracy, the choice of a suitable pressure sensor is very important.

In the second part, the implementation of online flow calculation is presented. For the estimation, the characteristic map of the resistance is determined. This is performed experimentally. The data is used as calibration points for the characteristic map, which is approximated using two higher order polynomials. The approximation is the basis for the online implementation. It has been shown that the quality of the approximation significantly affects the accuracy of the estimate. High accuracy is especially required for small volume flows. Finally, the online estimation of volumetric efficiency was tested with real aircraft consumers. The estimation shows high accuracy in an ideal test (load servo valve) and with real consumers.

The tests performed so far were done with an MPU that shows no degradation. Although the initial results are very promising, the TUHH Institute of Aircraft Systems Engineering intends to test the monitor with a custom-built test rig that emulates pump degradation. In addition, the limits for the volumetric efficiency as well as the influence of the fluid temperature will be determined. The presented PHM method uses an additional sensor (DPS) to determine the condition of the pump and since there are no available options yet known without an additional sensor, alternative solutions for this method will be investigated.

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