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LEAKAGE DIAGNOSIS FOR ELECTRIC MOTOR PUMPS IN AIRCRAFT HYDRAULIC SYSTEMS

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Abstract

In the present paper, the effect of internal leakages of an aircraft hydraulic system's electric motor pump is investigated model-based. This investigation is performed in the context of the development of a fault diagnosis system for aircraft hydraulic power distributions systems. For that reason, a detailed physics-based model of the pump is developed in AMESim. This allows simulating the effect of the deterioration of specific components of the pump.

Based on the model, it is analysed how the individual faults of the pump components that lead to internal leakages affect the overall pump performance. For this, the pump characteristic line is considered. It is shown that the pump characteristic line can be used to diagnose the extent of internal leakages.

A concept for a robust and cost-efficient on-board diagnosis system is presented. In this context, sensor implementation aspects are discussed as well as the operating points of the pump, which are required for the diagnosis of the pump's internal leakages.

1. INTRODUCTION

In order to avoid operation interruptions of aircraft due to unforeseen hydraulic system failures, a fault diagnosis system is required. Such a system enables an early detection of impending failures and thus allows the accomplishment of respective maintenance actions in advance. The joint research project ProReB [1], which is funded by the German aviation research programme LuFo IV, 2nd call aims at the development of such a system.

In the context of the development of a fault diagnosis system, it is necessary to investigate the impact of the deterioration of the individual components of the hydraulic system. By this, conclusions can be drawn concerning the detectability of such deteriorations on system level [2]. For this reason, a detailed physics-based model of a pressure-regulated electric motor driven axial piston pump is modelled in the simulation programme AMESim.

The focus of this model is the volumetric part of the pump and includes besides the usual submodels of the individual pistons, the hydro-mechanically operated control mechanism of the swash plate. To permit the analysis of the impact of leakages, special attention was paid for the modelling of internal leakage gaps.

Based on the model it is analysed, which impact leakages have on the overall operation behaviour of the pump, which is characterised by the pump characteristic line. The analysis is performed in order to find indicators that can be used for the diagnosis of the pump internal leakage. For these indicators, approaches are developed for the diagnosis of the extent of the leakages.

Other approaches such as e.g. [3] or [4] use vibration analyses in order to detect early stages of pump faults. In [5] the pressure pulsation is used for the detection of leakages. However, besides the power of these approaches, they require high frequency signal acquisition and a careful adjustment of the respective algorithms. The present paper aims at a robust approach, which is cost-efficient. For this reason, the focus is on the analysis of the pump characteristic line. A similar investigation has been carried out in [6]. Here, respective measurements have been performed on deteriorated industrial axial piston pumps. However, because the aircraft electric motor pump differs from that industrial pump especially concerning the hydro-mechanical pressure control, the conclusions of [6] cannot be transferred directly. This also motivates the model-based approach described in this paper.

This paper is organised as follows. In section 2 the functionality of the considered electric motor driven axial piston pump with hydro-mechanical pressure control is explained. A rough description of the corresponding physics-based model in AMESim is given in section 3. In section 4, this model is used to analyse the influences of internal pump leakages in the pump characteristic line and meaningful indicators are identified. Approaches for the diagnosis of the extent of the internal leakage are discussed in section 5.

2. AIRCRAFT ELECTRIC MOTOR PUMPS

Modern transport category aircraft are equipped with several hydraulic power distribution systems in order to provide power to consumers such as flight control actuators or the landing gear. The required hydraulic flow is usually provided by axial piston pumps. These are either directly driven mechanically by the aircraft engines, or by electric motors. The amount of discharged flow of these pumps is controlled hydro-mechanically in order to achieve an almost constant pressure level (usually 3000 or 5000 psi) in the hydraulic systems.

2.1. Function of Axial Piston Pumps

Axial piston pumps mainly consist of the axial pistons, which are fitted into a revolving barrel, see FIGURE 1. The pistons are free to move in axial direction and are equipped with piston shoes. These are supported by the swash plate, which forces the piston to stroke in the barrel as soon it revolves. The range of the stroke depends on the angle of the swash plate. The port plate connects the chambers, which are formed by the individual pistons and barrel, to the suction or discharge port, respectively. By this, the pistons allow the inlet of fluid while the chamber length is increasing and a connection to the suction port is established. In turn, the pistons will discharge the fluid to the discharge port while the chamber length is decreasing and a connection to the discharge port is established. As a consequence, a discharge flow Q is established, which is proportional to the rotational speed of the barrel n, the relative swash plate adjustment β, the volumetric efficiency η_{vol} and the theoretical maximum discharge volume V_{th} of all pistons during one revolution,

$$Q = n \cdot \beta \cdot V_{th} \cdot \eta_{vol} \quad . \tag{1}$$

2.2. Hydro-Mechanical Pressure Control

In order to achieve the desired pressure level in the hydraulic system, the discharge flow of the pump is controlled hydro-mechanically. For this, according to equation (1) it is meaningful to control the swash plate adjustment β. Usually, the actual system pressure is used to provide a resulting force, which counteracts against the swash plate spring that intends to swivel out the swash plate, as depicted in FIGURE 1. The spring force is adjusted so that as soon the system pressure has reached its nominal value, the swash plate will move back in order to decrease the discharge flow to an amount that just compensates the consumed flow. As the flow consumption of the system increases, the system pressure will decrease. This will force the swash plate to swivel out and the flow is increased in order to compensate the flow demand.

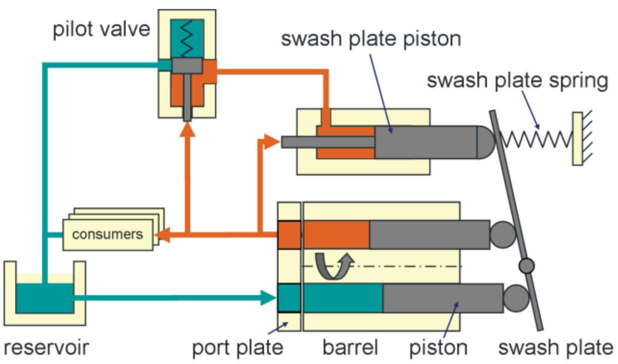

FIGURE 1: Pressure controlled axial piston pump

Due to the stiffness of the swash plate spring, the pressure will not be kept exactly to a constant pressure; instead, the pressure will decrease slightly with increasing flow demand. This effect is represented by the pump characteristic line, as depicted in FIGURE 2 However, especially for electric motor pumps, it is desirable to limit the maximum power that can be consumed by the pump. This allows to limit the motor size and thus saves weight. For this reason and because the hydraulic power is the product of the pressure and flow, for high flow demands the pressure that shall be kept by the pump is reduced. This so-called soft cut-off characteristic also can be observed in FIGURE 2.

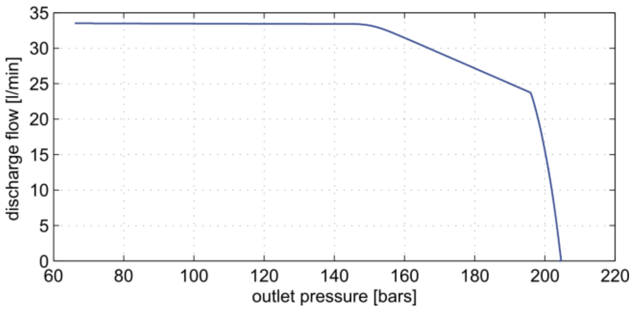

FIGURE 2: Nominal pump soft cut-off characteristic line

This soft cut-off characteristic is also achieved by a hydro-mechanical pressure control. For this, usually an additional pilot valve is used [7]. This pilot valve acts as a spring loaded pressure compensator. It augments the functionality of the said swash plate piston for a certain pressure range. The respective functional scheme is also depicted in FIGURE 1.

2.3. Internal Leakages

Axial piston pumps have internal leakages at several positions. These are essential for lubrication and cooling purposes, but reduce the volumetric efficiency η_{vol} of the pump. The amount of the internal leakage and thus η_{vol} is not constant. On the one hand, it depends on the operating point of the pump, especially the system pressure [8]. On the other hand, gaps and clearances may change due to pump deterioration [6]. For fault diagnosis, especially the latter effect is of interest.

Within this paper, the effects of the internal leakages at the following positions are investigated:

- at the annular gap of the pistons
- at the port plate
- at the swash plate piston

The leakage flow is drained from the pump housing, the so-called case, through the case drain line back to the reservoir.

In terms of fault diagnosis, it has to be investigated, how a deterioration driven seizure of the respective leakage points influence the pump overall behaviour. On this basis, meaningful indicators and fault diagnosis rules can be developed. In order to conduct the investigation, it is meaningful to use a detailed physics-based model of the pump. By this, several effects can be studied without causing damage to a real pump.

3. MODELLING OF THE PUMP

The modelling of the pump is conducted with the 1D–system simulation tool LMS Imagine.Lab AMESim. Here, pre-defined submodels of different domains (such as mechanical, hydraulic, etc.) can be combined to the system under investigation. The interfaces between submodels allow a bi-directional exchange of physical energy (i.e. flow and pressure in the hydraulic domain) in accordance to the bond graph theory. Thus, this programme allows a straight forward modelling of physics-based models.

In this paper, the focus is on internal leakages of the pump. Therefore, the model is limited to the volumetric related part of the pump. This includes the individual pistons, the swash plate, and the swash plate control mechanism. However, frictions of the pistons or the main shaft of the pump are related to the hydro-mechanical part of the pump and are not considered in detail. The main modelling approach is based on the respective solution example of AMESim for an axial piston pump.

3.1. Axial Pistons

Each piston is modelled as individual submodel as depicted in FIGURE 3. The core is the moving piston with a mechanical link to the swash plate. Due to the movement of the piston, the height of the piston chamber varies. This chamber is hydraulically connected to the high-pressure port (HP) or the low-pressure port (LP). In reality, this connection is controlled by the port plate. Here, the functionality of the port plate is modelled signal based as a function of the barrel angle, modulated to 360°. In addition, the relevant leakages are modelled in accordance to [8].

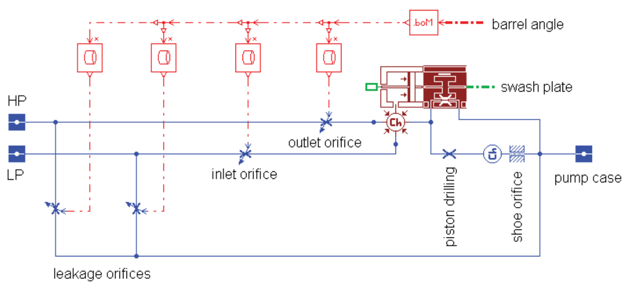

FIGURE 3: AMESim submodel of an axial piston

The annular gap of the piston is represented by a respective AMESim submodel, which provides a connection between the piston chamber and the case chamber of the pump. The flow Q_l through this annular gap at a given delta pressure Δp is calculated by

(2) $$Q_l = \frac{\pi}{6 \cdot \eta} \cdot \frac{\Delta p}{l} \cdot \frac{d}{2} \cdot h_K^3 \quad ,$$

with the kinematic viscosity of the fluid η and the diameter of the piston *d*. As a simplification, the length *l* of the gap is assumed constant. In reality, this is not the case, but the simplification is suitable for the purpose of the model. The radial clearance of the piston h_K is varied in order to simulate the deterioration of the piston.

For lubrication, the piston shoes are equipped with an axial drilling. The shape of the shoe surface leads to a hydrostatic support of the shoes on the swash plate. In the model, the respective flow is modelled as a laminar orifice with a specific height.

The port plate leakage is represented by variable orifices between high-pressure port and pump case, and pump case and low-pressure port, respectively. The intensity of each leakage depends on the position of the piston outlet bore in relation to the high-pressure port and low-pressure port. Thus, like the functionality of the port plate, the port plate leakage is represented by a variable opening of the orifices as a function of the modulated barrel angel. In order to simulate an increase of the port plate leakage, the maximum opening of the orifices is alerted by the parameter h_B, which represents the height of the gap.

3.2. Swash Plate Control

As described in section 2.2, the swash plate angle is controlled hydro-mechanically. This mechanism is modelled by two pressure compensators representing both, the pilot valve, and the swash plate piston, see FIGURE 4.

Here, the pilot valve is a pressure compensator between the high-pressure port and the pump case pressure. In addition, a spring load is modelled. Depending on the position of the valve, a connection between the high-pressure port and the control pressure port or between the control pressure port and the pump case pressure is established. The respective opening characteristic is represented by look-up tables.

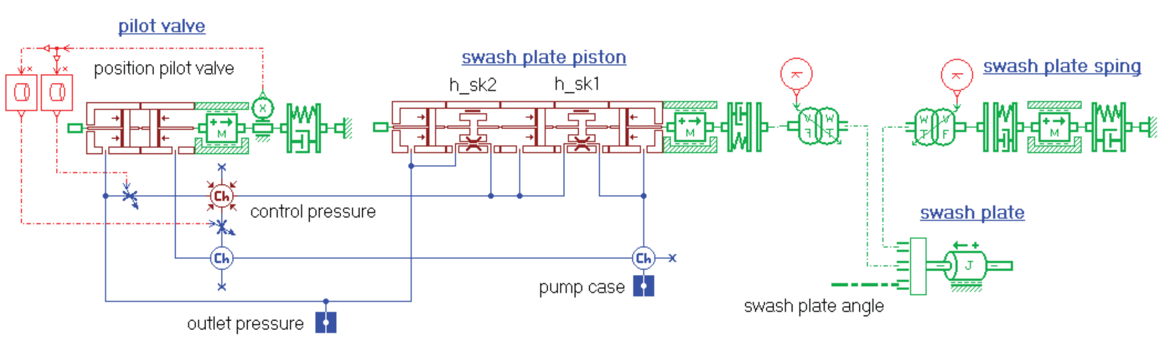

FIGURE 4: AMESim submodel of the swash plate control

The swash plate piston is modelled as a pressure compensator between the high-pressure port and the control pressure port on the one side, and the pump case pressure port on the other side. The swash plate piston is pushed against the swash plate in order to reduce its angle. This movement is opposed by the swash plate spring.

According to equation (2), annular gaps are modelled between the control pressure port and pump case pressure, as well as between high-pressure port and control pressure port. The radial clearances are adjusted by the parameters h_{SK1} and h_{SK2}, respectively.

3.3. Piston Kinematics

The axial velocity v of each piston is calculated in dependence of the swash plate angular velocity α' and the barrel angular velocity θ'. In AMESim, a specific submodel is provided that represents the respective equation for v,

(3) $$v = -R \cdot \alpha' \cdot \cos\alpha \cdot \cos\theta - R \cdot \theta' \cdot \sin\alpha \cdot \sin\theta \quad ,$$

where R is the radial distance between the piston axis and the axis of rotation of the barrel. The axial position of each piston is derived by the integral of equation (3), considering the respective initial value θ_{0i} of the barrel angle, which depends on the index i of the respective piston and the total piston number n,

(4) $$\theta_{0i} = \frac{i \cdot 360°}{n} \quad .$$

3.4. Validation of Nominal Pump Behaviour

The model parameters have been derived from drawings and specifications. By this, most of the parameter values were known, even though especially clearances are specified within a certain tolerance range. Unknown parameter values were tuned in order to achieve the specified nominal pump behaviour. This nominal behaviour is mainly characterised by the pump characteristic line under several boundary conditions and the amount of the case drain flow.

4. ANALYSIS OF LEAKAGE INFLUENCES ON PUMP BEHAVIOUR

In the following, the influence of internal leakages on the overall pump behaviour will be analysed model-based. As the model is physical motivated, the deterioration of the pump components can be represented by the variation of the respective model parameters. Within this paper, the focus is on the variation of leakage related deterioration.

4.1. Annular Axial Piston Gap

The deterioration of the pistons may lead to an increase of the radial clearance of the piston in the bores of the barrel. As discussed in section 3.1, this is represented by variation of the parameter h_K. In FIGURE 5 the effect of the increase of the radial clearance of all pistons on the pump characteristic line is depicted. Starting from the nominal value of the clearance, the value was increased to 600% and 1100% of the nominal value. It can be observed, that with increasing clearance the slope in the area of the maximum discharge flow is affected. In addition, the soft cut-off part of the line is moved towards lower flow rates. The intersection between these two areas is moved towards higher pressures.

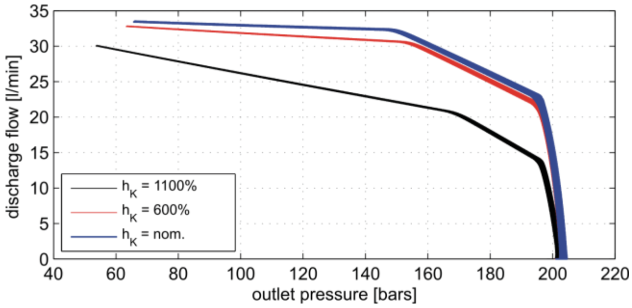

FIGURE 5: Effects of axial piston leakage

4.2. Port Plate

The deterioration of the port plate, e.g. due to cavitation erosion may lead to an increased leakage. As discussed in section 3.1, this can be simulated by increasing the values of the parameter h_B. As depicted in FIGURE 6, the nominal value was increased stepwise up to 1100%. The pump characteristic line is influenced similar to the increasing annular piston gap. The difference is that the influence is more distinct and that the intersection between soft cut-off and maximum discharge flow area remains at the nominal pressure.

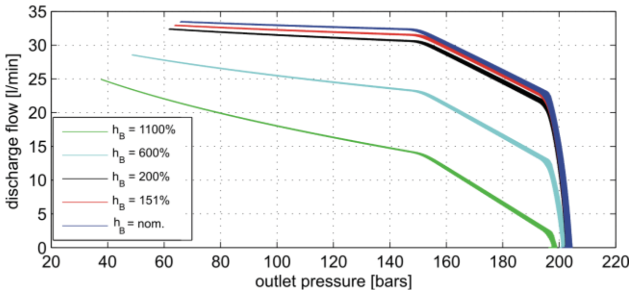

FIGURE 6: Effects of port plate leakage

4.3. Swash Plate Piston

The effect of the deterioration of the swash plate piston is simulated by the increase of the annular gaps, as described in section 3.2. This is achieved by variation of the parameters h_{SK1} and h_{SK2}. These two parameters have been increased simultaneously to 600% and 1100%. The effect on the pump characteristic line is depicted in FIGURE 7. It can be observed that a considerable effect only occurs for parameter values of more than 600%. The resulting effect is similar to the preceding cases, with the exception that the intersection between soft cut-off and maximum discharge flow area is moved towards lower pressures. In addition, an instable operation occurs if the gap is very large and the pump discharge flow is almost zero.

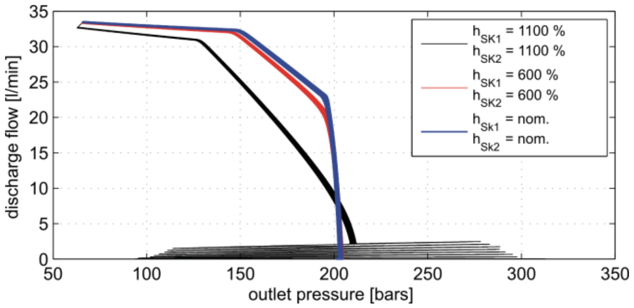

FIGURE 7: Effects of swash plate piston leakage

4.4. Conclusions on Leakage Diagnosis

It could be shown, that the extents of the different internal leakages have a certain influence on the pump characteristic line. For small extents of the leakage, only the area of the line is affected, where it is nearly horizontal, i.e. for maximum discharge flows of the pump. As the leakage increases, also the soft cut-off part of the pump characteristic line is affected considerably. Here, it can be stated, that a given discharge flow leads to a lower outlet pressure and vice versa. Thus, the maximum power of the pump is decreased. In addition, the point where the constant pressure part of the characteristic line, i.e. the part with the nearly vertical line, reaches the soft cut-off part is moved to smaller discharge flows.

Consequently, the shape of the pump characteristic line can be used as an indicator for the extent of the internal leakage of the pump. However, the change of the responsible component size or clearance has to be significant enough in order to be detectable.

This, in turn, is acceptable in terms of maintenance. If the degradation of the pump is not significant enough to be detectable, it will not have a significant influence on the pump performance and no maintenance action is required. However, in terms of early fault detection, it is desirable to detect impending failures as early as possible and thus during the smallest fault extent as possible.

5. APPROACHES FOR LEAKAGE DIAGNOSIS

As described in section 1, the intention is to detect an impending system failure in order to be able to rectify the problem early enough and before an aircraft operation interruption occurs. However, if the respective maintenance action should be kept as short as possible, not only the impending system failure should be detected, but also the faulty system component has to be identified. In terms of aircraft maintenance, the respective line replaceable unit (LRU) is the smallest unit that will be replaced during the maintenance action.

Considering the pump, the LRU that can be replaced during line maintenance is the electric motor pump itself. Consequently, it is not necessary to identify the faulty component inside the pump. It is rather necessary to identify the pump as a faulty component of the hydraulic system. Once the pump is identified and replaced, it will be disassembled and repaired or overhauled at the workshop. Here, the actual fault will be rectified during the maintenance procedure.

In section 4 it was investigated, how the considered individual leakage related faults of the pump influence the pump characteristic line. Thus, the shape of this characteristic line can be used as an indicator for fault diagnosis.

In steady state domain, it is especially the pump characteristic line, by which the nominal behaviour of the pump is defined. In practice, a certain band is specified, within which the pump behaviour is considered as nominal. In terms of the detection of impending failures, a certain margin towards the border of this band can be used to trigger the replacement of the pump in order to avoid a failure of the system.

5.1. Measurement Points

The assessment of the pump characteristic line should be performed on-line, i.e. during operation of the aircraft. Only by this, a permanent monitoring of the pump's condition and thus the early detection of impending failures is possible. For this reason both, the outlet pressure and the discharge flow have to be measured.

It is obvious, that this requires the on-board implementation of the respective sensors. While in typical aircraft hydraulic systems a pressure sensor is available downstream the outlet port of the pump, a permanently installed flow sensor is very unusual. On the one hand, such a sensor is not required for the system operation or the generation of flight warnings if a system failures occurs. On the other hand the use of a classic invasive flow sensor that e.g. is based on the meshing gear principle, may affect the system functionality in the case of a sensor failure.

A solution can be the use of a non-invasive flow sensor that relies on an ultrasonic principle. Such sensors are already in use for aircraft maintenance purposes, where they are temporarily clamped on the hydraulic pipes. Within the project ProReB, the permanent mounting of such sensors is investigated by the Flexim GmbH [1].

Thus, in order to establish a permanent monitoring of the pump, one flow sensor is required. On the technical side, this is feasible especially if a non-invasive flow sensor is used. On the economical side, the respective recurring costs have to be taken into account. However, these can be compensated by the reduction of e.g. the operation interruption rates due to the pump failures, which can be minimised by this monitoring approach. In addition, this sensor can also be used for the detection of faults of other system components [2].

5.2. System Operation Points

As discussed in section 4, the extents of the leakages influence specific sections of the pump characteristic line. Especially for small leakages, the affected sections of the characteristic line are in the region of high flow rates. In turn, these flow rates correspond to the flow that is consumed by the system consumers.

Thus, in order to be able to diagnose the extent of the internal leakage, the pump has to be running in the operation points at which the pump characteristic line is mostly affected. In other words, it has to be ensured that the system consumers require a certain minimum amount of hydraulic flow occasionally during system operation. For this, the hydraulic system, which is supplied by the pump, has to be considered.

In general, aircraft hydraulic systems contain several kinds of consumers during normal operation. Hydraulic cylinders of the flight control (e.g. linear actuators of rudders, ailerons, elevators and spoilers) are controlled by servo-valves. Due to the functional principle of these valves, their hydraulic pre-stage requires a certain permanent flow. The amount of the flow consumed by the actual actuators depends on flight conditions and is more or less random. For example during an approach with heavy gusts, the consumption is remarkably higher than during cruise with calm weather conditions. Thus, only the permanent flow consumption of the servo valves is assured; the actual consumption of the actuators can only be assured to a certain extent.

Hydraulic cylinders of the landing gear retraction / extension systems are very large consumers. In addition, it is ensured, that the landing gear will be both, retracted, and extended once during a flight. Thus, the considerable consumption of these actuators is assured during certain flight phases.

Hydraulic motors usually drive the high-lift system such as the flaps and slats. These actuators are only operated intermittently during take-off and approach. Like the landing gear retraction system, the operation of these motors leads to a considerable high flow consumption. For this reason, usually the operation of the high lift system and the landing gear retraction / extension system is not performed simultaneously. However, like the landing gear system, the high-lift actuation system also assures considerably high flow consumption during certain flight phases.

For the reference system of the project ProReB, the blue hydraulic system of the Airbus A320, several flight control actuators and the slat actuation system are consumers during normal operation. Considering only the permanent flow consumption of the servo valves and of the slat actuation system, the indicated area for the ensured minimum flow demand in FIGURE 8 will definitely be used during flight. This area can be used for the diagnosis of the pump's internal leakage. In addition, a certain flow of the flight control actuators would be added, if these were used during slat operation.

Beside this, specific test procedures on ground could be defined, at which certain consumers are activated during a maintenance mode for the hydraulic system.

5.3. Diagnosis of the Pump Condition

In order to diagnose the pump's condition on-line, the outlet pressure and the discharge flow are measured permanently. However, as no high dynamic effects have to be measured, the bandwidth of the sensors and the sampling rate of the sensor signals do not need to be considerably high. In contrast, the transient behaviour of the pump, e.g. the response of the pump to a sudden rise of flow demands, may disturb the assessment of the pump condition. Therefore, it is meaningful to average the measurement for a certain time range.

The measured flow defines the actual operating point of the pump. The respective value of the pressure is then used to diagnose the pump's condition. For this, the derived pair of flow and pressure is mapped to the pressure-flow chart as depicted in FIGURE 8. If the pair of values is located outside the nominal area that is bordered with the dot-and-dashed line, the pump performance is considered nominal. If the pair is very close to the nominal-limit or falls below it, a replacement of the pump can be triggered. However, in this situation

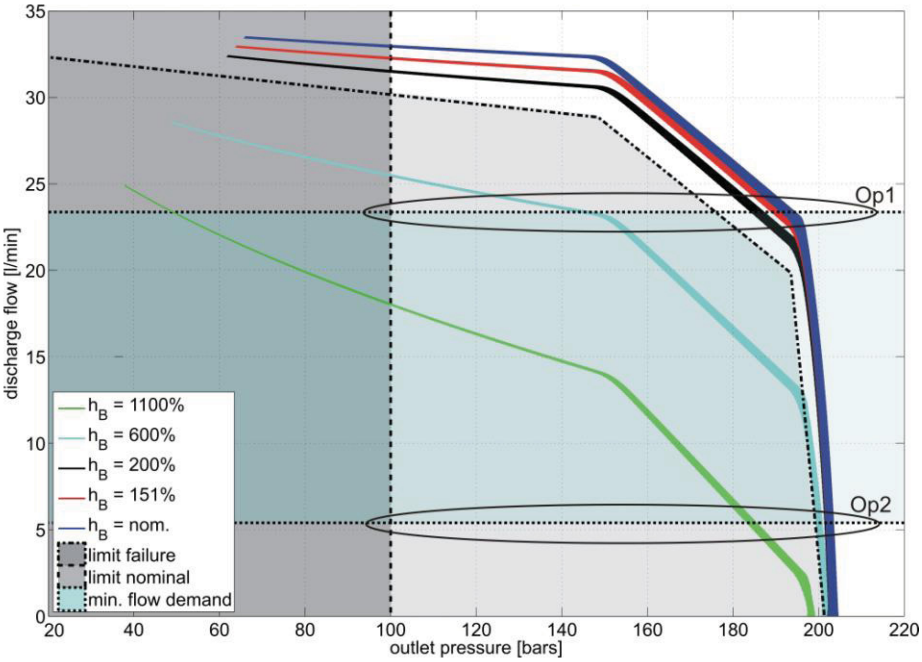

FIGURE 8: Operating points and limits for the fault diagnosis

the pump has not actually failed yet. Thus, an operation interruption of the aircraft would have been avoided.

With this approach, also the progress of the pump deterioration can be monitored. As an indicator, the distance between the measured pressure at a given operating point and the respective point of the nominal-limit can be used. This represents the margin towards a pump operation outside its specification. As this margin decreases with progressing pump deterioration, this indicator can be used for the prediction of the time at which the pump will not meet the requirements any more. This will allow the planning of the removal of the pump well ahead in time.

As an example, in FIGURE 8 the simulated pump characteristic lines for several extents of the port plate deteriorations are depicted (compare section 4.2). It can be assumed, that operating point 1 (Op1) is reached at minimum during take-off and approach. Here, a deviation from the nominal condition can be diagnosed, as the measured pressure at this point is lower than expected. In other words, the margin towards the nominal-limit is decreasing. By this, even if e.g. the gap size h_B accounts 151% of its nominal value, a pressure decrease of approximately five bars would be measurable. For larger extents of the fault, this value increases dramatically.

These severe faults could also be detected during flight, even if all consumers are idle and only the permanent flow of the servo valves is delivered by the pump. At this operating point 2 (Op2, see FIGURE 8), e.g. a gap size of 600% is already detectable.

It is obvious that the nominal-limit has to be selected very carefully. If the limit is chosen too large, a replacement of the pump would be triggered too early. If it is chosen too small, the pump might fail before a replacement could be achieved. Here, the limit in FIGURE 8 is based roughly on the respective limits that are used for the return-into-service tests after a pump was disassembled for maintenance.

Up to today, in aircraft hydraulic systems the pump condition is monitored only by pressure switches. If the outlet pressure falls below a predefined level (see the dashed “failure limit” line in FIGURE 8) the pump is considered to have failed. In this situation, the pump has to be replaced before the next dispatch of the aircraft, as the hydraulic system would be inoperative otherwise. This illustrates the advantage of the approach presented in this paper. By considering the actual value of both, the pressure, and the flow, an early detection of an impending pump failure is enabled.

6. CONCLUSIONS AND OUTLOOK

An approach for the on-line leakage diagnosis for an electric motor pump in an aircraft hydraulic system has been presented. For this, a detailed physics-based model was built in AMESim. With this model, it was possible to analyse the effects of individual internal pump leakages on the pump overall performance, which is characterised by the pump characteristic line.

Based on this analysis, a robust and cost-efficient approach for the on-line diagnosis of the pump’s internal leakages was developed. It relies on the permanent measurement of the pump outlet pressure and discharge flow. By comparing the resulting measurements with the specified limit pump performance, a margin towards an unacceptable operation of the pump can be derived. On this basis, the removal of the pump can be planned in time in order to avoid operation interruptions of the aircraft, which in turn will reduce the cost for flight delays or cancellations.

This paper focused on the effects of the pump’s internal leakages. The same approach can be applied to other pump faults as well. During next steps, these approaches will be further refined and validated on a respective test rig.

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