Evaluating Strategies to Mitigate Jamming in Electromechanical Actuators for Safety Critical Applications

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ABSTRACT

In this paper various techniques to mitigate jamming in Electromechanical Actuators (EMA) for safety critical applications in aerospace are evaluated. This paper highlights and assesses what has already been achieved and the challenges still to be addressed. Through Hierarchical Process Modelling (HPM), it was identified that Prognostics and Health Monitoring (PHM) and achieving fault tolerant designs in EMAs could be considered as means to mitigate jamming. The evaluation of past research revealed that achieving a fault tolerant EMA system through a reliable and robust anti-jamming system is currently at an early development stage for implementation within safety critical systems due to the increased design complexity (the anti-jamming system may even require PHM functionality itself).

It was concluded that a hybrid diagnostic approach to predict the onset of jamming would be the most optimal approach by using a combination of model based and data-driven techniques to capture any discrepancies between the predicted and observed behaviour to isolate and identify faults. Furthermore, in order to achieve a robust and reliable hybrid diagnostics functionality (to mitigate EMA ballscrew jamming), recommendations were made to improve modelling fidelity and test stand analysis methodology, these are discussed in more detail in this paper.

Keywords—Prognostics; Health Monitoring; Aerospace; Ballscrew; Electromechanical Actuators; Jamming

1. INTRODUCTION

EMAs are becoming an attractive proposition for aircraft manufacturers to replace traditional hydromechanical systems due to ease of maintenance and potential for precision control (Hoffman, et al., 1985). This is especially true for safety critical applications such as primary flight control systems and landing gear systems. The issue, however, has been the absence of reliable fail-safe mechanisms and redundancy to mitigate the single point of failure (ballscrew jamming) which has made it challenging to introduce EMAs to such systems (Balaban, et al., 2009). Therefore, the purpose of this paper is to evaluate the progress made so far in trying to mitigate the onset of EMA ballscrew jamming.

1.1. Background

Up until the 1970s, electrical power on commercial aircraft was predominantly used on electronic and utility functions with sparse application for other functions (Jones, 1999). Given the advances in permanent magnet materials and power electrical devices, the use of electrically powered applications in place of traditional hydraulics and pneumatics appeared to be more advantageous thus prompting a drive towards the concept of All Electric Aircraft (AEA) near the end of the 1970s (Jones, 1999).

Studies conducted by NASA in the mid-1980s (Hoffman, et al., 1985) concluded that whilst application of AEA technology is feasible and the benefits of achieving a reduction in operational costs due to the weight saving advantages and maintenance is possible, such wholesale changes would bring about more risk for the conservative and

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safety driven aerospace industry. Therefore, this has prompted the industry to opt for an incremental adoption of electrical technology within secondary aircraft systems thus the process is now known as More Electric Aircraft (MEA) (Jones, 1999).

As mentioned, much of the research for MEA has considered replacing actuation systems from traditional hydromechanical actuators to EMAs. Actuators on a typical commercial aircraft are principally found on the flight control surfaces as shown in Figure 1.

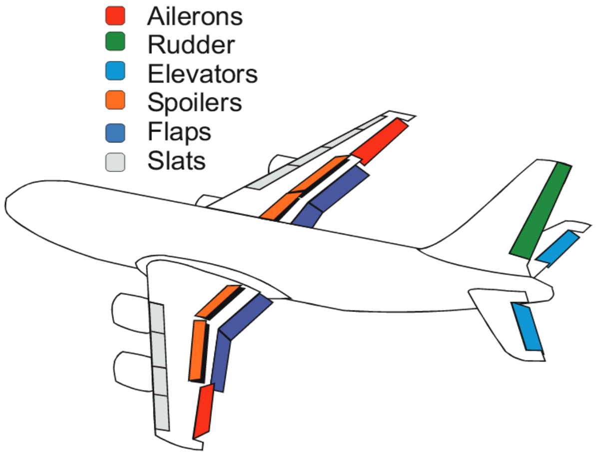

Figure 1. Flight Control Surfaces (Bennett J. , 2010).

The ailerons, rudder and elevators are classified as primary control surfaces and are safety critical applications. Another safety critical application that uses actuation systems is the landing gear system, in particular the extension/retraction mechanisms. Figure 2 shows an example of a typical main landing gear system.

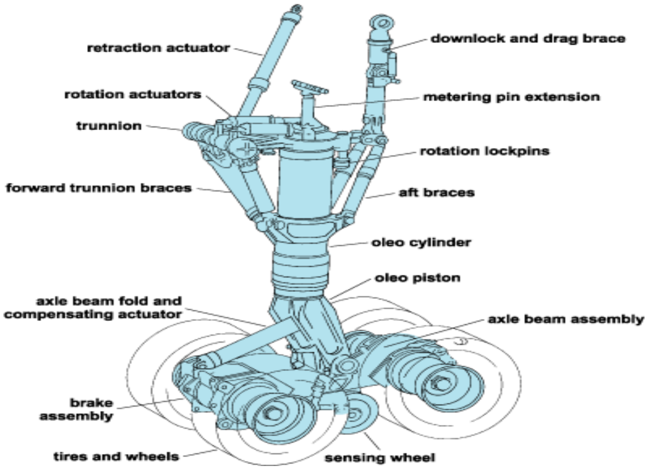

Figure 2. Example Main Landing Gear (Landing Gear parts, 2015).

EMAs consist of a motor, gearing and a ballscrew to provide incremental linear motion powered by the motor. Figure 3 shows a schematic of a typical EMA system.

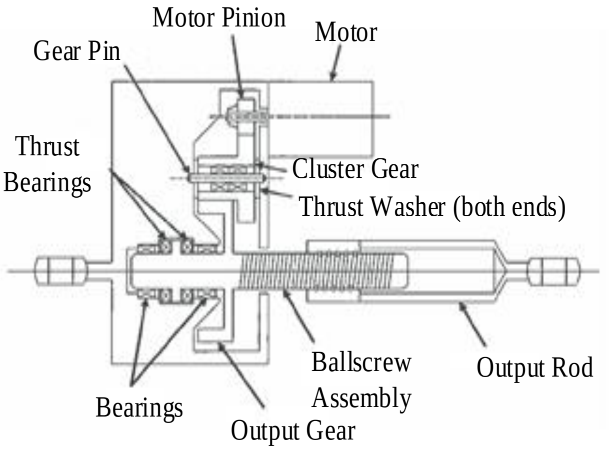

Figure 3. EMA System (Bodden et al. 2007).

EMA ballscrew jamming (a single point of failure) has been identified as a major factor in preventing EMAs from being more thoroughly considered as an actuator for safety critical applications (AIR5713, 2008). Another issue also arises on whether EMA redundancy can be designed to equal the flight safety reliability of dual/triple redundant hydromechanical systems (Leonard, 1984).

Significant research was conducted through flight test and development programmes in the early 1980s in order to gain more confidence in implementing EMA technology for aircraft actuation systems (Cooper, 2014).

Lockheed and Sundstrand collaborated in a research programme to develop a flight-worthy EMA for an aileron on the Lockheed C-141 military aircraft (Norton, 1986). The EMA replaced a traditional hydraulic actuation system (for starboard aileron) with 14 hours of flight tests conducted in 1986. The flight tests demonstrated feasibility for EMA implementation to primary flight control systems, however, issues were reported relating to variable performance due to temperature and increased sensitivity to autopilot inputs (Norton, 1986).

Lucas Aerospace have also been involved in EMA research development from 1968 with early focus on missile control surfaces (Croke & Herrenschmidt, 1994). Lucas Aerospace went on to design and develop EMAs for aircraft actuation systems in 1988. The design considered an EMA with a brushless DC motor powered by a 270 VDC bus. The initial design was only implemented for test bench purposes, however, advancements were made with preliminary designs factoring in installation to an aircraft envelope (with the assistance of a commuter jet manufacturer) (Cooper, 2014).

Boeing introduced EMAs to aircraft actuation systems to their Boeing 777 aircraft in the early 1990s. The EMAs were implemented as an electrical backup arrangement for the flaps and slats (Rea, 1993). EMAs also feature on the Airbus A380 slats and tail horizontal stabiliser (Adams, 2001). On more recent aircraft, EMAs have also been implemented on the Boeing 787 on 4 (out of 14) spoilers as well as for wheel braking (Mare, 2016).

Given the sparse implementation of EMAs in today's commercial aircraft actuation systems, Electro-hydraulic Actuators (EHA) are considered the intermediate solution between hydromechanical and electromechanical actuation systems (Bennett, 2010). EHAs are essentially a hybrid electrical and hydraulic device where the actuator is hydraulically operated with the hydraulic fluid self-contained and pressurised by an inbuilt motor to drive the actuation mechanism (Churn et al. 1998). EHAs are viewed as advantageous over conventional hydraulic systems with increased fluid pressure and power density during actuations (Moir et al. 2008). Loss of operation would inhibit the hydraulic rod in exerting a force thus defaulting to damping action allowing for an adequate fail-safe mechanism by enabling other actuators to fulfil the actuation (Bennett, 2010). This makes EHAs the preferred choice in safety critical applications today.

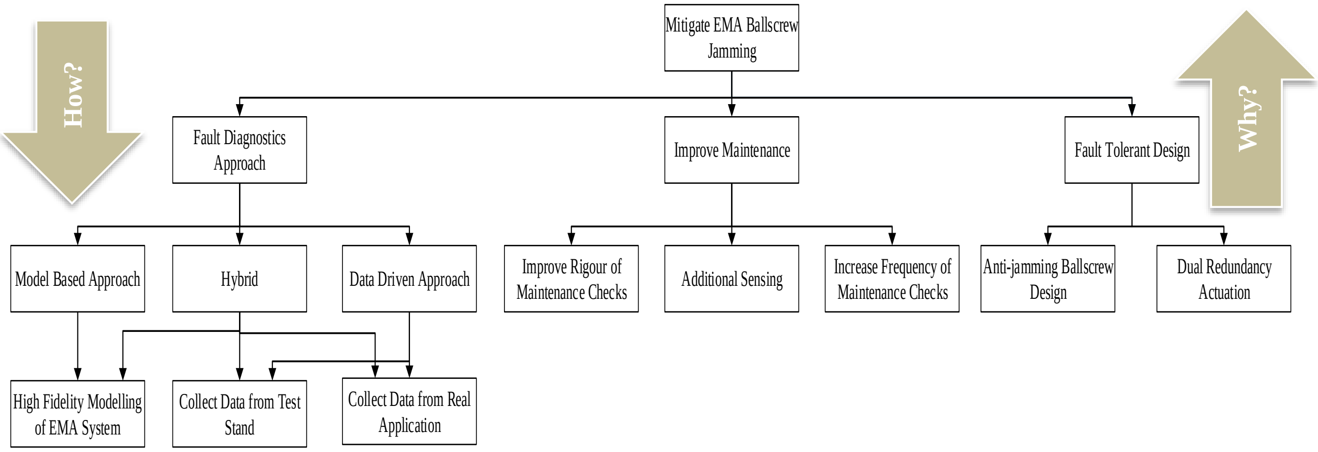

Figure 4. Hierarchical Process Model.

Significant research has been conducted in an attempt to either detect and predict the onset of ballscrew jamming using PHM or design for a fault tolerant design. This paper evaluates the current state of play in applying these approaches in more detail in the subsequent sections.

2. METHODS TO MITIGATE JAMMING

A Hierarchical Process Model (HPM) model was constructed to introduce a high-level understanding on what has so far been achieved and what could be considered in trying to mitigate EMA ballscrew jamming.

A HPM can be a useful way to manage complexity to a single problem. HPM modelling intends to show hierarchy with each level representing a more detailed decomposition of processes indicating transformational entities. HPM is driven by the need to support effective decision making whilst acknowledging issues related to risk and uncertainty. Pidd (2004) identified the need behind HPM by describing nature as being hierarchically organised with emergent properties at various levels of complexities.

The structure of a typical HPM model stems from an initial purpose statement, which then branches downwards by exploring how it could be achieved through various system levels, as more detail is added (Checkland et al. 2007). Figure 4 shows the HPM model with purpose statement 'Mitigate EMA ballscrew jamming'. At the same time, this enables one to establish purpose and reasoning of a solution when viewing the HPM bottom up (Checkland et al. 2007).

As can be seen from the HPM in Figure 4, there is a clear distinction between achieving a robust means of Fault Diagnostics and Fault Tolerant Design. Various approaches under each of these categories were considered historically. Sections 2.1 and 2.2 evaluates these more in detail.

The 'improve maintenance' node has been neglected from in-depth evaluation as this could prompt a change to existing maintenance policy by the Maintenance Review Board (Robelin, 2010). Additional maintenance actions would also incur further costs due to increased labour and aircraft downtime (Jennions, 2012).

2.1. Fault Tolerant EMAs

As has been discussed, one of the main drivers for moving towards MEA through implementing electrically actuated systems is to gain benefit through weight savings as well as reducing maintenance. In particular, the introduction of EMAs to replace hydraulic systems could make for easier connections by using electrical cables in place of hydraulic pipes, as well as eliminating the infrastructure required for a hydraulic based system (Stridsberg, 2005).

Significant research has been achieved in trying to achieve fault tolerant electric drives in aircraft systems. As mentioned, a fault tolerant electric drive reduces the overall likelihood of a failure for an EMA especially with the presence of dual/triple motor redundancy in aircraft systems. Bennett et al. (2011) reaffirmed that with each lane including an independent converter, a fault tolerant electrical drive can withstand failures associated to power supply and control interface and therefore increasing the number of lanes would skew the EMA reliability figure towards the mechanical components. Figure 5 shows an EMA fault tree with dual lane fault tolerant electric drive derived by Bennett et al. (2011).

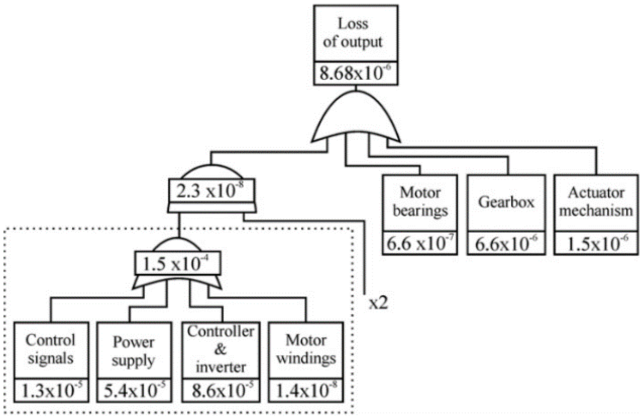

Figure 5. EMA Fault Tree with Dual Lane Fault Tolerant Electric Drive (Bennett et al. 2011).

As a result, this section evaluates the work completed on trying to achieve a fault tolerant EMA design through anti-jamming systems whilst keeping in mind the benefits of MEA as described above.

2.1.1. Anti-Jamming EMAs

There have been a few EMA designs which have factored in mechanical modifications in an attempt to prevent jamming.

Cronin (1985) proposed an EMA system with hydraulic coupling as a means to protect against mechanical jamming. The proposed arrangement was such that included an EMA connected to a control surface through an EHA (without a pump). The backup EHA exerted the same amount of force as the primary EMA, however, such an arrangement adds significant weight and complexity to the overall system thus deeming such solution unsuitable for implementation to safety critical aircraft actuation systems.

Collins et al. (2004) proposed a dual actuator system acting on a single flight control surface over a summing lever. The summing lever position corresponds with the sum of the positions of the actuators attached to it. Jamming of one of the actuators would result in the other actuator to compensate for the malfunctioning one in order to bring the flight control surface to a neutral position. The proposed design would include two EMAs and a link arm which not only adds weight but increases design complexity.

More recently, Nguyen et al. (2014) proposed an EMA design for jam tolerance which incorporates a damper assembly that becomes coupled to the output rod (connected to the moveable surface) during the event of a mechanical jam. This in turn decouples the ballnut from the output rod. The damper system ultimately enables a passive, controlled rate return of the EMA output to a fail-safe position along with a latch that holds the position (within fail-safe mode). The overall process relies on a complex mechanical arrangement which may in turn require additional scheduled maintenance actions and possibly condition monitoring.

Aside from achieving a jam-tolerant EMA system, aircraft manufacturers face other technical challenges for EMA implementation to flight safety critical systems. Todeschi (2011) highlights constraints in installation of EMAs (for flight control systems) whereby space may be limited to accommodate a complex EMA system architecture. Todeschi (2011) also emphasised that 'weight' would be another constraint during the design phase as well as design complexity which could impact maintenance scheduling and introduce further health monitoring.

Given the criteria described by Todeschi (2011), the designs presented (for anti-jamming EMAs) could bring about operator concerns on reliability, weight and implementation.

2.2. Prognostics Techniques

PHM attempts to provide insight into a component's health, and determine its Remaining Useful Life (RUL); PHM can thus increase availability by reducing unscheduled removals and reducing downtime, ultimately reducing Direct Maintenance Costs (DMC) (Jennions, 2012).

The Fault Diagnostics approach involves a process of identifying an instance of a component or system experiencing a behaviour that is different from the expected behaviour followed by locating the origin and cause of the fault(s). Significant research has been conducted in terms of trying to develop a health monitoring approach to mitigate the onset of ballscrew jamming both within academia and industry.

This section evaluates the progress made in PHM (for mitigating EMA jamming) with particular focus on modelling approaches, data-driven methods and the hybrid approach.

2.2.1. Modelling Approach

A physics-based approach through high fidelity modelling of an EMA system for fault detection and failure prediction has been considered to be a useful preliminary step in understanding system behaviour under normal and abnormal conditions. Modelling an EMA system in detail can enable the prognostics design engineer to trace back failure modes to relatable physical system parameters thus providing the engineer with helpful diagnostic information.

Byington and Stoelting (2004) presented a model-based approach to PHM for EMAs on flight control actuators. The methodology was centred around diagnosing failures associated to the motor, gear slippage and bearings. Failures were selected based upon the highest number of occurrence from in-service events. A mathematical dynamical model of the EMA system was developed using Matlab/Simulink of which was linked to the physical processes that drive the health monitoring of the EMA. This included emphasis on modelling friction co-efficients at key elements of the EMA drivetrain such as the motor, gearbox and ballscrew. This was varied to understand the impact on response time, motor current and load.

Modelling of a system to understand the physics of failure by monitoring system parameters is viewed as a cheaper alternative which is less time consuming and labour intensive than building a corresponding test stand. A high fidelity and exhaustive model of the system features can enable identification of parameters that are associated to the build-up of a specific failure mode. This can therefore allow utilization of parametric estimation for diagnostics application and state of health estimation, however, this is dependent on the level of modelling effort and granularity.

Whilst modelling is a useful means to get an initial perspective of a system, it is never a 'true' representation of the actual behaviour. For instance, Byington and Stoelting's (2004) approach utilized variation of friction coefficients as a means to perform sensitivity analysis to evaluate mechanical losses in the drivetrain. The reality, however, is that friction is prevalent in many areas of the drivetrain, therefore, it would be difficult to ascertain the location of the friction build-up. It would require one to quantify the amount of mechanical losses attributed due to friction by mitigating the effects of external loads, backlash and any other unwanted non-linear effects. It is therefore imperative that in the case for modelling the physics of failure behind ballscrew jamming, a more robust approach is taken in terms of modelling wear and friction by considering the most contentious areas of friction within such systems.

Maggiore et al. (2014) developed a Matlab/Simulink model of an EMA system to be utilised for fault analysis associated with mechanical failures due to progressive wear; this includes friction, backlash, coil short circuit and rotor static eccentricity. The research was focused on characterising and building system-representative models for these failure modes. The modelled EMA system was typical of an arrangement for a primary flight control system comprising a control and power drive electronics, a Brushless Direct Current (BLDC) motor, gearing and a ball/rollerscrew. Motor current, angular speed and position were the parameters being monitored. Subsequent failure maps were derived for fault detection/evaluation based on simulations of the different types of failures.

Maggiore et al. (2014) gave importance to the build-up of friction as a pre-cursor to the onset of jamming. The corresponding failure maps of motor current provided useful information in terms of evaluating friction torque at a system level by assigning thresholds for the onset of a failure. It, however, is not clear whether friction monitoring at local levels for contentious contact regions in the ballscrew (ball and nut, and ball and screw) could be characterisable especially when trying to diagnose for jamming faults from these contact areas.

2.2.2. Data-driven Approach

A data-driven method to PHM can be split up into two approaches:

(a) Retrieving data from a real application such as an in-service EMA;

(b) Retrieving data from a representative test stand.

Obtaining data from an in-service EMA can be seen as advantageous as the information generated will be a true representation of the application usage profile and system behaviour. By this, aerodynamic loads and other environmental effects are factored in. The issue, however, is the limited nature in which the data is obtained. Aircraft manufacturers are very reluctant to have additional sensing due to added weight implications and reliability (Donald et al. 2004), therefore making it challenging for diagnostics engineers to isolate a problem like jamming within the EMA drivetrain based on motor current signals alone. Such approach, however, is considered within a PHM framework through a combination of physical modelling and test stand data, of which is discussed later in this paper.

The building of a bespoke EMA test stand can enable one to perform run-to-failure tests as well as seeded failure tests. The advantage here is that more sensors could be added to improve the understanding of the system behaviour as well as characterise different types of failures modes. A significant amount of research has been conducted in this area with particular focus on simulated seeded failure tests to EMA test stands.

Bodden et al. (2007) seeded contaminant to an EMA test stand and cycled it until failure. The amount of debris was the key parameter for setting the rate at which a jamming would occur. A measure of actuator efficiency was quantified by taking the ratio of power output and power input of the system. It was found that as heat and vibration energy increased, the power input to the system increased and therefore increased the motor current demand. The test stand was also fitted with other sensors in order to identify other pre-cursors such as temperature and vibration in addition to motor current. Temperature readings were recorded (thermistors mounted on the rear of the motor housing) with increased temperatures observed which were attributed to the higher level of friction in the system due to the induced debris. Such readings, however, were not characterisable against the nature of the simulated fault therefore making it difficult to isolate the actual location of the increased friction in reality.

An EMA test stand was built with airworthy equipment in which in-flight data was post processed on the ground (Balaban, et al., 2009). This followed the philosophy of taking the data off aircraft and performing prognostics on the ground. Jamming faults were simulated on the test stand with results showing good agreement with developed thermal and mechanical models. The issue, however, was the abrupt nature in which the jamming occurs making it challenging to design a prognostics algorithm based on such data. Using the same test stand, Balaban, et al. (2010) also introduced spalling to the ballscrew to understand the effects on the system response of the EMA. Indentations were created in the test ballscrew at high stress contact points at dimensions of 0.3 mm depth and widths ranging from 0.3-0.5 mm to evaluate how the size of the initial spall affects the nature of its growth. An accelerometer was fitted to the nut of the ballscrew to monitor the frequency of the system. The results showed that there was increased vibration in the ballscrew due to the induced spalling.

Unless certain fault modes can be characterised through EMA test stand analysis, it may be challenging to isolate and identify a particular fault mode such as ballscrew jamming.

2.2.3. Hybrid Approach

The methods discussed so far have solely considered a modelling approach or a data-driven approach in isolation. A hybrid approach to fault diagnostics would entail employing a detailed model of an EMA system against an equivalent physical EMA system to capture any discrepancies from normal behaviour. This would then enable one to identify and isolate faults to prompt further investigation.

Narasimhan et al. (2010) presented a hybrid diagnostic approach that involved the fusion of model-based and data-driven based methods. The data-driven method was based on the previously built flyable EMA test stand by Balaban et al. (2009). A top level diagram of the hybrid approach followed is shown in Figure 6.

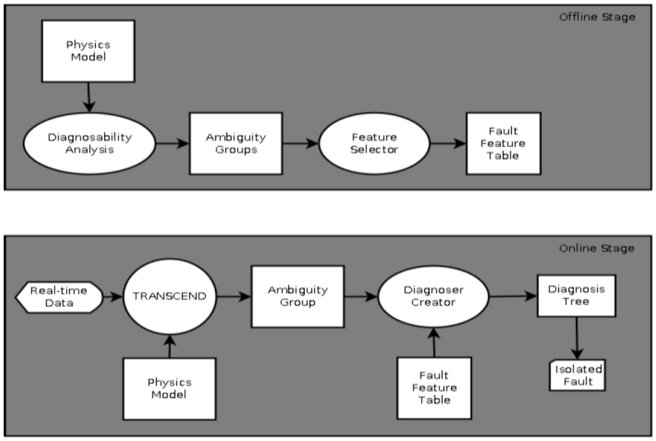

Figure 6. Hybrid Diagnostics Approach (Narasimhan et al. 2010).

The hybrid diagnostics approach presented by Narasimhan et al. (2010) not only combined model-based and data-driven methods, but considered offline and online stages in the diagnostic process. The offline stage involved use of an EMA system physical model to generate repeatable fault signatures, which were then categorised into fault feature tables. The online stage utilised real-time data (from the flyable EMA test stand) from which anomalies were detected and isolated using the physical model before classifying ambiguity groups.

A data fusion approach can be seen as advantageous as the combination of modelling and data-driven analysis can help to isolate and identify certain types of faults by comparing predicted and observed system behaviour.

3. RECOMMENDATIONS

Out of the strategies evaluated, many challenges remain in trying to mitigate the onset of EMA ballscrew jamming. This section proposes recommendations which could be made in pursuit of trying to solve this problem given the advances in the field so far.

A hybrid approach to fault diagnostics of the EMA jamming case could be considered the optimal approach (Sampath et al. 2003). The success of the hybrid approach would, however, still rely on the robustness of the modelling and data generated from an EMA test stand and/or real application. In order to fulfill this, the following recommendations have been suggested:

Test stand analysis

Seeded fault tests to EMA ballscrews have so far mostly included introducing debris as well as physical damage to the screw.

The balls within the ballnut of a ballscrew system can undergo thermal expansion due to heat caused by friction (Jeong & Park, 1992). This can lead to a degradation in performance and positioning accuracy. Figure 7 shows an example of temperature variations due to different ballnut preloads and Thermal Contact Conductance (TCC) using finite difference methods.

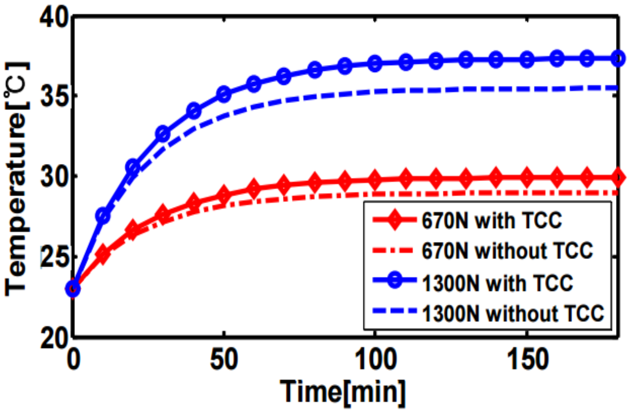

Figure 7. Temperature Variations due to Varying Nut Preloads and TCC (Min et al. 2016).

It is therefore recommended that such conditions be considered in test stand analysis by seeding deformed or slightly larger balls in the ballscrew to simulate and evaluate the effects of ball deformation due to thermal expansion.

Whilst useful information can be obtained from simulating seeded faults to a healthy actuator, limitations still exist in understanding the true nature from which a particular failure mode may initially manifest. It is therefore recommended to consider the re-use of older actuators that would have started to exhibit wear and degradation naturally from in-service application. This could enable one to distinguish and characterise properties for systems with lower mechanical efficiencies.

Modelling and simulation

For the purpose of conducting a modelling approach to identify the onset of jamming, it is proposed that the EMA should be modelled as a direct drive system as opposed to a gear driven system. The elimination of the gearbox would reduce the probability of jamming and therefore simplifies the analysis in diagnosing ballscrew related jamming failures (Gerada and Bradley, 2008).

It is also proposed that the modelling considers a 3-phase electrical motor model such as a Permanent Magnet Synchronous Motor (PMSM) for the EMA system. PMSMs and BLDCs are similar in that they both have a permanent magnet in the rotor and both require alternating stator currents to produce constant torque (Pillay and Krishnan, 1991). For 3-phase machines, Field Oriented Control (FOC) techniques can be applied where 3-phase AC quantities (I_A, I_B, I_C) can be reduced to DC quantities (I_D, I_Q) using Park's transform (Park, 1929).

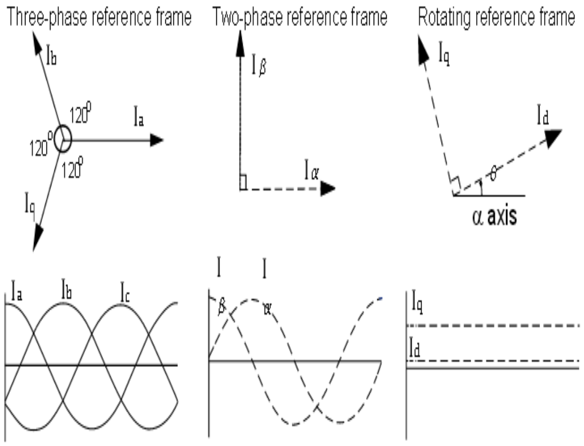

Figure 8. Reference Frames.

This can enable simplified analysis of the DC quantities which can provide in-depth motor understanding for condition monitoring and fault detection within the EMA drivetrain.

Buildup of friction is considered a pre-cursor to EMA ballscrew jamming (Balaban, et al., 2009). It is therefore proposed that modelling the most contentious areas of friction within the ballscrew (ball and nut, and ball and screw (Vahid-Araghi et al. 2011)) to a high fidelity can improve the characterisation of such features for fault detection.

4. CONCLUSION

Various approaches to mitigate EMA ballscrew jamming have been evaluated in this paper. Through HPM modelling, achieving a fault tolerant EMA system as well as a robust fault diagnostics algorithm were considered the two main ways to prevent the jamming case.

A review of literature showed that implementation of a fault tolerant EMA (anti-jamming EMAs) to aircraft safety critical systems was still at an early development stage due to aircraft manufacturer concerns to do with weight, reliability and installation constraints.

Literature and past research on PHM methodologies (mainly modelling and data-driven approaches) were also evaluated. It was viewed that a hybrid approach to diagnosing EMA ballscrew jamming faults could be most optimal. The performance of this approach could be maximized through data fusion between a model and test stand data in order to capture discrepancies between predicted and observed behaviour to then isolate and identify the fault from which would prompt further investigation. This is dependent on the granularity of the model as well as the observability of the test stand data.

In order to improve the robustness of the hybrid approach, recommendations were also made in this paper to consider modelling the EMA to a high fidelity with emphasis on modelling the most contentious areas of friction in order to improve characterisation of impending jamming faults. It was also proposed to consider learning from naturally occurring faults (as opposed to simulating seeded faults) by re-using older actuators that have started to exhibit wear from in-service application.

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