Vibration-based Fault Detection and Quantification for Primary Flight Control Electro-Mechanical Actuators

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ABSTRACT

Electro-mechanical actuators (EMAs) are an emerging and promising technology for primary flight control surfaces. EMAs can provide higher energy efficiency compared to existing hydraulic actuators. However, limited in-service experience of EMAs requires intensive research in order to show that they match the superior reliability levels of hydraulic systems. Recently, numerous studies have explored a reliability mitigation approach that uses a predictive maintenance system instead of scheduled checks and inspections, typically used for most aircraft systems. Predictive maintenance, comprising embedded sensors and health monitoring methods, is expected to predict crucial faults and their corresponding maintenance. This study aimed to investigate fault detection and quantification methods, for selected mechanical degradations, i.e. wear and localized spall, of flight control EMAs in support of predictive maintenance systems. This work is based on experimental investigations using fault-injected data sets collected from dissimilar EMA test stands provided by the German Aerospace Center (DLR) OMAHA-EMA testrig and the NASA Ames Research Center Flyable Electro-Mechanical Actuator (FLEA).

1. PROBLEM STATEMENT

Recent flight tests and accelerated-aging experiments have showed that the mechanical components of EMAs (e.g., bearings and ballscrews) have the highest potential for predictive maintenance (Bodden et al. 2007; Todeschi & Baxerres 2014). These components mainly degrade by two modes: distributed wear and localized spall. These modes have both been intensively studied under fault detection scope using model- (Balaban et al. 2009; Narasimhan et al. 2010) and data based techniques (Bodden et al. 2007; Isturiz et al. 2012; Chirico & Kolodziej 2012). A significant research gap related to the limited knowledge of wear and spall fault detection performance exists considering the wide loading conditions in which they operate, including no-load pre-flight check. In addition, fault quantification studies of EMAs are limited to the wear mode, and no prior research has been cited for quantification of the spall mode.

2. EXPECTED CONTRIBUTIONS

Two main research questions have been determined based on the current state-of-the-art literature. Several sensing technologies have been studied in the literature in separate investigations based on dissimilar operating and fault conditions. A significant research gap in the literature can be demonstrated by the following question: *What is the significance of utilizing three sensing technologies (EMA load current, vibration, and ultrasound sensors) considering identical and widely varying operating conditions, fault types, and severity levels?* This question encompasses two operating conditions cases for full load/speeds and for a pre-flight check. Fault diagnosis has not been studied intensively at no-load conditions, which is an important diagnostic opportunity during pre-flight checks.

The second question is related to fault quantification challenges. The fault-growth phenomenon in the case of localized faults (for ball bearings and ballscrews) has not been investigated in the literature for flight control EMA. The results of the first research question will be further extended to study fault growth based on different sensor features as follow: *What signal features are most correlated with fault-growth?*

3. RESEARCH CONTRIBUTIONS

3.1 An investigation for detecting bearing faults for ballscrew based EMAs

A challenge for detecting bearing faults within EMAs, using state-of-the-art industrial methods, is the presence of a ballscrew mechanism that produces a nominal vibration noise similar to that of faulty bearings. No prior research has investigated this problem. An investigation for vibration noise of EMAs with seeded bearing faults showed that the EMA ballscrews produce a vibration noise induced by a design element (the ballscrew return channel) that is independent of the health of the ballscrew or the actuator (Ismail & Windelberg 2017). This noise has a cyclic frequency modulated by a wideband carrier and may mask vibration noise generated by faulty bearings. In addition, fault detection performance has been experimentally evaluated by three sensing technologies: accelerometers, ultrasound, and phase current. The best sensors are an accelerometer, Power Spectrum Density (PSD) signal feature and an ultrasound sensor, pre-whitened RMS feature. Both of them achieve coverage scores of 100% for 16 different operating conditions with sensitivity levels higher than 100%.

3.2 Unsupervised fault detection and classification for EMAs jam and spall faults

An experimental investigation for vibration noise of EMAs injected by jam and spall faults showed that specific vibration signatures, that are correlated with EMA ballscrew kinematics, could be effective to detect and classify actuator jam and spall faults (Ismail et al. 2016). A new vibration-based technique has been developed for detecting two incipient EMA faults without needing an initial stage of fault feature learning. The two faults considered in the study are a high-criticality jam and a low-criticality spall (metal flaking) in the actuator ballscrew mechanism. The actuator position is used to resample variable-speed vibration measurements of a single accelerometer into constant-rate measurements. A set of health characterization signatures is derived theoretically based on the EMA ballscrew kinematics. These theoretical signatures are compared with the signatures extracted from vibration signals measured experimentally on the EMA test articles. The vibration signatures approach is also compared to the diagnostic approach based on EMA motor current measurements. The technique has been validated on fault-injected data sets collected on the NASA Ames Research Center Flyable Electro-Mechanical Actuator (FLEA) test stand.

3.3 Vibration response characterization and fault-size estimation of spalled ball bearings

Research efforts have increased to investigate the ability to quantify localized bearing faults, i.e., spalls. These efforts revolve around extending the useful service life of the bearing after the detection of spalls. A number of studies have investigated a linear correlation between the size of spalls and three geometric points that may be recognized in the vibration response: the entry into the spall, the exit from the spall, and a third impact point between the first two. The time difference between these points, calculated using different signal processing techniques, has been widely exploited for quantifying spall size (Sawalhi & Randall 2011; Randall 2011). Currently, there are two main challenges: the first is to enhance the entry point, which typically has weak excitation; the second is to distinguish the impact and the exit points investigated in the literature based on the spall size. However, for practical applications, there is no prior rough estimation of the fault size (i.e., small or large), and a method is needed for interpretation of responses. This study provides insights into the movement of the rolling element within the spall region and shows that the rolling element strongly strikes the bearing races at a minimum of two points (Ismail & Sawalhi 2017). Then, a new technique is presented to quantify the spall and determine the inherent scaling factor without comparison to any reference data. The technique is based on evaluating two root-mean-square (RMS) energy envelopes, one for the vibration signal and one for a numerical differentiation of this signal. A geometric scaling factor is then used to give a generalized quantification for the small and large spalls. Serviceable estimations of spall size have been achieved for several seeded faults measured on two dissimilar test rigs provided by German Aerospace Centre (DLR) and the University of New South Wales (UNSW). In 12 investigated cases from two dissimilar test rigs, the technique estimated the physical size of the spall with average errors of 12% and 13% and maximum bounds of 24% and 22% for DLR and UNSW data, respectively.

4. CONCLUSION

Experimental validation showed effective isolation of the fault conditions of interest significantly through vibration-based health characteristic frequencies and amplitudes. The electrical current-based signatures utilized in this study proved to be insufficient for isolating incipient wear and spall faults of EMA components. The ultrasound sensors could effectively detect mechanical faults if they are placed close to faulty components due to limited transmission of ultrasound energy. By contrast, vibration noise has adequate transmission energy through whole EMA because of its light structure. One accelerometer was sufficient, based on dissimilar EMAs, to detect and to quantify spall faults for ballscrew and ball bearings. The vibration-based techniques described in this study can be of benefit in predictive maintenance of aircraft by monitoring EMA degradation and alerting when maintenance intervention is required. This could, potentially, minimize unscheduled repairs and increase aircraft availability.

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