Review for State-of-the-Art Health Monitoring Technologies on Airframe Fuel Pumps

Tedja Verhulst[1], David Judt[1], Craig Lawson[1], Yongmann Chung[2], Osama Al-Tayawe[3] and Geoff Ward[3]

[1]*Cranfield University, Cranfield, Bedfordshire, MK43 0AL, United Kingdom*

tedja.verhulst@cranfield.ac.uk

david.judt@cranfield.ac.uk

c.p.lawson@cranfield.ac.uk

[2]*University of Warwick, Coventry, Warwickshire, CV4 7AL, United Kingdom*

Y.M.Chung@warwick.ac.uk

[3]*Airbus Operations UK, Bristol, Gloucestershire, BS34 7PA, United Kingdom*

osama.altayawe@airbus.com

geoff.ward@airbus.com

Abstract

Aircraft maintenance is an essential cost borne by the airline. Improving maintenance practices for day-to-day operations can lead to significant financial savings. The benefits of effective maintenance are derived from the avoided costs caused by unexpected breakdowns and from maximizing aircraft flight time transporting passengers. The fuel system is a crucial part of the entire aircraft as it ensures delivery of the fuel to the engine and a key component within this system are the fuel pumps. These airborne fuel pumps are classified between the pumps installed in the airframe fuel system and in the engine fuel system. Past works have investigated the performance characteristics of these pumps during flight, however there are no reviews related to the present Health Monitoring (HM) capabilities under flight conditions. HM refers to the field of diagnosing faults or predicting the remaining useful life (RUL) of the pump and the focus of this review is to highlight the HM technologies suitable for aircraft fuel pumps. It was found that there is a large scope for development for the HM airframe fuel pumps, based on reviewing the present state of the art. Furthermore, there are no clear strategies formulated by airframe manufacturers and equipment suppliers to test and implement existing HM solutions to operate under flight conditions. This highlights the need to develop HM in this field and a requirement for further research of these technologies.

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1. Introduction

Aircraft maintenance is an essential part of operations, as it does not only ensure the safety of flight missions but can also influence the profitability of the airline operator. The reliability of the aircraft fuel system is vitally important, as the fuel system not only ensures fuel delivery to the engine, but also provides the means for fuel transfer between tanks, fuel jettison and refuel/defuel of the aircraft on the ground (Langton, Clark, Hewitt, & Richards, 2009). Understanding the degradation mechanisms of these fuel pumps is therefore highly beneficial and can be used to predict the failure modes of the fuel pump components as the equipment deteriorates over time. This gives operators the ability to mitigate and action for these faults before the aircraft is unexpectedly grounded. This prevents the operator from incurring excessive costs resulting from unscheduled maintenance and associated out of service time (Kahlert, 2017).

Implementing a form of Condition Based Maintenance (CBM) and Prognostics Health Monitoring (PHM) can benefit aircraft operations by reducing costs through minimizing the number of unscheduled breakdowns experienced by the operator (Wen, Hou & Atkin, 2017). Health Monitoring (HM) consists of a set of functions for estimating the present, and predicting the future, state of health of an asset. It includes anomaly detection, fault identification and isolation, and predicting remaining useful life (RUL) amongst its capabilities. The concept of failure prediction is carried out by continuously monitoring and assessing the present state of the system, to synthesize information used for decision making (Soualhi, et al., 2018). This helps maintenance operators decide if any corrective action is needed (*diagnosis*) and schedule the exact moment to carry out the repair work (*prognosis*) (Kahlert, 2017). The present maintenance strategy for operators relies on time-based methods, where the pumping unit is replaced after a certain number of hours of operation or when the pump reaches failure. The former maintenance strategy is called preventative maintenance, while the latter is called breakdown maintenance. It is assumed that limited corrective actions have been applied by the operator before reaching these maintenance intervals or pump failure scenarios.

The operator would have to pay substantial fees and additional costs related to passenger compensation if the aircraft is unexpectedly grounded at a guest airport, having a large impact on the profits gained passengers. Another negative impact of unscheduled breakdowns is to the reputation of the aircraft manufacturer and its perceived reliability. It is therefore crucial, from a cost-saving perspective, for both the aircraft manufacturer and operators, to anticipate these failures. This reduces the number of times the aircraft needs to suspend operations outside its routine maintenance procedures by either detecting an incipient failure using diagnostics or by predicting the exact moment when the fuel pump needs replacement using prognostics. With the implementation of CBM with diagnostics and PHM with prognostics, the pump, in theory should never fail outside the maintenance interval. One approach is to adapt HM techniques, whether executed through diagnostics, prognostics, or a combination of both.

There are several types of pumps on the airframe-mounted fuel system, such as boost pumps, transfer pumps, and scavenge pumps for water management. The relationships between these components are outlined by Figure 1.

Scavenge pumps have no moving parts. The motive flow generated by the boost and transfer pumps induces flow on the scavenge pump suction inlet. One of the key functions of the Scavenge pump is to divert the water rich fuel from the tank sump to the booster pump inlet for combustion. This prevents accumulation of water in the fuel tanks and removes the water drain maintenance task for each tank. Another function of the scavenge pump is to minimize the quantity of unusable fuel inside the tank.

Both boost and transfer pumps are electrically powered centrifugal pumps but have different operating characteristics. The transfer pumps located at the center tanks must provide higher feed line pressures compared to the feed tank boost pumps. This serves to overcome the line losses from the longer fuel travel path to the engine-feed interface. For the A320 and B737 aircraft, the pump must supply at significantly higher pressures to close the boost pump outlet check valves by overriding the pump pressures. This allows the fuel from the center tanks to be depleted first before emptying the feed tank. Once the center tanks are emptied, the transfer pumps are shut off and the feed tank boost pumps take over to supply fuel to the engine. This ensures that the feed tanks are the last tanks to be emptied during the flight mission. Transfer pumps also provide wing load alleviation and ensure correct airframe CG by moving fuel across the different tanks (Langton et al. 2009).

The fuel pumps focused in this paper are colored in green on Figure 2**.** They are the feed tank boost pumps, which are part of the airframe fuel system and the engine high pressure pumps mounted on the engine. The airframe and engine fuel systems are segregated by the low-pressure (LP) valve located on the airframe, which separates and shut-off flow of fuel in the event of an emergency. The transfer pumps are mounted inside the center tank and are interfaced with the main feed tank within the airframe fuel system (Langton et al., 2009) as highlighted by Figure 1.

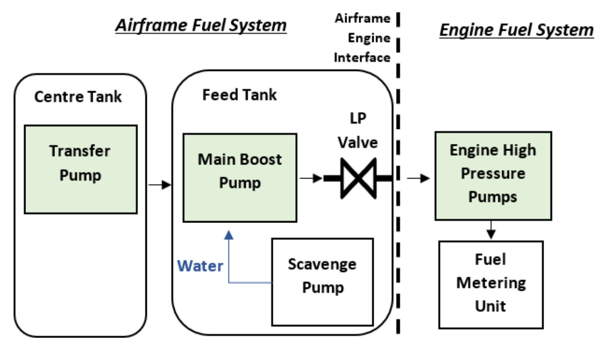

Figure 3. Key elements within the Airframe and Engine Fuel Systems

Like the transfer pump, the feed tank boost pumps can be utilized for fuel jettison in emergencies and to assist in de-fueling during ground operations (Messina, Cooper, & Heald, 2008). On the other hand, engine high pressure (HP) pumps' main function is to pressurize the fuel even further to engine combustor required levels and to deliver the fuel with the desired pressure over a wide range of operational speeds.

This paper reviews the literature of HM technologies that have been used on airframe mounted centrifugal boost pumps; these include not only the diagnostics and prognostics techniques used to perform HM on a specific fault, but also the sensing technologies that have been deployed. As there are few works related to the HM of airframe-mounted fuel pumps, technologies from other industries are referenced so that a comparison can be made for the present capabilities of fuel pumps found in aircraft with pumps from other industries.

The structure of this paper is sequenced as follows: Section 1 introduces the need for HM and its relevance for airframe fuel pumps. Section 2 discusses the relevant technologies related to the function of airframe fuel pumps. In Section 3, the HM technologies and concepts related to the HM of fuel pumps are examined to provide context to the reader. In Section 4, a literature review of faults on pumps and motor faults are carried out, from both aerospace and other relevant industries. Section 5: HM Sensing Methods introduces the commonly used sensing technologies used for the HM of fuel pumps. Finally, Section 6: discusses the present knowledge gaps related to aircraft fuel pump HM and technologies that have been applied, which are formulated based on the literature review findings in the previous sections. This section not only highlights the sensing technologies and signal processing techniques that have been used, but also elaborates on capability gaps where airframe fuel pump HM technologies could be developed in the future. The review of airborne fuel pump HM technologies ranges from the year of 1999 up to 2020, as this was the earliest published work found. At the present, few works have been done for the HM of airborne fuel pumps and there is large scope for development to address this knowledge gap.

2. RELEVANT TECHNOLOGIES

2.1. Airframe Fuel Pumps

Fuel pumps that are found on the airframe fuel system and the engine fuel system utilize two different types of pumps, respectively. These two fuel systems are separated by an LP shut-off valve mounted in the aircraft fuel system which isolates the engine fuel supply from the airframe when the engine is shut down or for emergency situations (Langton et al., 2009). Engine-driven fuel pumps are mounted on the engine to move the fluid directly through physical interaction between the rotor and the fluid, to supply a constant flowrate for varying pump inlet pressures. The centrifugal pumps found on the airframe fuel system move fluid indirectly by boosting the pressure and are powered by an electric motor. For transfer pumps, variations in the pump outlet pressure directly influences the flowrate of the fluid supplied by the fuel pump (Messina et al., 2008). The flowrate of the boost pump on the other hand is determined by the engine and its primary aim is to supply fuel under pressure to the engine interface regardless to changes in flow demand (Langton et al., 2009). HP positive displacement pumps are used on the engine interface as they can re-prime from a completely dry condition to deliver the required fuel pressure over a changing engine input speed. Excess flow from both the HP pump is bypassed and recirculated back to the inlet of the same pump. The ratio of fuel flow that gets bypassed or fed to the engine is calculated by the Fuel Metering Unit More information on the different types of airborne fuel pumps and their operation is found in textbooks that have been compiled by Langton et al. (2009) and Messina et al. (2008).

2.2. Airframe Fuel Pump Motor Types

Centrifugal fuel pumps that have been used in the airframe fuel system uses one of two types of motors: An Alternating Current (AC) induction motor or a Brushless Direct Current (BLDC) motor (Langton et al. 2009). Each type of motor has advantages and disadvantages over the other. Both BLDC and induction motors leverage the use of a rotating magnetic field on the stator to generate torque on the rotor. AC Induction motors work by inducing current on the rotor caused by the rotating magnetic field generated by the stator. The induced current in the rotor generates its own magnetic field that reacts with the stator magnetic field to generate torque. In the BLDC motor, the stator coils generate a magnetic field, and the permanent magnet rotor tries aligning itself to that field. Motion is generated by rotating the stator magnetic field, which is achieved by sequencing the excitation of the stator windings. Another difference between BLDC and an induction motor is the use of permanent magnets on the BLDC rotor (Hughes & Drury, 2019). Future aircraft are trending towards the use of high voltage (270 VDC) BLDC motors over their low voltage (115 VAC) AC counterparts due to its higher power-density and reduced wiring mass. Using high voltage DC allows the use of two thinner wires for the positive and negative motor terminations, instead of using three thick wires for each phase of the low voltage AC motor. More information on BLDC and AC motors be found from the textbook by Hughes & Drury (2019). Information related to aircraft fuel system application for both types of motors can be found in the work by Langton et al. (2009).

3. HM THEORY OVERVIEW

3.1. Health Monitoring Fundamentals

Health monitoring techniques can be categorized into diagnostics and prognostics. Diagnostics refers to the ability to create an appraisal of the equipment in question using some form of health indicator (HI). Prognostics is concerned with being able to estimate the RUL of that equipment rather than just the appraisal of its present state (Skaf, 2015).

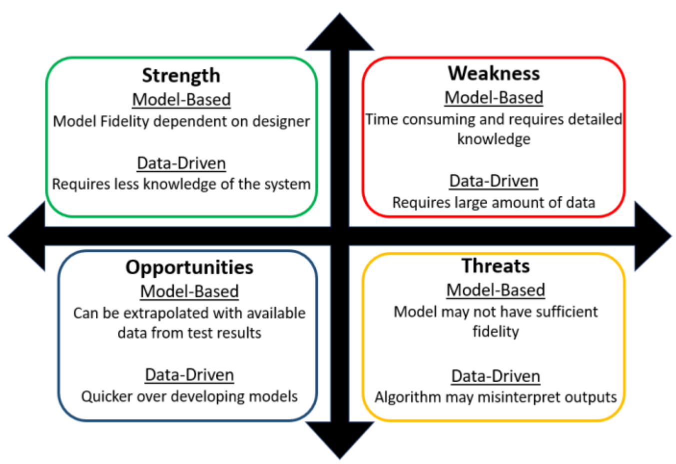

Figure 2. SWOT analyses comparing the merits of model and data-based HM (Skaf, 2015)

Within the two basic forms of HM, there are also two main ways for the data to be generated and synthesized. The implementation of HM can either be Model-based, Data driven or a hybrid, where the latter is a combination of both. Model based HM leverages the understanding of the physical and functional relationships of the system. This method is often used if the user has a deep knowledge of the system in question, so that those relationships can be modelled accurately. Data driven HM utilizes reasoning methods to extract patterns in the datasets, which can be used to build an understanding of the system and make predictions. This requires large quantities of historical data to train the algorithm before it can be used to generate useful results. Figure 2 depicts a Strength, Weaknesses, Opportunities and Threats (SWOT) analysis to compare model based and data driven techniques for HM. SWOT analysis used to compare the usefulness of the different HM approaches. A detailed explanation of the differences between the different HM methods is found in the works by Ezhilarasu, Jennions, & Skaf (2019).

3.2. Model-Based Approaches Applied to Aircraft Pumps

Model-based HM utilizes some form of reference physical model that has been experimentally verified to synthesize the state of health for the system, equipment or small component. The degree of accuracy of the model needs to be understood before it is utilized for HM. The model-generated datasets are used as reference points for a known condition of the equipment, as a baseline to be compared against the sampled data. The correlation or similarity of the sampled data is compared with the baseline data generated by the model before the health state for the equipment is generated.

Kang, Gong & Chen (2018) have published a literature review on degradation modelling for various motor-powered equipment across different industries. The authors summaries the algorithms that have been used to model the deterioration of specific equipment and accuracy of estimating a RUL.

Various authors such as Zhang, Chen, Bai, Wang, & Tomovic (2019) Qiu & Khonsari (2012) and Djamai, Brunetiere, & Tournerie (2010) have demonstrated that a model-based approach can be applied to an aircraft pump lip seal, which is a small component that is used to interface between wet-end of a pump with the motor bearing interface. These works have proposed physical modelling techniques focusing on heat transfer and thermodynamics, to understand the wear processes of mechanical face seals which interface with airborne pumps and optimize their design.

Shi, Wang, Wang, & Zhang (2018) have created a lubrication model for an airborne hydraulic pump and related lubrication changes to changes in the performance characteristics of the pump, such as speed and delivery pressures. These works show that model-based approaches can be applied to analyses specific components of motor-powered equipment within a larger system and yield good results.

An example of model-based health monitoring has been shown by Delaloye (2009). The inventor has developed a patent which is a model-based HM for an airborne lubrication system in a gas turbine, which takes into consideration the lubricant pressure and temperature as well as the rotation speed of the pump-motor. The sampled data from the pump is first compared with the generated data from simulation with the same input parameters, then an assessment of the pump health is determined from the comparison of the sampled against the modelled results.

Fan & Piao (2017) have modelled the fuel vapor distribution inside a centrifugal pump for the engine fuel system. It was found that adding a bypass flow inside the pump, significantly reduces the temperature of the fuel but at the cost of a higher fuel vapor distribution at the impeller eye. This made the pump more susceptible to cavitation despite lowering the temperature of the fluid.

There are other works which have characterized cavitation flows with high fidelity computational methods such as the previous example by Fan & Piao (2017). Further examples by Medvitz, Kunz, Boger, Lindau, & Yocum (2002); Tang, Zou, Wang, Li, & Shi (2017); Zhang, Yun, & Li (2018); Homa & Wroblewski (2014) are similar but are for non-aircraft applications. Brunhart et al (2020) has demonstrated the use of model-based approaches by utilizing CFD methods to evaluate the risk of cavitation erosion on diesel fuel pumps. Effects of cavitation are characterized using multi-phase simulation techniques. These examples do not explicitly use model-based HM for diagnosis but show how a re-occurring fault in a pump can be captured using modelling techniques and the results can be utilized for corrective action.

3.3. Model-Based Approaches Applied to Aircraft Pumps

Data-based approaches are often used when the behavioral characteristics of the system or single sub-system in question cannot be fully known, and a model-based technique is not viable. There are few published examples for purely data-based approach for HM of aircraft fuel pumps. Most HM techniques of airborne fuel pumps that utilize data follow the hybrid approach, where the use of an additional system model can give improved accuracy to the HM diagnosis.

Pandian, Pecht, Zio, & Hodkiewicz (2020) have investigated various equipment faults on a single type of commercial airliner using data-based methods. This study does not suggest a HM solution but highlights the information collection on certain faults, and how external factors such as logistics, manufacturing and organizational management can influence the aircraft reliability. This report has tried to predict the mean time before unscheduled removals for different aircraft equipment, such as pumps, based on the data sampled on the rate of individual equipment failures during aircraft operations.

Li D., Zhang, Zhong & Zhai (2014) experimented with the frequency of maintenance intervals of water pumps in a closed system, in order find the best combination of scheduled servicing and preventative maintenance. It was found that there is an optimal service interval which reduces the overall life-cycle costs of utilizing the equipment.

Marquez, Schmid, & Collando (2003) have carried out a case study for the application of a system-wide HM solution applied for various equipment deployed within an area of the UK rail network. Even though this is not specifically an aerospace application, this work highlights how the system is integrated, the data is processed and the operational cost-benefits of implementing such a system.

Even though these three HM techniques have not been applied explicitly to airborne fuel pumps, the techniques are still useful for this application. The previous methods demonstrate how a purely data-based approach can be used to improve maintenance operations for aircraft systems that rely on multiple pumping equipment. The work by Marquez et al. (2003) applied to the rail industry is also useful for diagnosis of aircraft components as it gives example on how to implement data-based HM on a very large system, with many different components, connected over a large distance.

3.4. Hybrid Approaches

The Hybrid approach utilizes a mixture of HM from both model-based and data-based methods to combine the advantages from each technique.

The work by Niculita, Jennions, & Irving (2013) describes the design process of a fuel test rig based on a UAV engine feed system. The entire test set-up compromises of the actual test-rig, but also various other tools which facilitate the use of fault detection and isolation: such as a failure-mode analyses, a model simulator, test-rig controller, fault injection unit and data acquisition. The simulation of the test rig can also inject faults in the virtual domain, so that the expected output could be studied first before executing the actual test on the experimental test-rig. The models are used to create reference points for healthy cases and hypothesis for fault scenarios. Data-based approaches can be used on model-generated data for algorithm testing, before application with test rig data. Furthermore, the model is continuously updated from the results from the physical test rig to minimize the discrepancies and to adjust for any changes to the physical system.

Another hybrid-based approach has been devised by Al-Tayawe et al., (2018) for the HM of airframe-mounted fuel pumps. The performance parameter of the pump is sampled, then a signal processing algorithm is utilized to generate the RUL. The signal is sampled when the pump reaches a known reference environment for consistent sampling. The sampled data is compared with the reference model at a known health state, representing the different conditions of the pump. A prediction algorithm is continuously updated to generate the RUL based on the previous and present sampled data, with reference to its closeness with the known health states.

Mkadara & Paulmann (2018) have concluded that a mixture of modelling and data-based approaches is required for the HM of hydraulic piston pumps. This is because the developed HM solution under laboratory conditions may not be robust as soon as the external environment is introduced. The HM algorithm is thus trained using the developed model initially and before it is supplemented with in-service data to create a robust fault identification algorithm. In this instance, the outlet pressure and leakage flow values are used as the HI to diagnose the health of the pump. Guo, Chen, Lu, Wang, & Dong (2019) have highlighted more HM technologies related to airborne hydraulic piston pumps and gives a general overview of the present state and future development for these types of pumps.

The methods described by Mkadara & Paulmann (2018) and Guo et al. (2019) have demonstrated general approaches at which HM can be achieved to synthesize the health of the equipment or sub-system. Both Model-based and Data-based approaches have their own advantages and disadvantages, depending on the application.

Li, Wang, Shi, & Ma (2017) have developed a hybrid method using particle filters to recursively prognose the health of airborne hydraulic piston pumps, based on the sampled return oil flow. The algorithm is continuously updated based on the error measured between the sampled data and predicted data. Through observing the two values of the pump return oil flow, the suggested method was able to predict the condition of pump with high accuracy. A similar technique was also devised by Centers and Price (1988) where quantity of debris on the lubricant is monitored using ferrography to assess the level of wear on aircraft engines. The sensor is installed at the lubricant pump outlet. Further information on ferrography and how it can be utilized to diagnose aerospace components can be found on the work by Hoffman (1981).

Li J., Jing, Dai, Jiao, & Liu (2017) devised another variant but for centrifugal fuel pumps utilizing the outlet pressure as the HI and wiener process algorithm for signal processing. The algorithm developed by these authors are also accurate for predicting RUL of the pump when compared with experimental data.

3.5. Health Monitoring Fundamentals

Model-based health monitoring techniques generally involve analysis of the motor electrical signature, or fluid-mechanical parameters of the pump such as flow and pressure. The data are compared to one or more performance indicators which are an estimation of the pump health. The pump is monitored for changes in its inputs and outputs, or some characteristic related to the performance obtained from sampled data. Examples of these parameters can include the flowrate, pump inlet and outlet pressures, as well as motor current and voltage. The pump model describes the behavior or input-output relationships related to the operation at known points as reference towards the condition of the pump. The differences between data sampled from operations and data generated from the models are compared to generate the health diagnosis of the pump (Al-Tayawe et al., 2018). A major drawback of existing health monitoring techniques is that in-flight operational pumps may not perform as expected from laboratory testing or as modelled in simulation. This could lead to inaccurate health diagnostics and prognostics where the timing of the next maintenance period is predicted incorrectly or an inaccurate prediction for the pump Remaining Useful Life (RUL) is generated by the system. This is especially a problem with Aircraft fuel pumps as it would often necessitate taking the aircraft out of service to maintain the equipment (Al-Tayawe et al., 2018).

4. COMMON FAULTS

4.1. Corrosion

The presence of water in the aircraft fuel system is unavoidable, and the centrifugal action of the impeller separates the water and fuel resulting in higher concentrations of each substance inside the pump. This build-up of water can cause corrosion, or freeze and damage the motor windings, or create blockages on the fuel pump.

The presence of water promotes the growth of microbial fungi which feed on the carbon content of the fuel to reproduce generating harmful compounds such as acids. This leads to corrosion in the fuel pump. The corrosion damages the components inside the pump and reduces the effectiveness of its operation. Another mechanism of pump corrosion is from the metal reacting with the acid levels of the fluid it is exposed to. Lacey (1993) carried out a case study to devise a mathematical formula on the general wear of engine fuel pumps over time when immersed in Jet A1 fuel. the wear was dominated by corrosion from the metal reacting to the acidity levels of the fluid, causing the surface to oxidize.

More information on damage related to microbial induced corrosion can be found in the work by Langton et al. (2009) and Digman (1962). The work by Neville, Hodgekiss, & Dallas (1995) studies how corrosion erosion for marine pumps can impact their operation. Even though there are slight differences to corrosion found on marine pumps, the damage mechanisms and associated performance penalties are similar to corrosion found on airframe fuel pumps. More information on the fault mechanisms related blockages and winding failures can be found in their respective sub-sections 4.3 Blockages and 4.6 Winding Failures.

4.2. Cavitation

The most common type of cavitation for an airframe fuel pump is hydrodynamic cavitation. Another problem related to cavitation is air entrainment, which occurs when there is an excess of air vapor trapped inside the pump. This is not a type of cavitation, but its effects can reduce the pump performance and promote the effects of cavitation (Messina et al., 2008)

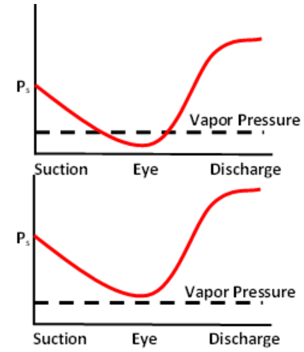

Figure 3. Pressure values across the pump

For an aircraft fuel pump, the impeller eye is considered to be the most vulnerable region, as this is the point at which the static pressure is the lowest in the entire pump (Messina et al., 2008) as show in Figure 3**.** If this point is lower than the vapor pressure, cavitation occurs and damages the impeller eye. The areas that are affected by cavitation are etched away smoothly, with a sandpaper-like effect, or the damage can be more severe and produce deep cavities with rough edges. For more detailed information on pump cavitation physics and its damage mechanisms reference can be made to the work that has been done by Sreedhar, Albert & Pandit (2017), Jahangir et al. (2021) and Palgrave (2019). Various authors such as Dular, Bachert, Stoffel, & Sirok (2004), Dular, Stoffel, & Sirok (2006) and Dular & Osterman (2008) have studied cavitation erosion extensively for various geometries such as flat surfaces, hydrofoils and radial pumps. For more information on the different types of cavitation and aircraft-specific cases, reference can be made to the Aircraft Fuel Pumps chapter on the work done by Messina et al. (2008)

4.3. Blockage

Both types of fuel pumps are protected by a filter that stops debris in the tanks from entering the feed lines. The presence of water in jet fuel is practically unavoidable and any contaminating water could freeze during long flights at high altitudes and low temperatures resulting in ice particles. These ice particles and snow clusters could block the filter protecting the pump as fuel is drawn into the pump through the feed line.

Blockages can also be caused by microbial growth as a result of the presence of water. The microbial fungus appears as sludge that restricts flow at not only the fuel pump filters, but other components in the fuel system, such as valves and pipelines. More information on blockages caused by ice for aircraft can be found in the work by Lam & Woods (2018) and by Lawson, Baena & Lam (2012). More information on blockages caused by microbial growth can be found on the book by Langton et al. (2009).

4.4. Axial Displacement

Axial displacements occur in the shaft coupling of an electric motor that is not properly positioned with the pump impeller. This misalignment creates an unequal air gap between the stator and the rotor and the variation in the gap distances can be called dynamic eccentricity. Bent shafts, shaft misalignment, imbalanced loads, and poor coupling can be classified under axial displacements as they cause the motor to deviate from its intended axis of rotation. Axial displacements can be tied to bearing faults or severe cases of cavitation as highlighted by Adamkowski, Henke, & Lewandowski (2016) and Jiao, Huang, Li, & Xu (2017) The axial displacement of the pump impellor causes imbalances the rotor and torque pulsations, which eventually weaken the coupling between the motor and impeller and cause failure. Figure 4 shows an illustration of a dynamic gap eccentricity caused by shaft misalignment. More information regarding the mechanism of this fault can be found in the publication by Rajagopalan, Aller, Restrepo, Habetler, & Harley (2006); Cameron, Thomson, & Dow (1986); and Hussain, Burrow, Henson and Keogh (2018).

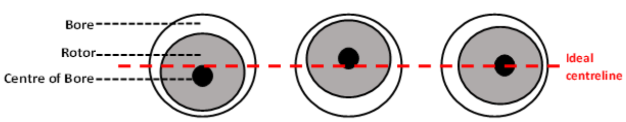

Figure 4. Dynamic air-gap eccentricity of motor

4.5. Bearing Wear

Bearings are used in rotating machinery to constrain the rotating movement into a single motion and to reduce friction between moving parts. Bearing wear can either happen inside the electric motor or within the rotating pump elements, increasing the friction and thus temperature in that specific area of the machine. This increased friction wear can also create vibrations of certain frequencies. More information related to pump bearing topologies and its wear mechanisms can be found in the Pump Handbook by Messina et al. (2008) whereas motor bearing faults can be found in the study by Rajagopalan et al. (2006) and Nandi, Toliyat & Li (2005). Aircraft-specific examples of this fault which extends the work of the previously mentioned authors can be found in the experiments devised by Johnston & Todd (2010).

4.6. Winding Failure

Winding-related failures are most often caused by the degradation of the insulation used of the copper coils, which are part of the rotor and stator windings of the electric motor. Another damage mechanism related to winding failures for airframe fuel pumps are from water build-up in the fuel system. Since the windings are cooled by the fuel flow, there is a possibility that the dissolved water from the mixture can freeze the motor windings and damage it. For a BLDC motor, this applies to the stator only, as its rotor is made of permanent magnets.

Coil degradation is caused by the continuous stresses related to large electrical voltages, winding currents, external vibrations, as well as thermal aging from multiple heating and cooling cycles. This breakdown of the winding insulation can result in turn-to-turn faults that eventually lead to short circuits to electrical ground, resulting in the so-called grounded stator windings. The move toward higher voltages in aircraft power distribution systems also introduces the risk of partial discharge in the motor windings that erodes the component. More information related to motor winding failures in general be found the literature review by Nandi & Tolayat (1999) as well as the experiments that have been devised by Kaufhold, Aninger, Berth, Speck & Eberhardt (2000). Aircraft-specific examples of this fault are explained in Haylock, Mecrow, Jack, & Atkinson (1999); Mecrow et al. (2004); Haus et al (2013); and De Martin, Jacazio, & Vachtsevanos (2017). The latter two works are applied to electric motors installed in aircraft but are applicable to pump motors.

4.7. Control Electronics Failure

Power switching devices within the BLDC motor drive can suffer failure due to excessive current, voltage and heating caused by their high frequency of operation (Liu & Wang, 2021). These damage mechanisms are even more significant due to the arduous environment of the aircraft fuel system that contribute to additional component stress (Langton et al, 2009). Although power transistor failures have been reported with in-service aircraft fuel pumps, there are no published sources that have investigated this type of fault for aerospace components. Liu & Wang (2021) and Fang (2015) have proposed methods to diagnose for transistor faults used on the inverter drive of an electronically controlled motor. While both proposed HM methods have successfully detected open and short-circuit faults, the experiments were carried out under lab conditions. Due to similarities in the motor and control architectures, the findings from this work are applicable to motors used on airframe fuel pumps.

4.8. Literature Review Summary

Table 1 summarizes the literature on common faults found on airframe fuel pumps. In addition, a detailed review on the HM techniques for aircraft-related equipment is provided in Table 2 within Section 5: HM Sensing Methods. This includes a detailed explanation of the fault mechanism with reference to non-aerospace specific sources. Further reading is then suggested to understand how the fault occurs for an airborne pump.

#	Fault Type	Type	Summary	Ref.
1.	Corrosion	Experimental	Wear model and experimental results for wear on engine fuel pumps	(Lacey, 1993)
2.	Cavitation	Theory	Basic definition and causes for cavitation erosion for pumps.	(Messina et al., 2008)
3.		Experimental	Experimental set-up used to evaluate the effects of cavitation erosion on centrifugal pump.	(Sreedhar et al., 2017; Palgrave, 2019)
4.		Simulation	Characterizing cavitation using high-fidelity computational methods	(Medvitz et al., 2002; Tang et al., 2017; Fan & Piao, 2017; Zhang et al, 2018; Homa & Wroblewski, 2014)
5.	Blockage	Experimental	Theory and design of a cold fuel test rig to investigate the effects of ice accretion on airframe fuel pump filter screens.	(Lam & Woods, 2018; Lawson et al. 2012)
6.	Axial Displacement	Theory and Experimental	Underlying theory related to axial displacements for motor-powered equipment	(Rajagopalan et al., 2006; Cameron et al., 1986)
7.			Aircraft specific examples of impeller rubbing caused initially by axial displacement	(Jiao et al., 2017)
8.	Bearing		Bearing arrangements and wear mechanisms	(Messina et al., 2008; Rajagopalan et al., 2006; Nandi et al., 2005)
9.			Bearing faults found on airborne fuel pumps	(Johnston & Todd, 2010)
10.	Winding Failures		Wear mechanisms related to winding failures and fault-finding experiments	(Nandi et al., 2005; Kaufhold et al., 2000)
11.			Winding failures on airframe fuel pumps	(Haylock et al., 1999; Mecrow et al., 2004)
12.	Fault Finding	Modelling	Cost-benefit analysis of implementing prognostics for general aircraft maintenance.	(Kahlert, 2017)
13.		Experimental	Study on various equipment faults on a single type of commercial airliner using data only.	(Pandian et al., 2020)
14.			Study on different maintenance intervals for water pump to minimize operating cost	(Li D. et al., 2014)
15.			Test set-up and fault-diagnosis techniques for a UAV fuel system.	(Niculita et al., 2013)
16.			Study on how data-based HM can be applied to a very large system with many components	(Marquez et al., 2003)
17.		Literature Review	Summarizes degradation modelling techniques used for different types of equipment.	(Kang et al., 2018)
18.			Summarizes present state of the art of airborne hydraulic pumps, with reference to HM.	(Guo et al., 2019)

Table 1: Summary of fault-related literature reviews

5. HM SENSING METHODS

This section focuses on prevalent detection methods for diagnosis. First, their operating principles is introduced, followed by a discussion of their respective merits and application examples. The state of the art between HM technologies that are used in airframe fuel pumps is compared with other aerospace pumps used in the engine fuel system. Further examples from relevant industries will be discussed to suggest how HM can be applied to airframe fuel pumps.

5.1. Thermal

Thermal monitoring of pumps involves measuring different areas of the pump by using thermocouples. It can be used as an indirect method to detect motor winding and bearing faults on other components of the pump. For example, a fault related to motor winding can lead to a temperature rise in the specific region of the fault. For bearing faults, the increased bearing wear increases the friction and the temperature in that region of the machine. HM that leverages temperature data is often used in conjunction with another measurement source, such as speed or an electrical signal (Rajagopalan et al. 2006).

Emmons (2018) has investigated thermal HM for application in aerospace, where an invention related to the fuel delivery system in a gas turbine engine is described. The technique assumes that the HI captured for one equipment are dependent on the condition of a neighboring element within the system. The position, speed, temperature, and sample time of the second component, such as the adjacent valve, is used to indirectly diagnose the fuel pump.

Emmons & Salminen (2019) have devised an application for aerospace fuel pumps, where a HM technique is described also for a gas turbine mounted pump. The life expectancy of the fuel pump is generated based on the position of the fuel-actuated actuator relative to the fuel pump speed value. The temperature of different components in the fuel delivery system are sampled and the RUL of the fuel pump is estimated. A prognostic algorithm is used to generate the RUL based on the time-history trend of health assessments from the collected data.

Li & Jiao (2006) have analyzed the effects of heat transfer from the pumped fluid, related to the flow-performance of the hydraulic piston pump found on the aircraft. Neither study incorporates HM directly, however, they show how modelling techniques using thermal parameters can be utilized to observe changes in the pump operating characteristics.

Physical thermal modelling is widely used to predict the behavior of an equipment item with the purpose of HM or performance optimization, as it allows accurate observations of changes in the behavior of the equipment due to temperature. Temperature-based HM is commonly used for the diagnosis of pumps, but it is deployed in conjunction with another measurement technique, such as rotational speed to diagnose the present health of the pump. An example of this has been highlighted by the invention previously discussed in this section, by Emmons & Salminen (2019). Temperature samples can provide some indication when the pump is about to fail. The main weakness of utilizing temperature-based monitoring alone is that the location of the temperature rise inside the pump cannot be exactly isolated unless multiple sensors are used (Rajagopalan et al. 2006).

5.2. Vibration

Vibration monitoring functions on the principle that mechanical vibrations at various frequencies are related to identifiable sources in the entire pump and can be used to provide an indication of the condition of the machine. The vibration energy of the machine is measured through the parameters such as displacement, velocity, or acceleration.

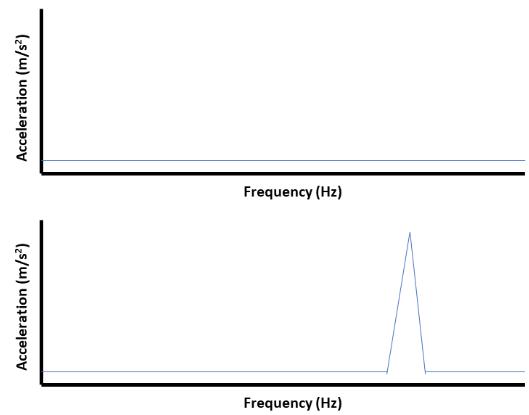

Figure 5. Vibration spectra for a healthy and faulty pump

Further background theory on vibration analyses and a list of pump faults that are detectable using it is given by Sinha & Rao (2006). Retrofitted vibration sensors are common for ground-based pumps, but are not as often used on airborne pumps, where the retrofit of these sensors may not be practicable and lead to re-certification of the equipment due to intrinsic safety requirements. Figure 5 highlights the vibration signatures from a healthy pump and a faulty pump. In the event of a fault, such as a bearing defect, the amplitude of acceleration increases at a certain frequency value. Each fault for the same machine can have a vibration spike at a different frequency.

Vibration monitoring has been applied to airframe-mounted fuel pumps under laboratory conditions. Adamkowski, et al. (2016) have highlighted how an already eroded impeller can produce further torsional vibrations on the pump shaft, which in turn can be detected using vibration analyses. Even though this is not an aircraft specific example, cavitation erosion is a common problem on airborne fuel pumps and detection techniques that have been devised in this work are useful for aerospace applications.

Du, Wang, & Zhang (2012) have devised a fault classification method utilizing the vibration power signals and a layered clustering algorithm for the diagnosis of airborne hydraulic piston pumps. It was found that this strategy was effective in classifying the different types of faults such as valve abrasion, low inlet pressure, bearing wear, swash plate eccentricities and variations in piston clearances.

Pecho & Bugaj (2018) have experimented with a method to diagnose bearing faults and loose pump rotors using vibration monitoring through an auxiliary HM device attached to an aircraft fuel pump when the aircraft is grounded. The Recurrence Quantification Analysis is a less computationally complex technique for carrying out diagnosis under controlled conditions and is an alternative to using the more widely employed time and frequency-based methods.

Jiao, Huang, Li, & Xu (2017) have experimented with a method which focuses on recording vibration monitoring on the x, y, z planes and pressure signals from an airframe fuel pump to detect bearing faults. Both inventions have relied on conducting HM while the aircraft is grounded under controlled conditions.

Feng et al. (2019) devised a method to implement model-based vibration monitoring for spur gears. This method utilizes vibration signals to correlate them to the level of abrasive wear on the gearbox and retrieve the RUL. Even though this work is for non-aerospace application, some pumps in the engine fuel system are gearbox driven. Hence, the findings from this work are applicable for implementing HM on such pump types.

Overall, vibration methods are an effective tool for diagnosis and fault classification, but its merits are often superseded by electrical signature analyses if the equipment is electrically powered, such as is the case with the airframe-mounted boost pump. The sensors required to perform electrical HM can be placed away from the flammable areas of the fuel tank, therefore bypassing intrinsic safety requirements. This is because modern pumps segregate the control electronics from the pump wet end.

5.3. Electrical

Stator current and terminal voltage monitoring fall under the category of electrical signature analyses (ESA). Unlike vibration analysis, the pumps mechanical faults are interrogated indirectly through the measurement of the motor electrical parameters (Kliman & Stein, 1992). ESA relies on placing current sensors across the stator or power supply to interrogate the present condition of the motor, which most BLDC motor drives include by design. It has been shown that there is a relationship between the motor vibration and the magnitude of the stator currents or terminal voltages at certain harmonics (Riley, Lin, Habetler, & Kliman, 1999). This relationship can be proportional to the mechanical vibrations, where the magnitude of the corresponding stator current harmonic components also increases along with it. More information on the basics of ESA for electric motors can be found in the work by Kliman & Stein (1992). Specific information on the relationship between vibration and ESA has been outlined by the work by Riley et al. (1999)

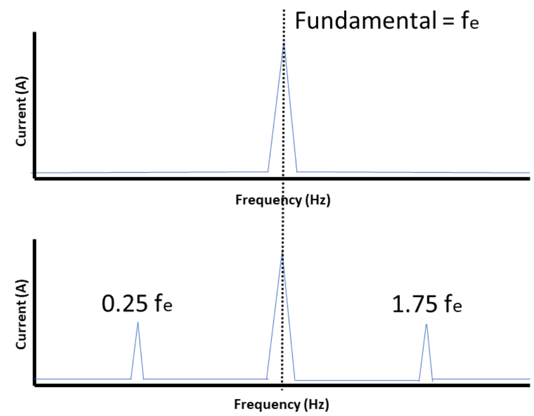

Figure 6. Application of ESA for detecting faults on electrically powered pumps.

Figure 6 highlights how a fault generates current signals at certain frequencies. The spike in the center represents the excitation frequency of the motor, which is known as the fundamental frequency, fe. After the occurrence of the fault, the sidebands on 0.25 fe and 1.75 fe becomes distinguishable. Note that unlike vibration analyses, faults signatures that are detected by ESA are observed in conjugate pairs such as on the example highlighted by Rajagopalan et al. (2006) Like vibration analyses, each fault has a spike in amplitude at different frequencies.

Lu & Kumar (2017) have devised a patent for electrically powered traction motor HM. This model-based technique relies on collecting the electrical signal of the traction motor and comparing it with a mathematical model representative of the same system to generate the system RUL. Even though this is applied for traction motors, the same principles could be applied to aircraft fuel pumps, where instead of evaluating tyre traction, the information regarding the flowrate could be interrogated instead. This invention is especially useful as it examines the operating environment before carrying out HM, a feature that can be applied for carrying out a HM for a fuel pump during flight.

Other past work focused on the diagnosis for cavitation on aircraft such as with Schmalz & Schuchmann (2004) where the authors have devised a method for cavitation detection on airframe centrifugal fuel pumps using phase voltages and currents. The sampled signal is compared with some known thresholds for the faulty condition to indicate the working condition of the pump when the aircraft is grounded. Unsworth et al. (2004) as well as Haynes & Eissenberg (1989) have devised a similar technique to diagnose cavitation for a non-aircraft pump using ESA. Both works are similar in that their solution is designed to detect cavitation in pumps, but the pump application and utilization of electrical signals are different.

Haylock et al. (1999) and Mercrow et al. (2004) have discovered methods whereby a shorted stator coil on a permanent magnet-based machine for an airframe fuel pump could be detected by analyzing the increased current ripple on the control signal inputs. The information is then used by the motor to switch off the faulty phase winding and operate with a missing phase. This circumvents the motor from operating with a shorted stator coil.

Schumann et al. (2021) proposed a method to monitor the health of a battery by monitoring its terminal voltages. Other ESA methods that depend on monitoring the motor currents to diagnose various faults applied to aerospace motors have been carried out by Hussain et al. (2018), De Martin et al. (2017) and Haus et al. (2013). All of these methods focus on HM on electric motors but the methods described can be applied to motors that control aerospace pumps.

There are few published sources that are related to the ESA for airframe fuel pumps, most published works are for diagnosing electric motors or non-aerospace pumps. ESA holds promise to be used for HM, as it is generally simpler to install the HM equipment compared to vibration sensor counterparts. Furthermore, the sensors tend to be more reliable than vibration sensors at they are not exposed to the stresses that are sourced from the pump. The primary disadvantage of ESA is that the equipment needs to be powered by an electric motor. Another disadvantage of ESA is that this method cannot isolate the vibrations that originate from the motor or the pump. It cannot distinguish faults which have the similar electrical signatures when the origin of the vibrations is unknown. For the few published examples of ESA on airframe fuel pumps, all the existing HM work has been done while the aircraft is grounded under a controlled environment.

5.4. Pressure

Pressure based HM is performed by monitoring changes in pressure across the fluid-mechanical network of the system. It can be applied by adding pressure transducers at various points in the flow network to interrogate specific areas of the system. These pressure transducers can be installed at different areas within the fuel system network or on an individual component where there is a likely pressure change, such as on a pump or a valve (Niculita et al., 2013). The measured values of the pressure can be observed nominally (Johnston & Todd, 2010) or with the aid of some signal processing technique such as in Niculita, Skaf, & Jennions (2014) to synthesize patterns within the pressure pulsations and gain some form of useful indicator to diagnose and estimate the present state of the equipment.

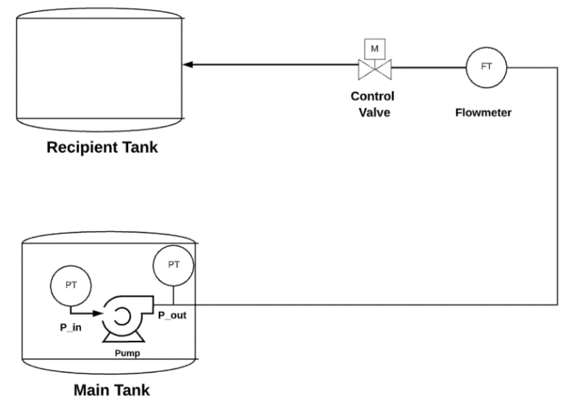

Figure 7. Installation of pressure and flow sensor on a fluid-mechanical system.

Niculita et al. (2014) have presented a novel method, where the pressure pattern changes are monitored at the valve inlet. These patterns are recorded and used to anticipate sudden valve shut offs by utilizing a Bayesian change point algorithm. The change in valve pressures is done by throttling direct proportional valves, which in turn mimics different levels of severity from sudden valve blockages. Jung, Niculita, & Skaf (2018) extends this work by comparing different signal processing techniques to evaluate their effectiveness for detecting the same fault.

Skaf, Eker, & Jennions (2015) have also used the same test rig devised by Niculita et al. (2014). but for RUL estimation of valve filter clogging, which is also simulated through throttling the proportional valve. The devised HM technique leverages resulting pressure differential across the valve and flowrate to train the prognostic algorithm and generate the RUL of the valve.

A technique devised by Wang, Dong, & He (2019) utilize the suction dynamics of aircraft hydraulic pumps during transient conditions to conduct HM. The scheme uses two models: The first models the pump dynamics and the second are for transient values on the pump inlet line, which are both validated using a test rig. The duration of pressure transient signals is compared with the reference value. The longer the deviation from this baseline value, the more likely the pump is to cavitate.

Figure 7 outlines a simple two-tank system consisting of a centrifugal pump, control valve, four pressure sensors and a flowmeter. The pressure sensors are installed in pairs to monitor pressure changes between the valve and pump. The flowmeter is installed only once as the flow value is the same across the network. There may be multiple flowmeters if there is a junction within the network, as the information related to the ratio of flow between one junction and another may be useful. As highlighted by this diagram alone, pressure sensors are more likely to be sensitive to changes to the condition of an individual component. Therefore, pressure is more often used as a HI performing pump HM, whereas the value of flow is influenced by multiple components that share the same flow network.

Johnston & Todd (2010) have utilized pressure sensors placed between LP and HP pumps as well as the valve interface to diagnose bearing faults. Specific flight conditions such as external temperature, and pump pressures dictates how the system performs HM. The measured values are processed with time and frequency domain techniques to evaluate the health of the pump. The external environment is simulated with a rotary valve, generating air ripples to simulate the environmental disturbance. Full details on the experimental set-up used to simulate the aircraft environment, has been outlined by Johnston & Edge (1991).

Flint (2007) has devised an invention that relies on the use of an electrical solenoid to conduct HM on a gas turbine engine for aircraft. HM is performed by comparing the percentage valve demand against the actual position of the valve-actuator, or by comparing the percentage difference between the servo pressure line and the control value of the pressure line. When the difference reaches a certain value for either of those comparative parameters, an engine warning is given to warn operators.

Lu, Wang, & Wang (2017) have devised a method to synthesize the health of airborne hydraulic pistons using three health indicators: pump outlet pressure, system line pressure and the displacement of the recipient actuator. The combination of these sources is not only better to detect and distinguish faults but ensures reliable HM if one of the pressure sensors fail.

Ma, Wang, Shi, Li, & Wang (2018) have devised a different HM solution for aircraft hydraulic piston pumps. The proposed model-based method attempts to diagnose leakage flows inside the pump by monitoring the output pressure and the swashplate angle. This method is unique as it attempts to incorporate the flight dynamics into the model and the non-linear behavior caused by it.

Pressure measurements have been widely used for HM of pumps, either by sampling and observing the raw signals nominally or with additional signal processing. Either of these approaches can yield useful outputs for HM. Pressure is often used as it is indicative of the pump performance, and any deterioration in this value can intuitively be linked to pump health. Pressure based HM has been researched for both airframe fuel pumps and engine fuel pumps.

5.5. Flow

Flow based monitoring relies on the measurement of the flowrate along a certain path of a fluid-mechanical system. One flow sensor is deployed across a certain network or path, as the flow is likely to be the same for all elements in that flow path. This is unlike pressure-based monitoring, where the transducer is implemented before and after the equipment in question to monitor the pressure rise or drop (Niculita et al., 2013). HM approaches using flowrates have been done in conjunction with another parameter. This is because although the flowrate measurement can indicate a clear reduction in flows within the system, it may not be able to detect steady deterioration over time. For example, Johnston & Edge (1991) showed that flow measurements did not detect any noticeable change as the pump deteriorated to a failure condition. Flow is useful when combined with pressure signals to synthesize the health of the pump as supplementary information. The quality of fluid in the flow can also be monitored to assess wear on aircraft engines, such as with Centers & Price (1988) where the quantity debris is monitored at its lubricant pump outlet to assess engine health. Hoffmann (1981) also mentions a similar technique but carried out under lab conditions. The Method devised by El Adraoui, Gziri, & Mousrij (2020) utilizes the flow output to assess the RUL of a generic pump under lab conditions.

Griffiths (2005) has invented a method which utilizes flow control for HM of leakages for a fuel pump in a gas turbine engine. The leakage flow at a specific speed is established through a calibration and the leakage flow is compared at the same reference speed again. The flow values are adjusted based on the temperature of the fluid for consistency of measurement.

Bergada, Kumar, Davies, & Watton (2012) have outlined the relationship between the flow leakage and output pressure ripples for airborne hydraulic piston pumps. The results are used to assess the present conditions of the components inside the port barrel plates inside the pump. The higher the observed flow leakage, the larger the clearance of the components inside the port barrels, which can be used to diagnose the degree of wear for the pump.

A flowrate signal is a useful indicator for HM; however, it is often used in conjunction with another HI, such as pressure. Flow is mostly used for HM on hydraulic pumps installed on the engine fuel system, as leakage flows captured from the barrel ports are easily measured. For airframe fuel pumps, outlet pressure signals alone are better to interrogate specific points of the fluid network and generally are more responsive to external disturbances.

5.6. Rotational Speed

The rotational speed is often employed to aid the execution of HM using the techniques mentioned above for a pump. Like temperature, using this parameter in isolation may not useful but can achieve diagnostics when used in conjunction with parameters such as motor current or pressure as shown in the following examples for pumps installed on the engine fuel system (Emmons, 2018; Emmons & Salminen, 2019; Griffiths, 2005; Flint, 2007). Further details are provided in the relevant sub-section within Section 5. In these situations, the primary parameter being monitored has been regulated to a set value by the control system. Once the controlled parameter, such as the pump outlet pressure, reaches the desired value, the motor speed at that moment is analyzed and is used as the primary HI. The HM diagnosis begins by assessing the motor speed. The purposes of this initial health check are to justify more detailed HM diagnosis to be performed by the system, such as taking temperature samples across the engine fuel system for the aircraft.

Villeux (2019) has devised a HM method for an aircraft gas turbine mounted fuel pump. The speed is reduced from a known value as the fuel flow is initiated by the ignition system. During this process, the outlet of the pump pressure is initiated to the desired pressure and the gas turbine engine is monitored to verify if light-off is successfully achieved, which is when the correct ratio of air-to-fuel mixture is achieved. The pump motor speed at which engine light-off is achieved determines the health status of fuel pump.

Rotational Speed is often used as a secondary HI in addition to a primary parameter such as pressure, temperature, vibration, or ESA. This parameter is often used to diagnose the health of the hydraulic pumps installed on the engine fuel system and is not used for centrifugal pumps installed on the airframe fuel system.

5.7. HM Literature Review Summary

Table 2 provides a summary review of different types of HM detection methods and related faults used on either the airframe fuel system or engine fuel system. Note that a distinction has been made between the engine fuel pump and the aircraft hydraulic pump. Engine fuel pump refers to the entire engine fuel pumping sub-system, including the centrifugal pressure backing pumps and the hydraulic pump that is installed in series. Aircraft hydraulic pump refers to that type of pump itself. This same type of pump may be installed individually on other systems such as helicopter hydraulic systems. The airframe fuel pump refers to the centrifugal pump that is installed within the airframe fuel system.

Some non-aerospace examples have been mentioned in previous sub-sections of Section 5: HM Methods but have been omitted from Table 2. In total there are 11 publications for the HM of aircraft hydraulic pumps, 10 for airframe fuel pumps and 8 for pumps for the engine fuel pump. There are also a few publications for engine fuel metering pumps, fuel valves and lubrication pumps which constitute part of the engine fuel system. These sources are from a range of publications since the year of 1999 up to 2020. The earliest work was carried out by Haylock et al. (1999) which was a method for HM for winding failures using ESA, intended for airframe fuel pumps. Work by Johnston & Edge (1991) attempts to simulate the aircraft environment for testing engine fuel pumps, but this work does not have any HM-specific content, and therefore is excluded from Table 2. The techniques that have been developed by Johnston & Todd (2010) are a continuation of the aforementioned work.

Most methods of HM for airframe fuel pumps are pressure based and ESA, with 3 publications for each method. The success of each method is not known, as there are no in-service data to provide evidence for their reliability. Most of the HM works have been tested under lab-conditions and no evidence has been shown for their function during flight conditions. The work by Johnson & Todd (2010) for an engine fuel pump, has made some attempt to simulate HM for flight conditions by creating a disturbance using a rotary valve. The work that has been devised by Al-Tayawe et al., (2018) gives an indication on how the HM might be executed when there are external disturbances from the aircraft environment, but no working prototype has been demonstrated. This highlights that there is large scope for development for HM of airborne fuel pumps, principally for airframe fuel pumps, as there are few published works which attempt to diagnose common faults. More value can be added to future findings if these works can not only diagnose faults but also perform HM when exposed to the aircraft environment. This also applies to publications for both engine fuel pumps and aircraft hydraulic pumps, where the HM is carried out under lab conditions.

Flowrate measurement have not been widely used for the HM of airframe fuel pumps as leakage flows are not easily captured on centrifugal pumps and often the flowrate captured is influenced by the behavior of other equipment in the same flow network. Isolating faults using flowrate quantities alone for an airframe fuel pump is not practical.

#	Detection	Fault	Method Summary	Equipment Type	Ref.
1.	Thermal	General degradation	Utilized parameters of one equipment to determine the health of another	Aircraft Fuel Pumps and Valves	(Emmons, 2018)
2.			Recorded temperature across fuel system to estimate RUL	Engine Fuel System	(Emmons & Salminen, 2009)
3.			Physical modelling techniques used to analyze temperature influences on component performance (used on hydraulic pumps)	Aircraft Mechanical face seals	(Zhang et al., 2019; Qiu & Khonsari, 2012; Djamai et al., 2010)
4.				Aircraft Hydraulic Pump	(Li & Jiao, 2006)
5.	Vibration	Bearing	RQA method on vibration for diagnosis of bearing-related faults on pumps.	Airframe Fuel Pump	(Pecho & Bugaj, 2018)
6.		Bearing, abrasion, low pressure, clearances	Experimental methods using frequency domain analyses methods to detect and classify common faults.	Aircraft Hydraulic Pump	(Du et al., 2012)
7.		Axial displacement, Impeller erosion, rubbing,		Airframe Fuel Pump	(Jiao et al., 2017)
8.	Electrical	Cavitation, Blockage			(Schmalz & Schuchmann, 2004)
9.		Winding	Leveraged input current ripples to diagnose for shorted coil windings		(Haylock et al., 1999; Mecrow et al., 2004)
10.	Pressure	Bearing	Like the frequency domain methods above, but includes a model to compare the sampled signals for HM	Engine Fuel Pump	(Johnston & Todd, 2010)
11.		Blockages	Algorithms that utilized pressure points in fuel system to predict sudden blockages and valve shut offs.	Aircraft Fuel System	(Niculita et al., 2014; Skaf et al., 2015)
12.			Prognostic algorithm based on pump outlet pressure to estimate RUL	Airframe Fuel Pump	(Al-Tayawe et al., 2008; Li J. et al., 2017)
13.				Aircraft Hydraulic Pumps	(Mkadara & Paulmann, 2018)
14.		General degradation	Adjusts speed of pump to desired output pressure and samples the motor current for HM	Engine Fuel Metering Pump	(Parsons & Alstrin, 2007)
15.			Leverages a reference model to compare the sampled signals	Airborne Lubrication Pump	(Shi et al., 2018; Delaloye, 2009)

16.			Records the position of the valves and line pressures then compares it to some reference value	Aircraft Fuel Valve	(Flint, 2007)
17.		Cavitation	Model used to predict cavitation occurring by monitoring transient pressures across system		(Wang et al., 2019)
18.		System Leaks	Utilized multiple pressures sampled across system and actuator position to classify faults		(Lu et al., 2017)
19.	Flowrate			Aircraft Hydraulic Pump	(Ma et al., 2018; Bergada et al., 2012)
20.			Prognostics algorithm based on return oil flow to estimate RUL of equipment		(Li T. et al., 2018)
21.		General Degradation	Hybrid approach using a reference model and in-service data.		(Mkadara & Paulmann, 2018)
22.			Monitors the quantity of debris at pump outlet to assess engine health	Engine Fuel Pump	(Centers & Price, 1988)
23.		System Leaks	Hybrid based approach using a reference model and in-service data.		(Griffiths, 2005)
24.	Rotational Speed	General Degradation	Utilized rotational speed at which light-off is achieved for diagnosis		(Villeux, 2019)

Table 2: Summary of HM detection methods and related faults

A similar work was carried out by Hoffman (1981) under lab conditions. This not only highlights an alternative method of HM by monitoring flow quality, but also demonstrated how sensors attached to airborne pumps can be used to carry out HM for other components within the system.

Other works concerning predictive maintenance on aircraft have been carried out by Kahlert (2017) and Pandian et al. (2020) outline the benefits of applying HM to aircraft operations and propose a general strategy on how an HM solution could potentially be implemented with existing aircraft maintenance routines. These works, however, do not provide specific detail on how a test and certification regime could be applied to an already-developed HM solution. There is also no detail on how the HM diagnosis is implemented for fuel pumps. The method proposed by Lacey (1993) mathematically models the wear rate on engine fuel pumps that is mostly caused by corrosion, but no information is given to how a HM solution can be implemented to maximize its RUL.

6. CONCLUSION

This paper has provided a comprehensive overview for the HM of aircraft fuel pumps and incorporates consideration of other aerospace pumps used in the fuel system. This work also has summarized recent developments for airframe mounted centrifugal fuel pumps, highlighted the gaps in knowledge in relation to similar aerospace fuel pumps, and has discussed related HM technologies from relevant industries which could be applied to such pumps.

Various HM technologies have been successfully applied in other industries, such as vibration and electrical monitoring. However, not all the technologies are appropriate when taking the fuel system environment into consideration. Within the airframe, the pump is integrated within a limited structural space and submerged in fuel. In this hazardous environment, the conventional sensors may not work as effectively, or are simply deemed unsafe due to representing a new ignition risk. These constraints need to be considered as part the HM development, specifically when devising the most appropriate sensing techniques for airborne fuel pumps. Furthermore, the HM techniques that have been developed and tested under laboratory conditions are found not to be robust enough to deal with variability introduced by the external environment. HM of airborne pumps thus far has only been implemented under laboratory conditions. Developing novel HM technologies with prognostics will give operators forewarning of pump failure and enable implementation of preventative repairs. Despite the ongoing work in the HM of fuel pumps, there are still open questions that need to be addressed if HM technologies are to be realized for aircraft fuel pumps. Through this literature review, the following future research opportunities related to the HM of airframe fuel pumps for the benefit of industry and academia have been identified:

1. **Sensing Technologies:** Further research is required to establish which sensing technologies are most appropriate to be adapted for the hostile working environment inside the fuel system. Deploying multiple types of sensors may be a solution, however the reliability and integrity of these individual sensors is yet to be determined and a linked HM approach developed.
2. **Pump Control Integration:** At the present, no HM solutions have been implemented on in-service airframe fuel pumps and future HM solutions are proposed as an add-on feature. Future research is required to understand the benefits and limitations of applying HM as an auxiliary solution to the pump, or if the HM technologies could be better implemented as part of the innate design of the fuel pump motor controller.
3. **System Integration:** Hardware integration and fusion of HM-related data across the aircraft fuel system requires further study. The HM solution sensors and their data will need to be combined with the existing Fuel Control System and the Flight Warning System. This synthesis of data on the flight atmospheric and fuel system conditions will also need to be understood to enable HM approaches for the fuel pumps.
4. **Baseline Information:** There is a lack of operational and sensor information of aircraft fuel pumps under environmental conditions, which are representative of flight conditions. Simulated faults, accelerated life and performance tracking experiments, as well as capturing the fuel system environmental data during flight will require verification of the appropriate baseline and threshold values, for a HM implementation of aircraft fuel pumps. The design of an experimental program to generate such data, or data processing and mining methods of published operational data.
5. **Prediction Models:** More prediction models are needed which can generate the RUL from existing sensing technologies. How far in advance the warning information can or should be provided, as well as how to adjust the maintenance strategy based on the outputs of these predictive models, are open research questions. Present health monitoring solutions have not been fully optimised, and the effects of system performance deterioration are unclear, and require further study.
6. **Cost Evaluations:** Financial assessments related to the deployment of novel HM technologies for aircraft fuel pumps have not been studied. The implementation costs compared to the return on investment from the improved prediction accuracy will need to be examined.

This review has shown that there is scope for development in conducting HM for airborne fuel pumps. Despite the differences in operations with pumps used in aircraft fuel systems, there is large possibility for HM technology transfer from other industries. The airline operators would benefit if these existing HM solutions could be integrated with aircraft fuel pumps in the future.

ACKNOWLEDGEMENTS

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NOMENCLATURE

HM	Health Monitoring
HI	Health Indicator
LP	Low Pressure
HP	High Pressure
CG	Centre of Gravity
RUL	Remaining Useful Life
DC	Direct Current
BLDC	Brushless Direct Current
AC	Alternating Current
ESA	Electrical Signature Analysis
CBM	Condition Based Maintenance
EPO	European Patent Office
USPTO	United States Patent and Trademark Office

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BIOGRAPHIES

Tedja Verhulst Tedja is an EngD Research engineer who is currently pursuing his doctorate degree. He has an integrated Master's degree in Electronics engineering Meng (Hons) from the University of Manchester. Prior to starting his degree, he worked in British Steel and Airbus. In British Steel he worked in the maintenance department, where he had to manage various assets in the steelworks, such as pumps and motors. In Airbus, he worked in the Fuel Systems department where he filed a US/UK patent at the end of his year there in health monitoring of fuel pumps.

David Judt Dr. David Judt is a Lecturer in Airframe Systems Design in the Centre for Aeronautics at Cranfield University. He teaches Airframe System Design, Design for Manufacture. He has 10 peer-reviewed full articles including 6 articles in journals and 4 in ISI/Scopus indexed proceedings. He has been the first author of 6 articles and presented at major international conferences, such as AIAA's ATIO (2012), NATO's STO/AVT (2012) and SAE's ASTC (2018). Through his developing publication impact, he has become an active reviewer in the domain of heuristic search algorithms and airframe system design, for publications such as the RAeS Journal, Integrated computer aided engineering and EPSRC funding proposals.

Craig Lawson Dr. Lawson is a Reader in Airframe Systems at Cranfield University, UK, and his teaching responsibilities include lecturing aspects of aircraft design and performance at postgraduate level. He has a BEng (Hons.) in Electrical and Mechanical Engineering from the University of Edinburgh, UK and a PhD in Aerospace Engineering from Cranfield University, UK. He has been Principal Investigator on grants totalling more than GBP£1.3m, with a focus on aircraft level impact of novel systems. He has published 60+ research papers. He is a CEng, FHEA, FRAeS.

Yongmann M. Chung, Dr. Yongmann Chung is an Associate Professor of Computational Fluid Dynamics (CFD) at the University of Warwick. His expertise is High Performance Computing (HPC) and CFD of turbulent flows. Dr Chung worked on several EPSRC projects on aircraft skin-friction flow control in collaboration with Airbus Group. Dr Chung worked on the EU-funded AirPROM project; a multi-scale lung modelling project involving expertise in physiology, radiology, image analysis and computational modelling. His research team developed medical-image based, patient-specific CFD modelling methodologies. Dr Chung has published over 100 journal and conference papers

Osama Al-Tayawe is fuel Systems engineer from airbus UK. He specialises in the fluid-mechanic side of fuel systems and has over 20 years' experience in the department. He has worked on various components in the fuel systems but specialises in fuel pumps and motor-actuated valves. He obtained his doctorate from Bristol University and has worked as lecturer King Fahd University of Petroleum and Minerals in Saudi Arabia. He has worked for almost aircraft programmes for Airbus from the A300, to the latest A350.

Geoff Ward is a fuel Systems engineer from Airbus UK. He specialises in the control and electronics of aircraft fuel pumps and has experience working on other avionics components within fuel systems. He joined Airbus in 2008 but has also worked for the company even longer as a consultant for the A380 program. Prior to working for Airbus, he worked as electronics engineer for various aerospace-related projects.