



**PASSIVE LOAD TESTING FOR EVALUATION OF ELECTROMECHANICAL
ACTUATORS**

THESIS

Jeremiah R. Hoffman, Second Lieutenant, USAF

AFIT-ENY-MS-18-M

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY**

Wright-Patterson Air Force Base, Ohio

DISTRIBUTION STATEMENT A.
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the United States Government. This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

AFIT-ENY-MS-18-M-263

PASSIVE LOAD TESTING FOR EVALUATION OF ELECTROMECHANICAL
ACTUATORS

THESIS

Presented to the Faculty

Department of Aeronautics and Astronautics

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Astronautical Engineering

Jeremiah R. Hoffman, BS

Second Lieutenant, USAF

March 2018

DISTRIBUTION STATEMENT A.
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT-ENY-MS-18-M-263

PASSIVE LOAD TESTING FOR EVALUATION OF ELECTROMECHANICAL
ACTUATORS

Jeremiah R. Hoffman, BS
Second Lieutenant, USAF

Committee Membership:

Anthony N. Palazotto, PhD
Chair

Lt Col Kirk Johnson, PhD
Member

Nicholas Niedbalski, PhD
Member

Abstract

While aircraft control surfaces traditionally use hydraulic actuators, many designers are moving towards electromechanical actuators (EMAs) as they have potential to be lighter, lower maintenance, and more robust [1]. However, EMAs require more research regarding force-fight characteristics, power requirements, performance specifications, and more. The Air Force Research Laboratory in Dayton, Ohio is conducting some of this research, and operates a test rig which provides a passive load to a pair of EMAs [2]. This rig is designed for simple test profiles, not representative of real maneuvers, for investigating force-fight; if it could be used to represent actual flight profiles, the rig could be used for a much wider variety of tests. The focus of this project is to evaluate the test rig's suitability for such profiles by developing a linear model of the test rig, using this model to determine whether flight profiles can be reproduced with the rig hardware, and finally by running examples of these profiles on the test rig to validate the capabilities of both the model and the rig. The linear model that was developed was able to reproduce two sets of data from early test rig characterization tests, as well as several profiles representative of those an aileron control actuator would experience during flight. Validation of these profiles on the test rig has shown accurate replication of flight data with rig hardware and rig test data with the model, indicating that the test rig would be useful for actuator characterization and design.

Acknowledgements

I would like to thank my advisor, Dr. Anthony Palazotto, for his advice and direction over the course of my research. His assistance on a topic in which I initially had little expertise was invaluable.

I would also like to thank Dr. Nicholas Niedbalski for all his contributions. Without his knowledge, advice, and information this project could not have been successfully completed.

Finally, I would like to thank the researchers at AFRL, in particular, Dr. Quinn Leland and Mr. Dan Wroble. Their data provided the starting point for this thesis, and their continued involvement and support was essential for its completion.

Table of Contents

Abstract	iv
Acknowledgements	v
List of Figures	viii
I. Introduction	1
Background	1
Problem Statement	5
Research Objectives	6
Methodology	7
Assumptions and Limitations	10
II. Literature Review	13
Electromechanical Actuation	13
Aircraft Control Applications	15
Spacecraft Control Applications	16
AFRL EMA Testing	17
MATLAB Methods	19
Function Minimization	19
Solving Differential Equations	20
Simulating Linear Systems	21
III. Methodology	23
Model Development	23
Hingeline Damping Test	32
Free Response Test	35
Flight Test Data Modeling	38
Flight Test Data Reproduction	42
IV. Results and Discussion	47
Model Development Results	47
Hingeline Damping Test Results	47
Free Response Test Results	49
Flight Test Data Modeling Results	52

Flight Test Data Reproduction Results	55
V. Conclusion	59
Conclusions	59
Future Work	62
Appendix A	65
Appendix B	68
Appendix C	72
Bibliography	88

List of Figures

Figure

1. AFRL Passive Electro-Mechanical Actuator Test Rig [AFRL]	4
2. AFRL PEMAT Rig – CAD Model [AFRL].....	4
3. Linear Model of PEMAT Rig.....	24
4. AFRL PEMAT Rig - CAD Model [AFRL].....	24
5. PEMAT Rig Turnbuckle Assembly	26
6. PEMAT Facility Hingeline Damping Test Configuration	33
7. Hingeline Damping Test - Right Actuation, 0.35 rad/s	34
8. PEMAT Facility Free Response Test Configuration.....	36
9. Free Response Test.....	37
10. NASA EPAD F/A-18 Aircraft [NASA]	39
11. Actuator Deflection during Aileron Reversal Maneuver	40
12. Actuator Deflection during Roll Doublet Maneuver	41
13. PEMAT Evaluation Test Profile - Left Aileron Reversal	43
14. PEMAT Evaluation Test Profile – Eight Point Roll.....	44
15. PEMAT Evaluation Test Profile - Four-G Left Turn	45
16. Hingeline Damping Test - Rig and Model Response	48
17. Free Response Test - Rig and Model Response	50
18. Aileron Reversal Maneuver - Actuator Flight and Model Data	52
19. Roll Doublet Maneuver - Actuator Flight and Model Data.....	53
20. Aileron Reversal Load Profile - Rig and Model Response	56
21. Eight Point Roll Load Profile - Rig and Model Response	56
22. Four-G Left Turn Load Profile - Rig and Model Response	57

PASSIVE LOAD TESTING FOR EVALUATION OF ELECTROMECHANICAL ACTUATORS

I. Introduction

Background

The primary method of aircraft control surface actuation has long been hydraulic, and the considerable body of research and knowledge regarding its application has been a staying force in maintaining its preeminence. However, as the thrust of aircraft research continues to push towards efficiency, agility, and integration, alternative methods of actuation are under consideration [1].

Prominent among the alternatives to traditional hydraulics are electromechanical actuators (EMAs), which utilize an electric motor and a screw gear or similar mechanism to produce a linear actuation. These EMAs have the potential to provide several benefits to the aircraft designers, maintainers, and operators: they can provide better force/weight characteristics, allowing for smaller, lighter actuators which contribute to benefits in both efficiency and footprint [3], they do not require the pumps, working fluid and other infrastructure necessary for hydraulics, again reducing both weight and volume, their relative simplicity in construction allows for a reduced maintenance cycle, they can provide finer control fidelity [4], and, particularly interesting for those abreast of the rapid growth in the space sector, they can be utilized on spacecraft, where all power is electrical, maintenance is nonexistent, and operation is conducted in vacuum.

Unfortunately, EMAs do not have the benefit of a large body of experimental data like that which has been amassed for hydraulics. While recent aircraft have begun utilizing EMAs and similar electrical actuators in secondary or tertiary flight control surface systems [5] there are several challenges facing EMA designers and integrators before these actuators can be considered a mainstream alternative to hydraulics: for example, EMAs require a significant input of electrical power which requires more robust power generation systems, operation envelopes and capabilities vary from traditional hydraulic systems, and issues unique to electrical systems can come into play as well. One such issue is force-fight, wherein two or more actuators which are connected to the same control surface, generally for redundancy, are slightly misaligned from one another resulting in the actuator loads increasing greatly as each begins pushing against the other. In a hydraulic system, the solution can be as simple as a release valve to let off some pressure and equalize the output; with an electrical system, there is no analog to a release valve, and various control scheme solutions must be explored [2].

As the United States Air Force is continually in pursuit of technological advancement in both aircraft and spacecraft, it is unsurprising that EMAs and similar control surface actuators have become an area of interest, and it is in an attempt to solve some of the challenges in utilizing EMAs that the Air Force Research Laboratory (AFRL) has allocated some of their resources [2]. The Passive Electro-Mechanical Actuator Test (PEMAT) Facility, designed, constructed, and operated by Dr. Quinn Leland, Dr. Nick Niedbalski, Mr. Dan Wroble, and additional AFRL personnel in conjunction with MOOG Aerospace, is a passively-

loaded test rig intended to aid in the exploration of methods for detecting and mitigating force-fight conditions in EMAs. Shown in photograph in Figure 1 and as a CAD model with labeled components in Figure 2, it utilizes a center hingeline which has a removable inertia disk at each end and a coupling mechanism at its center which connects to a quartet of flexible metal rods which serve as /torsion springs, two each at the north and south, which are also removable. Data is gathered from a pair of each torque cells and angle sensors, one of each on either side of the flex coupling. An EMA can be attached on either side of the hingeline, which represents the control surface or other element which the EMA system is intended to actuate, either one at a time or both together, and the desired load can be adjusted by including or removing the inertia disks and torsion springs. In this way, any number of tests can be conducted to induce a force-fight condition between the two actuators while under external loading, and from the position and torque data as well as the commanded position, power consumption, and other data available from the actuators themselves, various detection methods, control schemes, and mitigation strategies can be explored and evaluated [6].

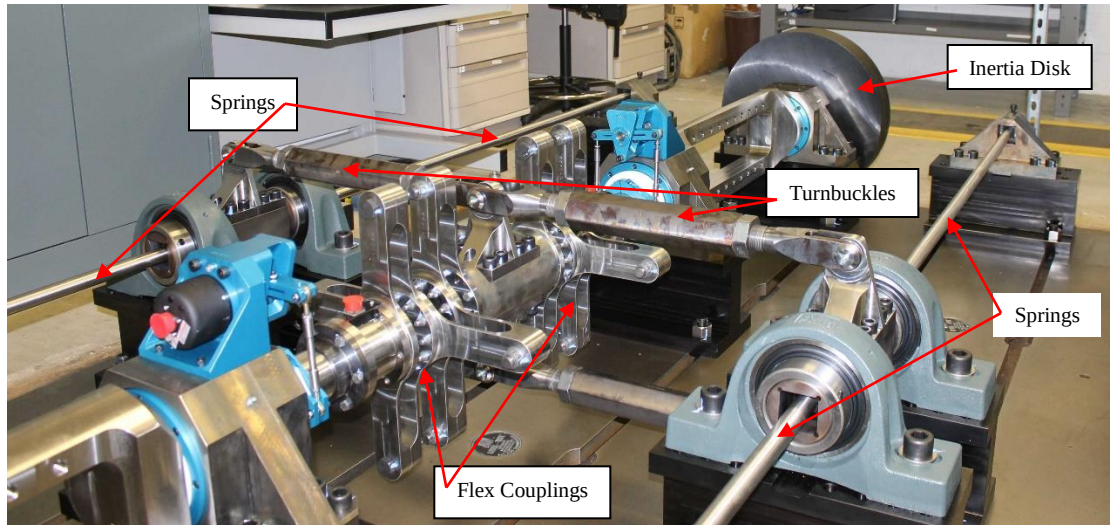


Figure 1. AFRL Passive Electro-Mechanical Actuator Test Rig [AFRL]

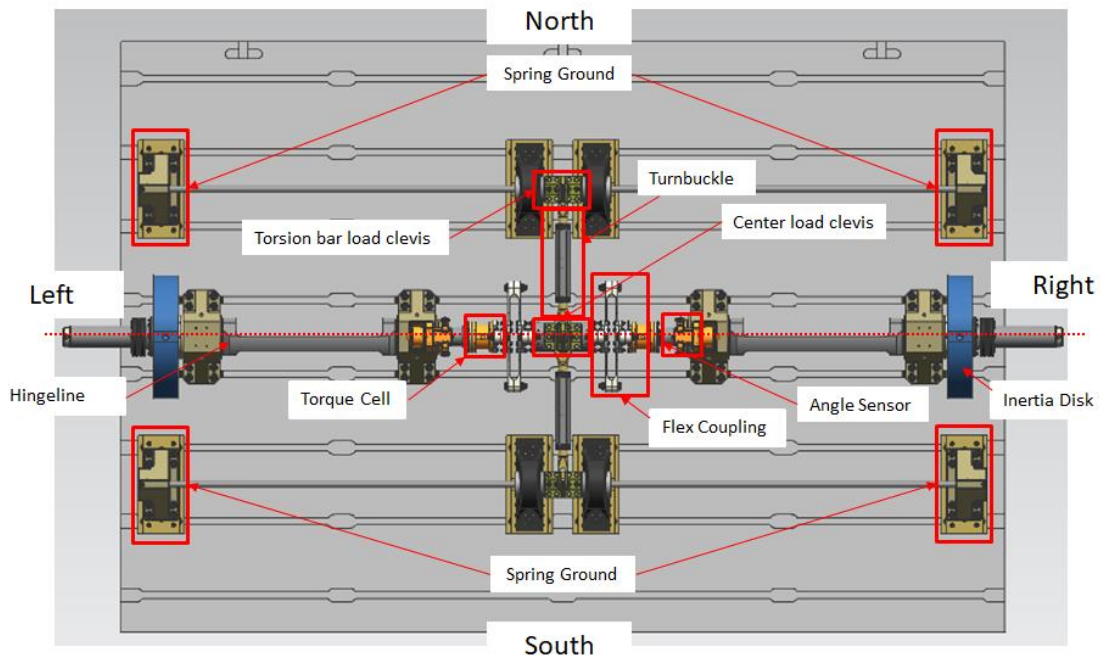


Figure 2. AFRL PEMAT Rig – CAD Model [AFRL]

Considering the relative ease and lack of expense with which further experimentation could be conducted on an already-built, passively-loaded test rig, AFRL is interested in exploring additional use cases for the PEMAT facility in

support of future test and development campaigns; such is the focus of this research. Since the desired outcome for this project is a deeper fundamental understanding of force-fight, the rig was designed to evaluate performance for simple position profiles, i.e. a sine wave [2]. With these simple profiles in mind, the rig was not developed to represent any specific actuator application. However, if the rig could be used to represent a real-world system, e.g. an aircraft aileron, a rocket control fin, or an antenna pointing system, it would be highly valuable both in evaluating the suitability of currently produced EMAs for use in these systems and in the development of requirements for future such EMAs.

Problem Statement

As the PEMAT test rig was designed only to provide an easily characterizable load to the pair of actuators, the dynamics would not necessarily correlate to those of a control surface or other device which would require actuation. In order to conduct testing aimed at evaluating EMAs for these types of applications, knowledge of this correlation is required. In order to maintain a sufficiently narrow scope, and to maximize the amount of data available for comparison, this research focuses on developing knowledge of the PEMAT rig's suitability for aircraft control surface actuator evaluation, leaving the aforementioned additional potential applications for future research. Because of the passive loading system, comprised of springs and inertias, it was expected that the rig would not be able to approximate real systems above the first order; that is, while the major

characteristics of an actuator's response could be represented, the highly complex effects stemming from atmospheric variability, engine vibration, etc. could likely not. As the hypothesized use case of the PEMAT rig was for first-pass testing intended for development or evaluation of the basic requirements for a control surface actuator, this level of fidelity would be sufficient, providing enough knowledge to either eliminate an EMA as a candidate or pass it along for more application-specific testing. With this information, the purpose of this research is to determine whether the PEMAT rig can be used to represent the loading conditions of an aircraft control surface to a sufficient fidelity to allow the first iteration of EMA evaluations for aerospace applications.

Research Objectives

There are several intermediate objectives which must necessarily be satisfied before the primary goal of this research can be met. First, a sufficiently accurate model of the PEMAT rig was necessary. This model was needed to evaluate the rig's response to a variety of maneuver profiles, determining the general ability of the rig to reproduce real-life data as well as proactively identifying any conditions under which the rig should not be operated due to physical hardware constraints. This model needed to represent at a minimum the first order response of the rig, as this was the level of fidelity expected for the end results. Once an adequate model was obtained, the next objective was to compare the model response to that of a real control surface to which an EMA could be attached. The use of real flight data

was desired for this step, to eliminate any inaccuracies that could result from the use of simulated data. The actuator loads resulting from the same position profiles could then be compared between the model and the flight test data, and the variable model elements (inertia disks and torsion springs) adjusted to provide as close a reproduction as possible. With this model-produced reproduction and the insight which could be gleaned from it, the final objective was to move into testing on the PEMAT rig itself. Tests which had shown promise during the model testing would be run on the rig, and the resulting torque profiles compared to both the model output data and the flight test data, the former to further validate the accuracy of the model, and the latter to satisfy the objective of the research. Successful completion of each of these objectives would indicate the potential for real-world application testing of EMAs in the PEMAT facility in the future.

Methodology

In order to understand the capabilities of the PEMAT rig, it was first necessary to obtain a model of the rig's dynamics with which to simulate the types of maneuvers an aircraft EMA could experience. While in the course of preparing for and conducting the series of force-flight experiments which preceded this research AFRL developed software models of the PEMAT rig, the method chosen was a complex, nonlinear MATLAB Simulink representation [2]. This method, benefitting from the accuracy of including many nonlinear effects and an intuitive graphical interface, was effective for supporting their test campaign, but would be

less effective for the much more complex input signals needed to represent the motion of an aircraft control surface actuator. Determining complex effects such as static and dynamic friction changeover and asymmetry would be computationally difficult. As the rig characteristics were expected to prevent perfect representation of higher-order control surface dynamics, as discussed above, the additional precision from modeling nonlinear effects in the rig would not provide enough useful insight to justify its inclusion. For this reason, the decision was made to develop a linear model of the test rig. While this model would require more simple approximations of the dynamics, particularly in the friction characteristics, it would allow for much more time efficient evaluation of maneuver profiles, as well as allowing easier mathematical insight into the response dynamics while still providing the level of representation precision necessary for the purposes of this research.

With an accurate PEMAT rig model developed, the next step would be to begin evaluating the capability for flight control surface representation. As this research is focused on control surface actuators, this requires knowledge of what loads control surface actuators can see. In order to obtain the most detailed data for this purpose, the ideal source would be extensive data gathering instrumentation on the particular control surface or range of control surfaces for which the EMA is intended. Since this level of experimentation is well beyond the scope of this research, and in fact the range of specific applications is as yet undefined, an alternative source of data must be found. Another option would be to utilize a computational fluid dynamics model to produce an expected load profile, digitally

modeling the effects of the atmosphere and flight conditions on the actuator system. While this would not provide the assurances of validity that come with the use of experimental data, it would allow the production of data for any number of different control surface types in a variety of scenarios. However, as CFD requires extensive computer resources and expertise, it too was decided to fall beyond the scope of this research. The decision was made to restrict the investigation to control surfaces in applications for which the requisite data had already been gathered and made available. While this restriction may prevent the current analysis from extending to a specific application, it would still allow a baseline general actuator profile for evaluation.

With representative real-world actuator data, the rig model could then be utilized to compare the PEMAT rig response to the same profile. The difficulty in this step lies in the manipulation of the rig response to sufficiently reproduce the data. Unlike in an active system, the load profile cannot be directly controlled. As previously discussed, the variable elements on the rig include a pair of removable inertia disks and two pairs of similarly removable torsion springs, one pair each on the north and south, as shown in Figure 2 [6]. Adjustment of the inertia of the system would allow manipulation of the magnitude of the system's response, while spring coefficient contributions of the various torsion spring layouts would influence response frequency; however, the variable elements do not allow a direct impact on the rig's damping characteristics. This lack of capability could provide a source of discrepancy in the damping characteristics of the rig and the system which it is meant to represent. Additionally, the use of currently available hardware

does not permit fine discretization in the adjustment of either inertia or spring coefficient, as the elements can only be included or removed, and not replaced by smaller, larger, stiffer, or softer elements as may be desired.

Once the level of reproduction capability of the PEMAT rig is evaluated by use of the linear model, the final step of this research is to validate these results on the rig hardware. Initial evaluation with the model provides both a baseline performance expectation and a method to identify some of any capability limitations before shifting to the use of hardware, but in order to fully evaluate the usefulness of the PEMAT facility for actuator EMA testing, the performance results from the rig itself are necessary. The results from this evaluation are also useful as additional data to define the variation between the rig and its model. There are some inaccuracies to be expected in a linear model, but if the results from each profile on the model and rig match each other, it can be shown to be effective in developing test profiles in the future.

Assumptions and Limitations

While many of the assumptions made during the course of this research are discussed in preceding or subsequent sections, they are included here as well for completeness. The performance of the PEMAT rig is limited by the passive loading design: with a limited number of discrete values available for both inertia and spring coefficient and no method by which damping or other characteristics can be directly influenced, the dynamics of the rig are not finely tunable. In contrast to an

active load system, this is expected to result in an inability to represent higher order effects in control surface dynamics data, restricting the application of the PEMAT rig to baseline or preliminary EMA evaluation for the purposes of aircraft integration.

The use of a linear model required several assumptions in the process of its development. As mathematically shown in following sections, any nonrigidity in the turnbuckles connecting the hingeline to the torsion spring load clevises would result in a nonlinearity. While some deflection will be present in any such physical coupling under a load, the nonrigidity in the turnbuckles relative to the motion of the hingeline and torsion springs is insignificant enough to assume the connection is rigid for the purposes of this research. Similarly, asymmetry between the north and south sides of the turnbuckle assembly would introduce a nonlinear response, but the precision of the match between the two sides is sufficient when compared to the size and contribution to dynamic characteristics of additional rig components to neglect any nonlinear effects. Even with the satisfaction of these assumptions, however, since a linear model does not include effects such as the transition between static and dynamic friction, there will necessarily be introduced some amount of error into the results. This error will need to be considered when comparing the performance of the PEMAT rig and the rig model.

As a result of the approximations necessary to reduce the PEMAT rig physical characteristics to the set of elements used in the linear model, several limitations to the application of the model were introduced. First, resulting from the variation

between the damping characteristics of the rig and of the model, the model accuracy is decreased in cases where the motion approaches zero. Because the model does not account for stiction, it can predict motion from an actuating torque before the rig will actually move, and expect a longer oscillation period after actuation is halted than the rig will experience. Additionally, as the variations between model-predicted behavior and actual rig dynamics can build up over time, the accuracy of the model can degrade over longer periods of operation, exhibiting positive or negative trendlines in the running average deflection of the hingeline while the rig motion remains centered at zero. Each of these effects imposes limits on the rig operating conditions which can be accurately modeled, but as in the type of aerospace applications which are intended to be represented by the rig, particularly for flight control surfaces, the profiles include mainly large deflections and relatively short maneuvers, preventing the model limitations from significantly impacting evaluation capabilities.

II. Literature Review

Electromechanical Actuation

While actuation, electrical or otherwise, is found in some form in nearly every system on an aircraft or spacecraft, this research is primarily focused on those applications related to control surface actuation, for several reasons. The first is that various electrical actuation devices including EMAs have a greater history of use and body of knowledge regarding smaller-scale applications than control surfaces, leaving more room for research and advancement of the latter [1] [3]. Second, more pragmatic and derived from the first, is that the scale of the PEMAT facility is conducive to testing actuators of the appropriate size and power for aircraft control surfaces, having been designed with the same in mind [2]. Therefore, in gathering information regarding EMAs, the focus was on the types of actuators which would be useful for control surface applications and how those systems would relate to the traditional hydraulics they would be intended to replace.

At the simplest level, an electromechanical actuator consists of an electric motor (usually brushless), reduction gearing, a ball or worm screw to convert rotational motion to a linear actuation, and a power off brake [8]. This simple design, along with the potential desirability of using electric power [1] can provide several benefits over traditional hydraulic actuation systems. Without the need for hydraulic fluid storage, pressurization, and delivery systems, the relative lack of complexity inherent in EMA systems leads to lighter systems with fewer failure modes [5]; a lighter aircraft has better range and performance, and less complexity

means less and easier maintenance. Additionally, the lack of potential for leakage means the capability for long term storage or use in a vacuum environment is improved in EMA systems, and with no fluid characteristics with which to contend, EMAs tend to provide stiffer and more efficient actuation systems than their hydraulic counterparts [8].

Despite the many potential benefits of integrating EMAs in place of hydraulic systems, there are several possible drawbacks as well. First, and previously mentioned, is the relative novelty of large EMAs. Hydraulics have a long history of integration aerospace vehicles, and their design benefits from this technological maturity, while the first commercial aircraft application of electrical actuation being the backup actuation system on the A380 in 1995 [3]. While this currently presents a roadblock to adoption of EMAs, its mitigation is the goal of this research and that of growing numbers of others [1] [9], and will decrease over time. With electrical systems, the potential for fires or other damage due to short circuit is increased, and care must be taken to mitigate this risk [1]. The power density of EMAs is generally lower than that of hydraulic systems, and requires more power generation capability to meet the same requirements, mitigating some of the benefit of removing the hydraulic infrastructure [1]. Finally, in a parallel-redundant EMA system, there is the potential for force-fight conditions to develop, in which misalignment and control inaccuracies lead to each actuator fighting the other, potentially causing spikes in power consumption, overstress of actuator or control surface hardware, and a loss of control authority [2]. Whereas a hydraulic system can mitigate similar situations by a small release in fluid pressure, EMAs require

Careful hardware and software design to reduce the likelihood of a force-fight state developing as well as to alleviate any which do occur.

Aircraft Control Applications

While hydraulic actuation has accounted for most large aircraft flight control systems for many years, a growing number of aircraft designers have begun utilizing or investigating the use of EMAs instead [5]. In order to determine how the PEMAT facility could best contribute to the effort of evaluating EMAs and developing requirements for their design, it was necessary to gain an understanding of these applications.

The flight control systems of aircraft generally fall into one of two categories. Primary flight controls consist of those which affect the aircraft attitude, i.e. yaw, pitch, and roll, which are controlled by the rudders, elevators, and ailerons, respectively. Secondary flight controls either affect the lift generation characteristics of the aircraft, e.g. wing flaps, or provide passive load reduction to the primary flight controls, e.g. trim tabs [9]. In each of these control surfaces, the primary load comes from the air through which the aircraft is flying. Thus, loading conditions are dependent on both environmental conditions and flight maneuvers. As a result, the deflection of control surfaces is limited in order to avoid either overcontrol of the aircraft or overstress of the control surface or actuation system [10].

Primary flight control systems are of particular interest for the application of EMAs for several reasons. These systems, particularly in larger or higher

performance aircraft, see many more loading cycles than secondary systems, as the former are used to control every flight maneuver. In the course of these maneuvers, they can also be subjected to higher loading conditions. Both of these factors can lead to high levels of wear on the control surface actuator. Additionally, due to both the larger size typical of primary control surfaces and to the extreme consequences of a loss of primary flight control, these systems each require multiple actuators for dual or often triple redundancy [3] [5].

With these considerations in mind, EMAs for aircraft control would need to provide enough force to actuate a large control surface with enough precision to control the aircraft flight path accurately and respond to changing atmospheric forces, maintain their performance over a heavy duty cycle, and perform well in parallel-redundant systems.

Spacecraft Control Applications

A significant potential application for EMAs is highly analogous to their use in aircraft: the first step in any spacecraft's operative lifetime is launch, and aerodynamic control can be a major component in the in-atmosphere portion of the launch rocket's flight – particularly for booster recovery in the growing arena of reusable rockets [11]. While such applications are similar to those of aircraft control, rockets carry additional requirements in the form of high-g loading, high speeds, a highly vibrational environment, and high operating temperatures, which

provide additional challenges to the implementation of EMAs, as well as additional potential for enhanced performance as a result of such implementation [12].

The other primary method of control for rockets, thrust vectoring, also presents opportunities for the use of EMAs. Used in both launch vehicles and on-orbit propulsion systems, this method uses various schemes to alter the direction of the exhaust flow of the engine and thus the thrust vector, allowing for directional control of the vehicle [13]. As several of the methods which are used to produce this effect, e.g. a controllable vane placed in the exhaust flow of the rocket or the use of a movable nozzle, have similar actuation requirements to those of aerodynamic control surfaces, EMAs have been used in various upper stage applications [14] [15], while interest has been shown in applying them to larger systems as well [4].

In addition to the requirements discussed for aerodynamic control surface EMAs, thrust vectoring systems need to provide varying performance characteristics based on both thrust level and altitude, to the extreme of operation in a freefall, vacuum environment [12].

AFRL EMA Testing

As has been discussed, the purpose for this research is to expand the potential utilization of a passive test rig built by AFRL and MOOG Aerospace and used by AFRL to conduct EMA force-fight experiments [6]. In order to develop the

potential for flight system representation using the PEMAT rig, it is important to understand the rig's current utilization.

In light of the limited amount of research which has been conducted regarding force-fight in parallel EMAs, AFRL wanted to examine the characteristics of force-fight conditions induced by introducing phase lag, gain, and offset errors in a dual-EMA setup on a passive test rig. This would allow the comparison of loading and power draw characteristics between each condition, providing insight into detection and severity estimation methods applicable to future flight systems. With knowledge of force-fight characteristics as they develop, mitigation strategies could be found to prevent damage to equipment or loss of control [2].

In pursuit of this goal, a careful characterization of the elements of the rig was conducted, including inertias, spring coefficients, static and dynamic friction measurements, and natural frequencies. Using these measurements, a MATLAB Simulink model was built and was used to develop and validate tests. Validation of this model confirmed reproduction of the first mode of the rig response, with more error present in higher modes, consistent with the expectations for a lumped-mass modeling approach [2].

The EMAs that were used for subsequent testing were derived from the NASA X-38 program [16], as they were representative of a general control surface actuator, and provided current draw and position information during usage. To provide easily analyzed data, each of the force-fight tests, with variations between the command input of each actuator as described above, was conducted from a

baseline sine wave of 5° amplitude and 1 Hz frequency. Both electrical and mechanical data acquired during each of these tests was analyzed, providing valuable information regarding EMA force-fight detection and mitigation [2].

MATLAB Methods

Function Minimization

In order to develop the linear model used in this analysis, it was necessary to conduct estimations of the properties of several parts of the rig, particularly those related to damping. The data from several rig characterization tests was available, and so a method to estimate the unknown properties of the rig using this data was developed. While the characterization tests and the details of the estimation method are discussed in later sections, the heart of the algorithm is the MATLAB function “fminsearch”. This function is designed to “Find [the] minimum of [an] unconstrained multivariable function using [a] derivative-free method” [17], and was used to minimize the variation between the data from the rig and that produced by the model for the same input torque, with the elements to be estimated input as variables. This function was chosen as it allowed the estimation of multiple elements concurrently, which was necessary for this problem as the rig configuration during the characterization tests prevented the isolation of each of the estimated elements in the data. As the instrumentation on the rig does not capture derivatives of the motion, the lack of a requirement for knowledge of the derivatives simplified the implementation.

The “fminsearch” function makes use of the Nelder-Mead Simplex Method, a direct search method which constructs a simplex on the range of the function to be minimized, with one more vertex than the number of variables; for this application, as each estimation involved two unknown elements, it would construct a triangle. Each iteration of the method varies the bounds of this simplex by reflection, expansion, contraction, and shrinkage, until the function values on the simplex reach a minimum. At this point, the variable values which give the lowest function value on the final simplex are output [18]. More detailed discussion of this method beyond the scope of this research can be found in many publications, e.g. Lagarias et al in [18].

Solving Differential Equations

Once the model was developed and the load resulting from a given actuator position profile was needed, it was necessary to solve the differential equations of the model to determine motion at the load springs. Since these equations are formulated as a system of explicit, non-stiff ordinary differential equations, it was possible to solve them using the MATLAB default solver “ode45”. This function utilizes a Runge-Kutta method, specifically the Dormand-Prince (4,5) Method [19]. Like other Runge-Kutta methods, it involves calculating values at subsequent steps by determining a simple estimate of the subsequent value, using this estimate to construct one or more interpolants, and finding a more accurate estimate of the value at the subsequent step using a weighted sum of the value at the current step

and the interpolants. This process of interpolation is repeated in higher order solvers like Dormand-Prince, which is of order 4, until the final estimate is reached, and the solver moves on to the next step [20]. This method operates with a variable step size, allowing it to account for regions in which the rate of change of the function varies. These characteristics allow a simple implementation of “ode45” to provide an accurate result without significant computational difficulty or operation time, provided the characteristics of the differential equations do not preclude the use of the Dormand-Prince Method.

Simulating Linear Systems

While some of the data comparison in this research involved determining loads from position profiles as described in the preceding section, others required the reverse: a determination of the position profile that would result from a given torque. This was a simpler problem to solve, as it did not involve numerically solving the equations of motion. As the rig model was constructed as a state space representation, its response to a torque input could be simulated by the use of the MATLAB “lsim” command. This function is a generalized version of more commonly used functions such as “step” and “impulse”, generating a system response to an arbitrary input as opposed to a predefined one. It generates this response from the state space system, input data, and discretized time vector. The “lsim” command is only available for linear, time-invariant systems, but as these conditions are met for this application, and model and test data were already in the

necessary format, it allowed for a simple and efficient determination of the model response for comparison [21].

III. Methodology

Model Development

The first step in this research was to develop a model of the PEMAT rig to be used for subsequent development of test rig configurations which could represent the actuation systems of interest. As the test rig does not need to represent all of the higher order effects of the real-life system, the model does not need to capture the higher order response of the rig. With the first order response being of interest for this application, it was hypothesized that a linear model would provide sufficient fidelity while allowing for less computational difficulty, easier adjustments of constituent elements, and more ready insight into the dynamics of the model. Therefore, for each of the tests used to develop model parameters as well as those used to evaluate the model, the relevant test rig components were represented as a spring-mass-damper system shown in Figure 3. The CAD model of the rig is included again in Figure 4 for comparison. For the purpose of illustration only two of the load springs are included in the model, one each on the north and south; all four springs can be included in the model in any configuration, and would not affect equation development.

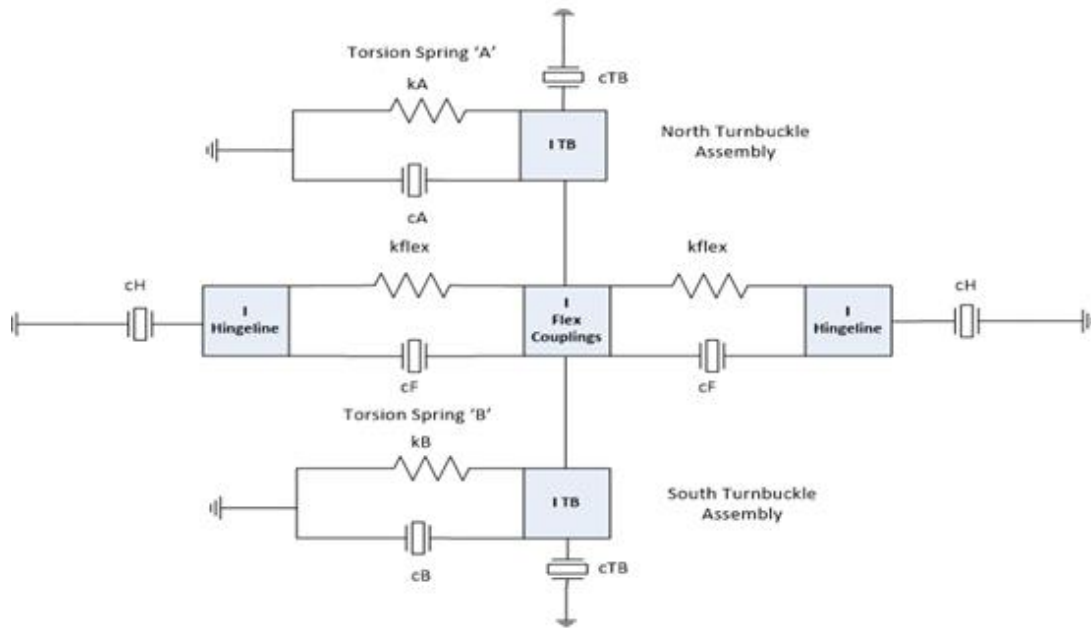


Figure 3. Linear Model of PEMAT Rig

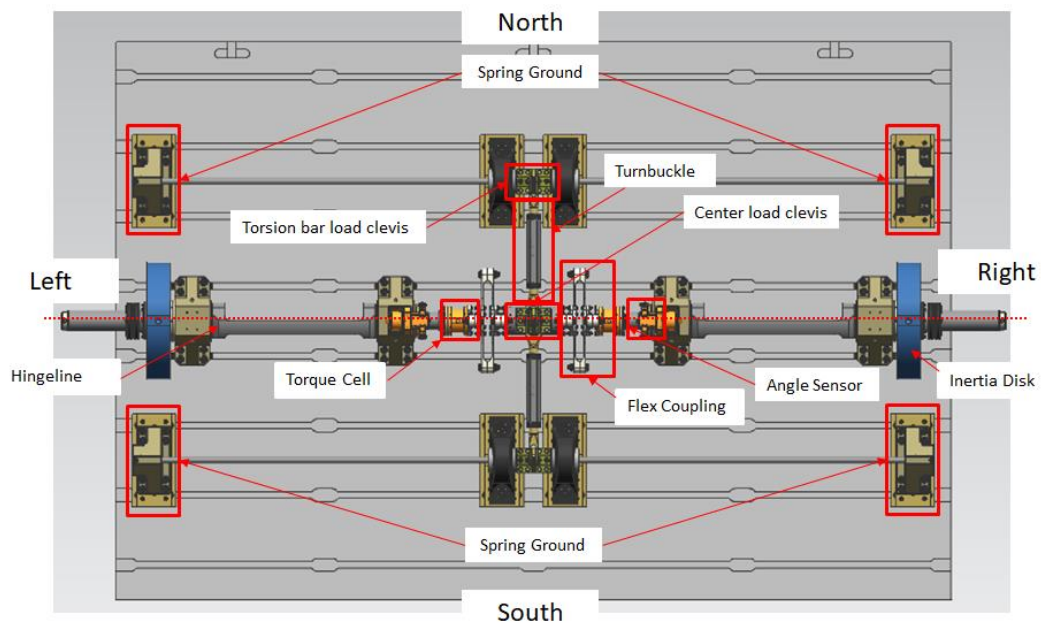


Figure 4. AFRL PEMAT Rig - CAD Model [AFRL]

In this diagram, there are four spring coefficients shown, denoted by “ $k_{_}$ ”. While the two of these on the north and south sides of the rig (k_A and k_B , respectively) represent the load springs discussed above, the other two (k_{flex}) are included to represent the characteristics of the flex couplings. Since these elements allow a small amount of deflection between the turnbuckles and the hingeline, they will contribute a spring-like, angular displacement-dependent force between the rig elements.

The constituent elements of the flex couplings also experience friction as they rotate. These effects are combined into the flex coupling damping coefficients (c_f) on either side of the rig. There are several bearings on the rig which also contribute to damping: the effects on the hingeline are accounted for by the damping coefficients on the far right and left ends of the rig (c_h), and those on the turnbuckles by the coefficients on the far north and south (c_{TB}). The torsion springs also experience internal damping as they rotate, an effect which is captured in the model by elements c_B and c_A .

While each component of the rig, of course, has a mass and accompanying inertia, for the purposes of this model, the inertia of each individual component was combined into one of five inertia elements, I_{TB} , I_H (x2), and I_{Flex} (x2). This allowed for a much simpler implementation of the model, as well as permitting easy adjustment of the model parameters for the inclusion or exclusion of the inertia disks: to include one, the inertia of the disk could simply be added to corresponding hingeline inertia element in the model.

It is worth noting that while the initial design of the model is reflected in Figure 3, further development in several cases allowed for the combination of several elements into a single mathematical representation; for example, the damping coefficients of both turnbuckle assemblies could be modeled by a single element.

With this system model, equations of motion could be developed, following simple Newton's Second Law development principles. Development was begun by analyzing the turnbuckle assemblies, shown in Figure 5.

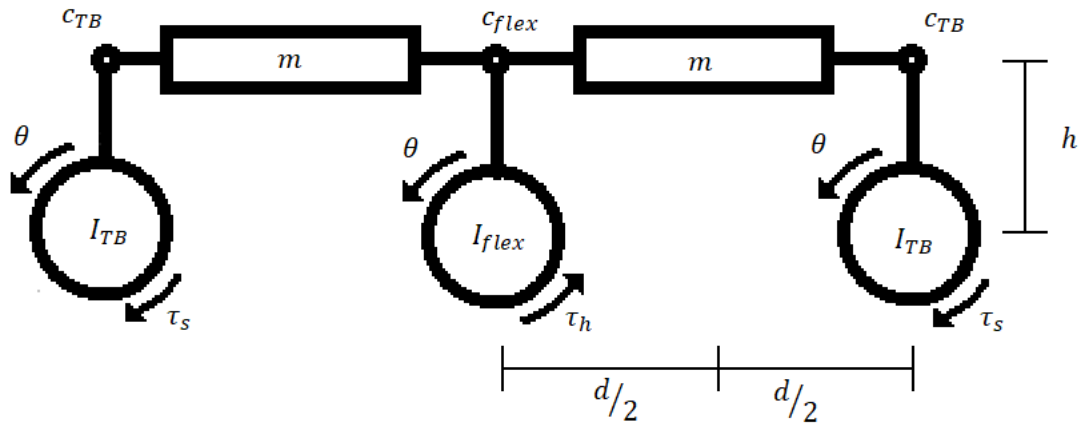


Figure 5. PEMAT Rig Turnbuckle Assembly

Note that in this diagram, the connections between the flex couplings and the turnbuckles have been assumed to be rigid. The necessity of this assumption is shown in the mathematical analysis to follow, and can be justified by the observation that any flexing or extensibility in the vertical or horizontal members of the linkage would be insignificant in comparison with measurement noise, and thus should not affect the experimental results.

In order to integrate this set of elements into the model, it was desired to reduce the assembly to an effective inertia and effective damping coefficient to retain linearity; variations of either of these quantities with rotational displacement would prevent this. For the assembly shown in Figure 5, the effective inertia can be described as follows. The inertia of each rotating element can simply be summed together, while the effective inertia of the linkages requires some trigonometry. They are not centered at an axis of rotation, so their inertia is described by Equation (1), wherein I is the total inertia of the element, I_{cm} is the moment of inertia about the element's center of mass, m is the element's mass, and R is the instantaneous distance from the axis of rotation to the center of mass of the linkage.

$$I = I_{cm} + mR^2 \quad (1)$$

By choosing the axis of rotation to be the center of the hingeline, an expression for the instantaneous radius can be developed in terms of the quantities shown in Figure 5 by relating this distance to the vertical and horizontal displacement of the linkage from the hingeline by the Pythagorean Theorem. Since the linkages are on opposite sides of the hingeline, it is necessary to develop separate expressions for each one. These expressions are shown in the following equations.

$$I_{right} = I_{cm} + m \left(\sqrt{(h \cos \theta)^2 + \left(\frac{d}{2} - h \sin \theta \right)^2} \right)^2 \quad (2a)$$

$$I_{left} = I_{cm} + m \left(\sqrt{(h \cos \theta)^2 + \left(\frac{d}{2} + h \sin \theta \right)^2} \right)^2 \quad (2b)$$

These inertia expressions can then be summed with the flex coupling and turnbuckle inertias:

$$I_{eff} = I_{flex} + 2I_{TB} + 2I_{cm} + m \left(\sqrt{(h \cos \theta)^2 + \left(\frac{d}{2} + h \sin \theta \right)^2} \right)^2 + m \left(\sqrt{(h \cos \theta)^2 + \left(\frac{d}{2} - h \sin \theta \right)^2} \right)^2 \quad (3)$$

By algebraic manipulation, this equation can be simplified to the form shown in Equation (4). This simplification requires the angular deflection of the hingeline and each of the turnbuckles to be equivalent, implying a rigid connection between the elements as described above. Also necessary is the assumption that the dimensions of the north and south turnbuckle assemblies are identical, which can be justified by again comparing the magnitude of potential variation in the dimensionality to the displacement which is expected to be seen. Since the contribution of any realizable variation would be insignificant in comparison, the system can be assumed to be symmetrical.

$$I_{eff} = I_{flex} + 2I_{TB} + 2I_{cm} + 2m \left(h^2 + \frac{d^2}{4} \right) \quad (4)$$

With these assumptions in place, an expression for the effective damping can also be easily developed, and is shown in Equation (5).

$$c_{eff} = c_{flex} + 2c_{TB} \quad (5)$$

Using the elements shown in Figure 3 as simplified in the preceding discussion, the mathematical model of the test rig could be assembled. With the rigidity assumptions previously described, the system can be described by three differential equations, two representing the dynamics of each side of the hingeline, respectively, and the last describing the flex coupling and turnbuckle motion. These equations, developed from Newton's Second Law for a rotating system, $I\alpha = \tau$, are shown below. The left side of the equations is represented as simply as in Newton's Second Law with angular acceleration α represented by $\ddot{\theta}$, whereas on the right the generic torque τ has been replaced by expressions for the contribution of each spring and damper element, as well as the input torque. Equation (6) corresponds to the flex coupling and turnbuckle dynamics, Equation (7) to the left hingeline section, and Equation (8) to the hingeline section on the right side of the rig.

$$I_{eff}\ddot{\theta}_c = -k_{eff}\theta_c - c_{eff}\dot{\theta}_c - k_{fl}(\theta_c - \theta_l) - c_{fl}(\dot{\theta}_c - \dot{\theta}_l) - k_{fr}(\theta_c - \theta_r) - c_{fr}(\dot{\theta}_c - \dot{\theta}_r) \quad (6)$$

$$I_l\ddot{\theta}_l = -k_{fl}(\theta_l - \theta_c) - c_{fl}(\dot{\theta}_l - \dot{\theta}_c) - c_{hl}\dot{\theta}_l \quad (7)$$

$$I_r \ddot{\theta}_r = \tau_{in} - k_{fr}(\theta_r - \theta_c) - c_{fr}(\dot{\theta}_r - \dot{\theta}_c) - c_{hr}\dot{\theta}_r \quad (8)$$

For each of these equations, I represents an inertia, k a torsional spring coefficient, and c a rotational damping coefficient. Variables of differentiation are represented by θ , unaccented for angular displacement, and with a single or double dot to represent the first and second time derivatives, respectively.

The additional terms on the right hand side of Equation (6) arise as the effective turnbuckle characteristics only directly affect the rotation of center of the rig, whereas each element on either side of the rig hingeline has a corresponding element on the opposite side. As should be expected, spring coefficients provide a force in proportion to a rotation – either an absolute rotation when referenced to a ground state, or a relative rotation when the spring is between two movable elements. Analogously, damping coefficients provide force in proportion to a rotation rate, either absolute or relative, subject to the same conditions as the spring coefficients. The input torque, τ_{in} , is here shown acting on the right side of the hingeline, as this was the configuration used for future tests, but for development purposes this is arbitrary; input torque could be included on either side or on both sides, corresponding to which EMAs are used for a given test.

For easier implementation in MATLAB, the computer program used to simulate this model system's response, the system of equations was translated to a state-space representation, with the states chosen to be each of the three angular displacement variables and the first time derivatives thereof; that is, the angular

velocities. This formulation is particularly useful, as it allows for a simple comparison between PEMAT rig data and rig model data: test data is gathered for both torque and angular position on either hingeline end, which can then be directly compared to the corresponding state of the model.

$$\dot{\mathbf{X}} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ \frac{-(k_{eff} + k_{fl} + k_{fr})}{I_{eff}} & \frac{-(c_{eff} + c_{fl} + c_{fr})}{I_{eff}} & \frac{k_{fl}}{I_{eff}} & \frac{c_{fl}}{I_{eff}} & \frac{k_{fr}}{I_{eff}} & \frac{c_{fr}}{I_{eff}} \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \frac{k_{fl}}{I_l} & \frac{c_{fl}}{I_l} & -k_{fl} & -(c_{fl} + c_{hl}) & 0 & 0 \\ 0 & 0 & \frac{1}{I_l} & \frac{1}{I_{fl}} & 0 & 1 \\ \frac{k_{fr}}{I_r} & \frac{c_{fr}}{I_r} & 0 & 0 & \frac{k_{fr}}{I_r} & \frac{-(c_{fr} + c_{hr})}{I_{fr}} \end{bmatrix} \mathbf{X} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{I_r} \end{bmatrix} \tau_{in},$$

$$\mathbf{X} = \begin{bmatrix} \theta_c \\ \dot{\theta}_c \\ \theta_l \\ \dot{\theta}_l \\ \theta_r \\ \dot{\theta}_r \end{bmatrix} \quad (9)$$

With a developed linear system model, the next step is to determine the numerical values of the various parameters used. When possible, these parameters were directly calculated. Such elements as hingeline inertias and spring coefficients were measured by AFRL researchers in the course of characterization testing prior to the beginning of this research [2]. These measurements, conducted on individual components prior to integration, prevented the necessity for complex analysis to decouple system-level characteristics and greatly simplified the model development. Other elements could not be directly measured. Damping

coefficients, which include the effects of various phenomena at, in the case of the turnbuckle assemblies in particular, several locations, needed to be backed out from system-level test data. Similarly, the effective inertia of the turnbuckle assemblies and flex couplings could not be directly measured, as it was not conducted before these elements were integrated into the rig. In order to determine the numerical values of these parameters, several sets of data from early characterization testing conducted on the PEMAT rig by AFRL were used [6], with the response of the model compared to the rig test results. The model response was determined by the use of the MATLAB “lsim” function, and the estimation of the desired model elements carried out by the “fminsearch” function. In order to compare the model and rig data, the root mean squared error (RMSE) between the two data sets was calculated, with the estimation function tuning the parameter values until a sufficiently accurate reproduction was produced. These characterization tests and the results of the model element approximations are detailed below.

Hingeline Damping Test

The first set of data used to develop the model parameters focused on the hingeline, denoted by the red box in Figure 6. The turnbuckles (labeled in Figure 2) were detached, allowing the hingeline to move freely of the load springs. The rig was then actuated at a constant rotation rate four times, from the left side and the right side each at both 0.175 and 0.35 radians per second [6].

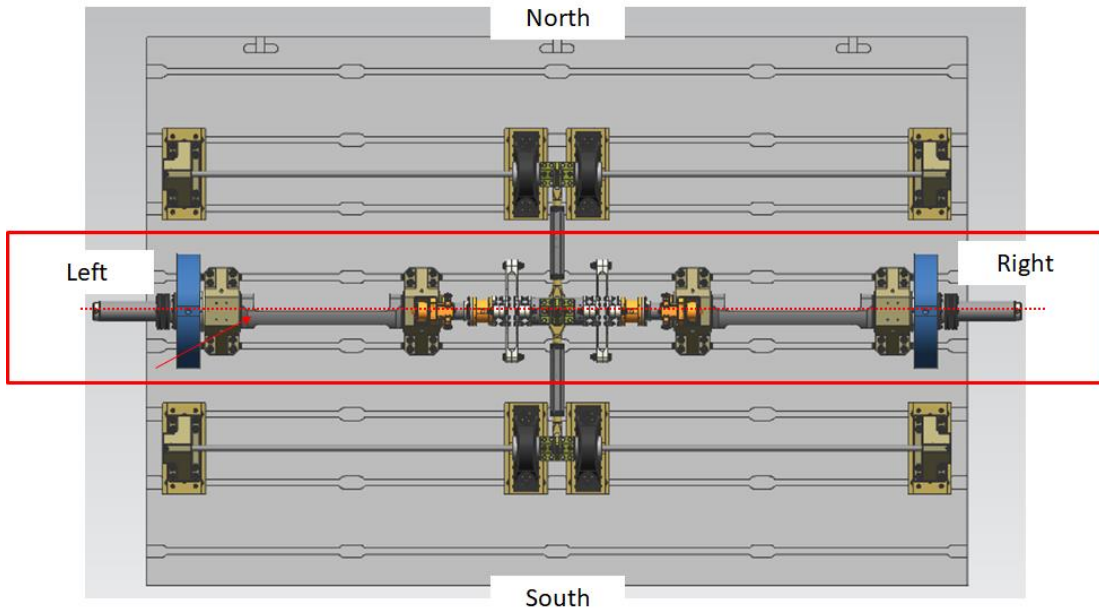


Figure 6. PEMAT Facility Hingeline Damping Test Configuration

An example of the torque and position data obtained from the PEMAT rig during these tests is shown in Figure 7, with the remainder contained in Appendix A. Note that this figure contains only the input data and response of the rig; the model response with which it was compared is presented and discussed in the subsequent chapter.

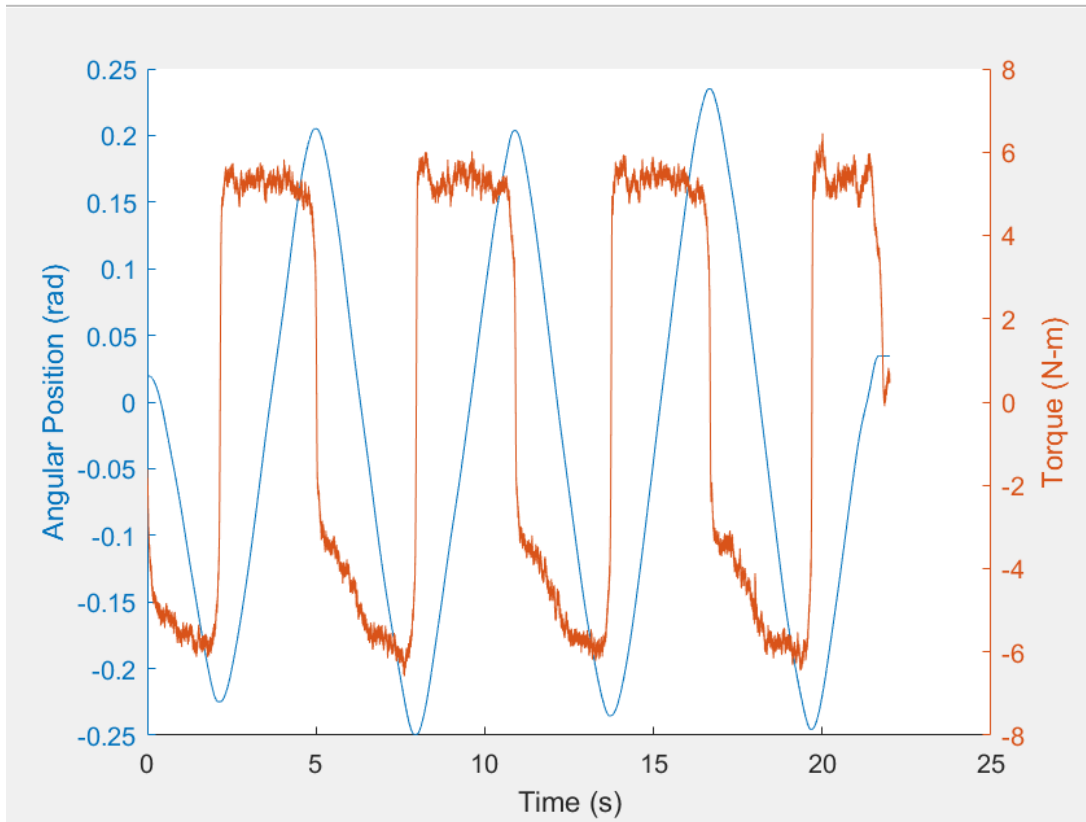


Figure 7. Hingeline Damping Test - Right Actuation, 0.35 rad/s

This data was used to develop approximations of the friction coefficients in both the hingeline bearings (c_h) and the flex couplings (c_f) shown in Figure 3. In order to accomplish this, the turnbuckles were removed from the model, simulating their disconnection from the rig, and the appropriate values for inertias and spring coefficients inserted. The resulting state space model was implemented in MATLAB, and internal functions were used to analyze the response of the model to the measured torque data as described above: the data from the AFRL test was read in from a provided Excel file, the “lsim” function was used to generate the

response of the model to this data, and the 'fminsearch' function to minimize the RMSE between the modeled response and the test data by varying the two approximated friction coefficients. An example of the results of this estimation, a comparison between the model response and the PEMAT rig response to the same test shown in Figure 7, can be seen in the following chapter, with additional data sets in Appendix A.

Free Response Test

The second test used for parameter determination was conducted with two springs attached, one each on the north and south assemblies. The rig sections of interest are denoted in Figure 8 by the red boxes.

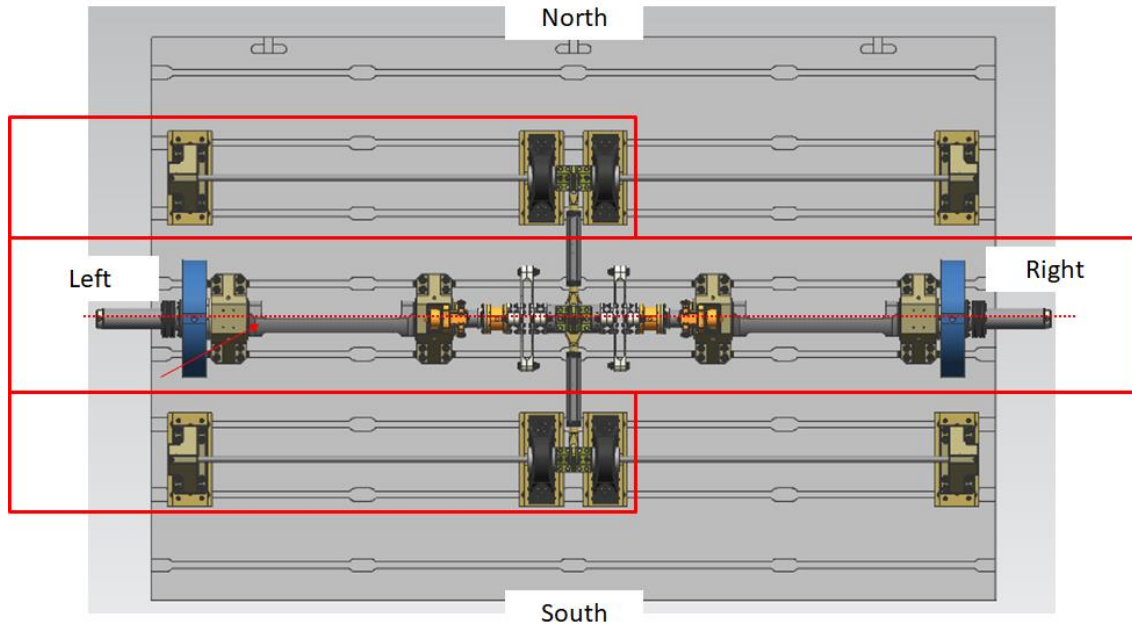


Figure 8. PEMAT Facility Free Response Test Configuration

With the rig in the proper configuration, the hingeline was rotated by 0.05 radians (3°), and allowed to freely oscillate to rest, and the torque and position time histories were again recorded [6]. This data can be seen in *Figure 9. Free Response Test*Figure 9. As it was for the hingeline damping test, the model response data is presented and discussed in the following chapter. Note that as the rig response in this test is unforced, the torque measurement is a result of the differences between the angular displacements of the hingeline elements and the flex coupling and turnbuckles, yielding the much higher frequency of oscillation in torque than in displacement itself.

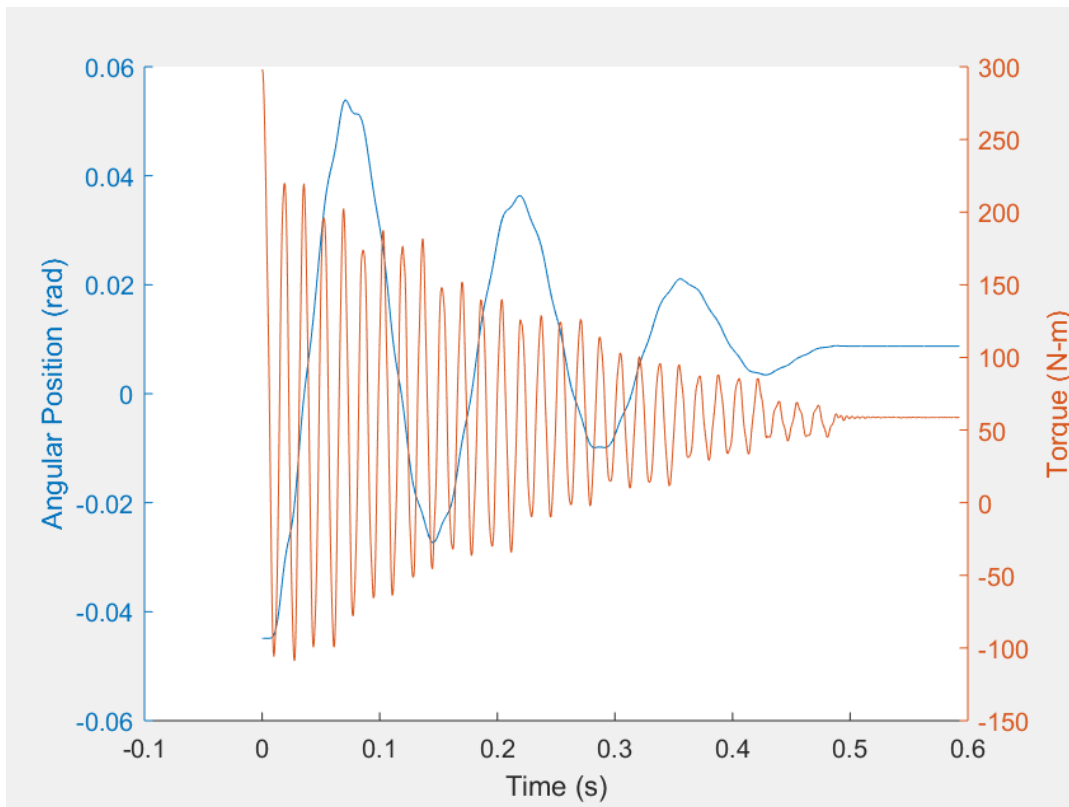


Figure 9. Free Response Test

With this data, the final two unknown model parameters can be estimated: the effective damping coefficient and effective inertia of the paired turnbuckle assemblies. Each of these elements was estimated by the same method as the damping coefficients in the hingeline test, once those coefficients were integrated into the model with the predetermined parameters. For this test, in order to match the configuration of the rig, all elements of the model were included except for the springs on the top and bottom right corners. The model response to the input torque data was produced using the “lsim” command, and the variable elements estimated

using “fminsearch”. The resulting position time history for the model as well as the PEMAT rig are shown in the following chapter.

Flight Test Data Modeling

With a linear model developed for the PEMAT facility, the next step was to use the model to assess the capability of the rig to reproduce the dynamic characteristics of a potential EMA application. As was previously discussed, the focus of this research is on aircraft control surface actuation, with the end goal being to conduct tests representative of the loads control surface actuators would experience in flight on the PEMAT rig hardware itself. Therefore, several load versus position profiles were developed from the basis of NASA flight maneuver test data, after ensuring the magnitude and velocity of the deflection would fall within the operating regime of the PEMAT facility hardware. This data, from NASA’s Electrically Powered Actuator Design (EPAD) program, showed the time history of torque loading experienced by the actuator, as well as the actuator’s angular deflection [22]. The subject of the EPAD program’s test campaign, a heavily modified F/A-18, is shown below.



Figure 10. NASA EPAD F/A-18 Aircraft [NASA]

Since these profiles are examples of the data this project eventually intends to gather for a variety of actuators, applications, and maneuvers, it was uniquely suited for use as rig validation test cases. Two profiles were used, the first an aileron reversal maneuver and the second a roll doublet. For each, the data gathered corresponded to an aileron actuator. These flight maneuvers, including the actuator torque load and position, are shown in the following figures.

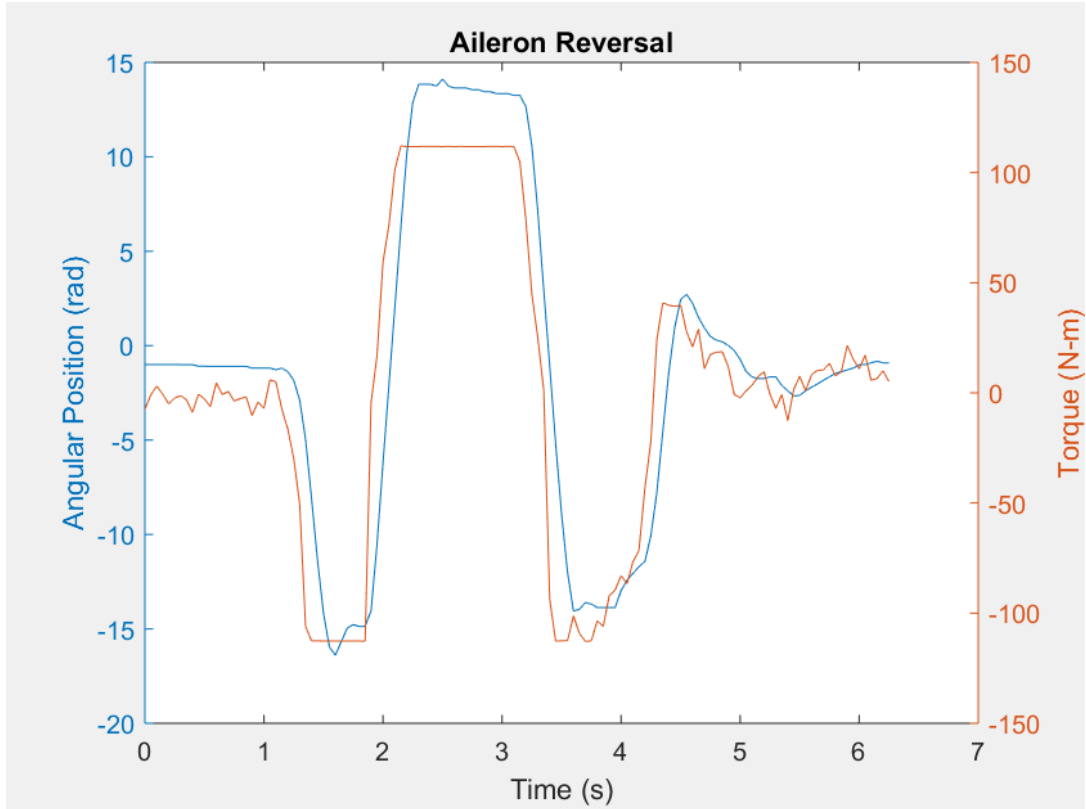


Figure 11. Actuator Deflection during Aileron Reversal Maneuver

In the aileron reversal maneuver, the actuator is commanded to deflect the aileron down to achieve a roll condition, then reversed for twice the duration to attain the same roll of the aircraft in the opposite direction, then reversed again to bring the aircraft back to straight and level flight.

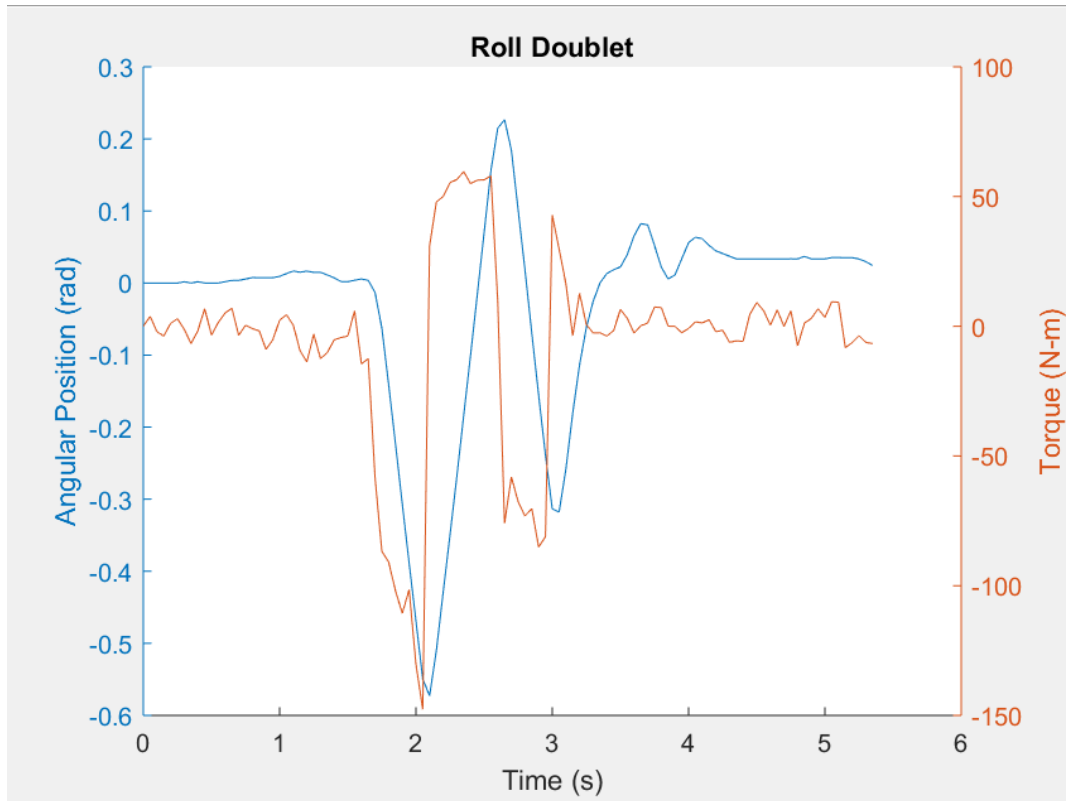


Figure 12. Actuator Deflection during Roll Doublet Maneuver

The roll doublet is similar to the aileron reversal, but in this maneuver, the aileron input is reversed as soon as it reaches its maximum deflection, keeping the aircraft in a constant state of changing roll rate.

By adjusting the variable elements in the model – i.e. by including or removing the various inertia disks and rotational springs – the model response was made to reproduce the test data as closely as possible. The response for each of these configurations was assessed with “lsim”, and the RMSE between the flight test data and the model data compared. The results of this analysis are contained in the following chapter.

Flight Test Data Reproduction

Once the model response to the EPAD flight profiles was determined and evaluated, the next step was to produce response data from the PEMAT rig. This data would be used both to further verify the validity of the developed linear model as well as to experimentally verify the capability to reproduce aircraft control surface actuation system characteristics in response to the appropriate flight maneuver profile. For these tests, the methodology for generating the test profiles mirrored that of the previous section: data from a series of maneuvers conducted on the NASA EPAD aircraft was used as the baseline [23], with adjustments made by scaling down the magnitude of the profile to fit the capabilities of the rig. Unlike those for the model performance tests, however, these profiles contain only the position time history and not the torque load profile, as the latter information was not available for all of the desired tests.

Seven maneuvers were chosen to represent as wide a variation in the scenarios as possible, including fast and slow actuation, repeated cycling, and both high- and low-G conditions. A wide swath of maneuver types was necessary, as each set of data came from the same aileron system. Evaluating performance across a breadth of conditions permits much more generalizable conclusions to be made; as this research is intended to ascertain the potential for EMA testing not just for an aircraft aileron control system, but for those integrated on a variety of aircraft elements, of rocket control surfaces, and of satellite articulation or component

pointing mechanisms, generalizable conclusions would be invaluable. Several of these maneuvers demonstrating the desired condition variation can be seen in the following figures, with additional profiles contained in Appendix B.

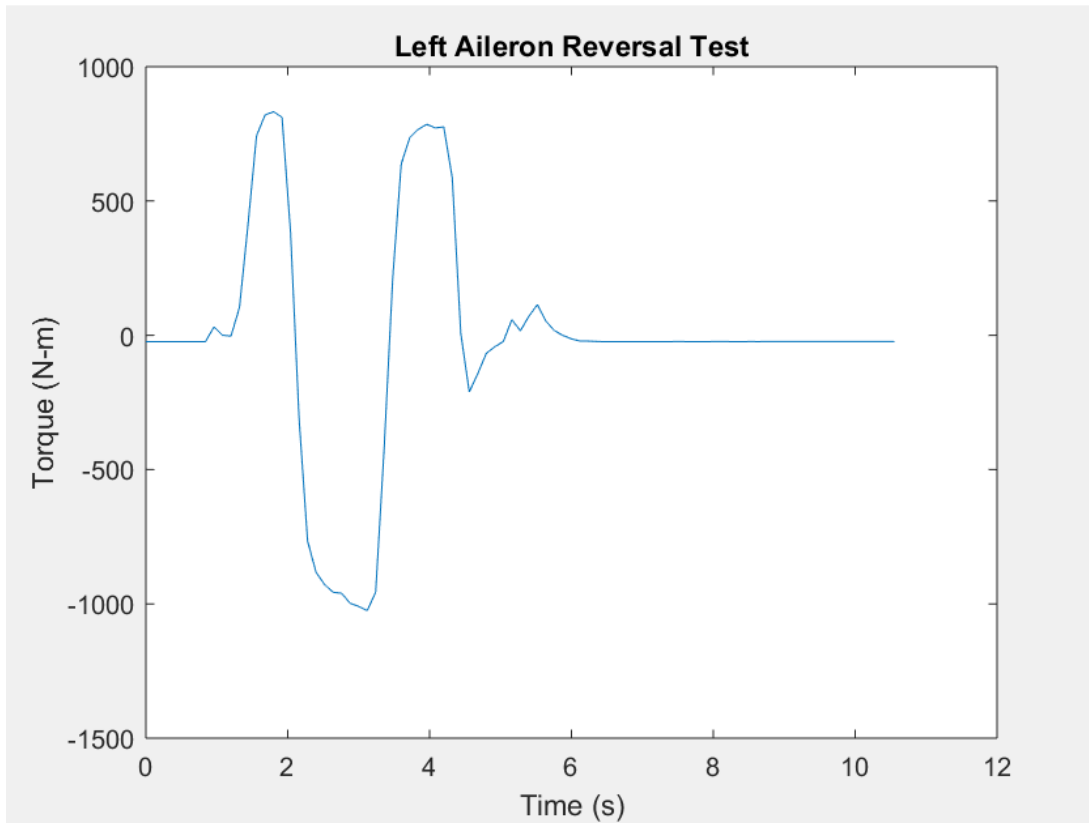


Figure 13. PEMAT Evaluation Test Profile - Left Aileron Reversal

In this profile, mirroring that used to compare the model response to flight data, the aileron is deflected in one direction by a desired amount, then reversed for twice the duration to attain the same roll of the aircraft in the opposite direction, then reversed again to bring the aircraft back to straight and level flight.

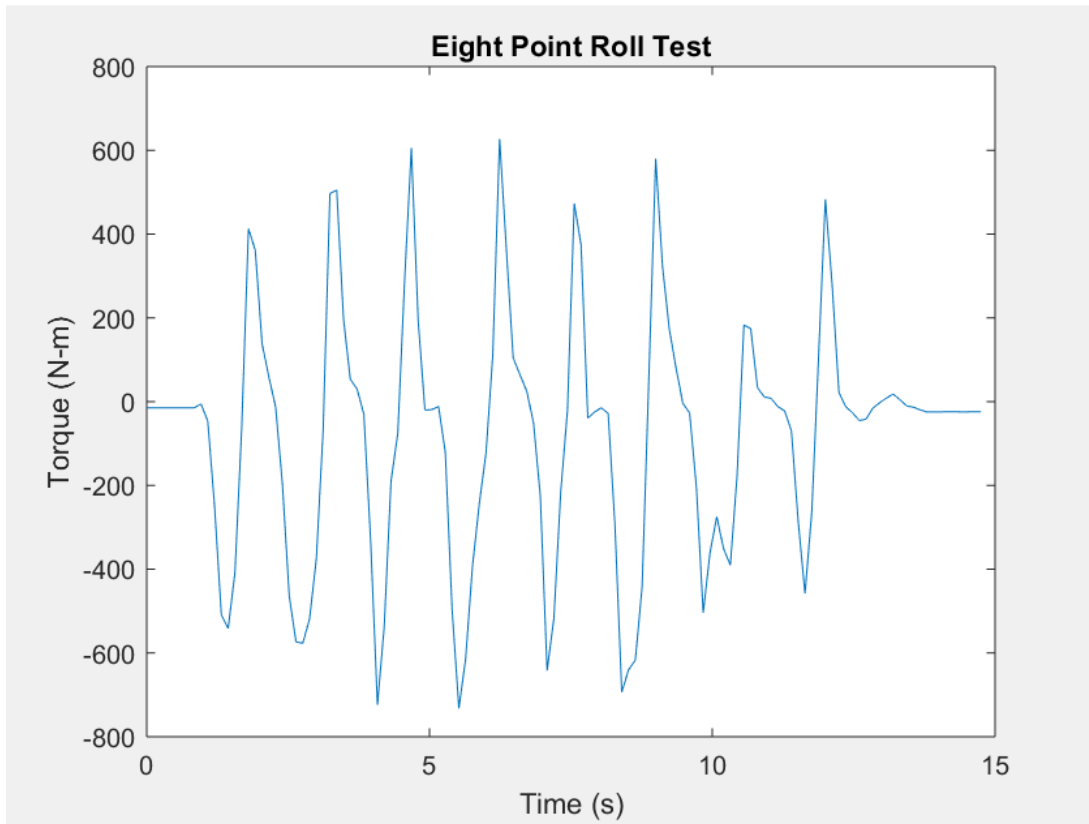


Figure 14. PEMAT Evaluation Test Profile – Eight Point Roll

In the eight point roll, the aircraft is rolled by approximately 45° by a deflection of the ailerons, shown by the initial negative spike in torque, then held in place momentarily at this rotation angle, seen in the smaller positive spike. This is repeated eight times to complete a full roll.

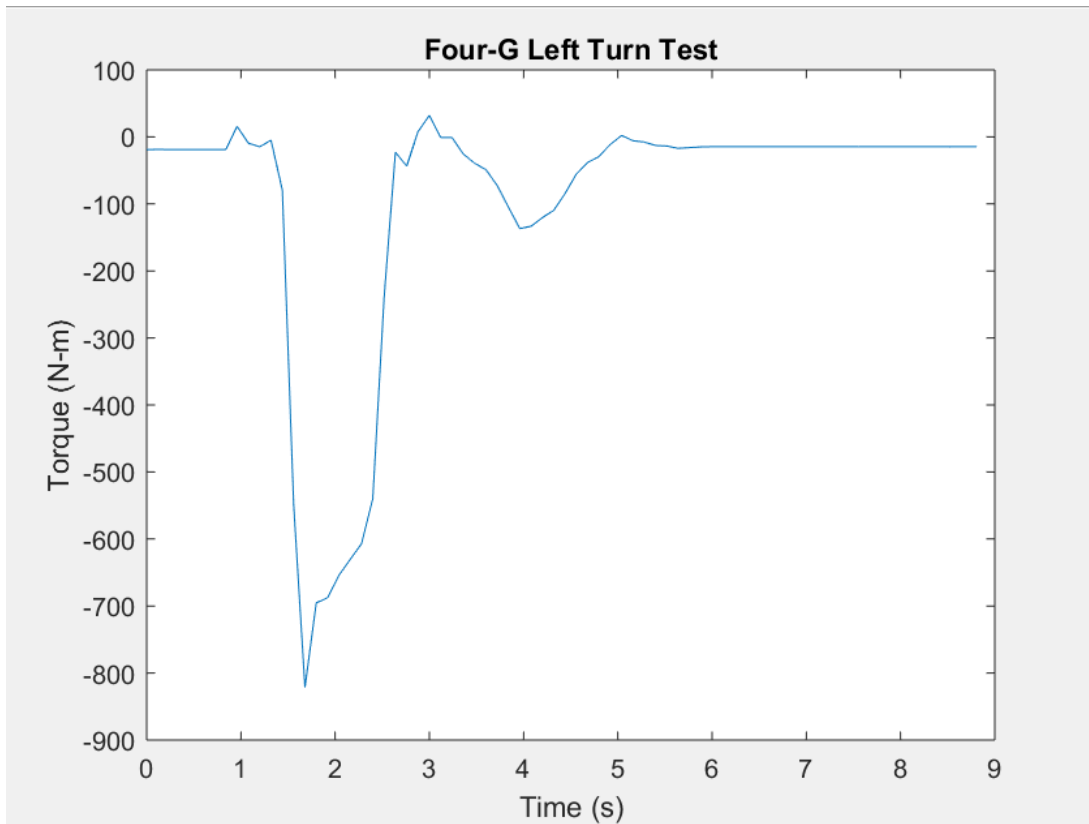


Figure 15. PEMAT Evaluation Test Profile - Four-G Left Turn

The four-G left turn is the simplest maneuver shown here, where the aileron is used to conduct a single banked turn before the aircraft is leveled off.

For each of these test maneuvers, the rig was configured with one spring each on the north and south and both right and left inertia disks. While a comparison between the rig and model response for additional configurations may have been useful, because of constraints on the time available for testing, it was not possible to reconfigure the rig for each test. However, as the two-spring, two-inertia disk configuration provided the best results in the initial testing phases on the model, it was expected to also provide the most similar level of performance for these tests

as well, as the test data was derived from the same aircraft system in the same configuration as before, in one case completing the same maneuver. With configuration alteration possible within the model, and successfully performed for earlier tests, so long as the performance of the rig and model matched each other well for these representative maneuver profiles in the configuration providing the most accurate reproduction, the rig could be judged for its general suitability for aircraft control surface EMA evaluation, as well as for evaluating EMAs for applications which mirrored the dynamics of an aircraft control surface.

Once each of these tests was run on the PEMAT rig and the position and torque data gathered, the results could be compared to the model response data. In order to accomplish this, as the parameter of interest for EMA evaluation is the load performance from a given position profile, it was desired to invert the process previously used for comparing model and test rig data. In order to determine the model torque requirements from the angular position time history, rather than vice versa, the first two time derivatives of the position profile at the actuator were found (i.e. the angular velocity and acceleration), and this information was used to evaluate Equations (4) through (6), using MATLAB's "ode45" solver. This provided the time history of the motion of the rest of the rig, from which the torque load on the actuator could be determined. The results of these analyses are contained in the following chapter.

IV. Results and Discussion

Model Development Results

Hingeline Damping Test Results

When the model parameters had been set up in the correct configuration, with estimates of the hingeline and flex coupling damping coefficients, the response of the model to the rig data gathered during the hingeline damping test was assessed using the MATLAB function “lsim”. This data was compared to the rig response data, and the root mean square error between the two was calculated. The damping coefficient estimates were then updated by the “fminsearch” function, and the process repeated. When the function was unable to improve the estimate any further, the results were plotted. This final data can be seen in Figure 16.

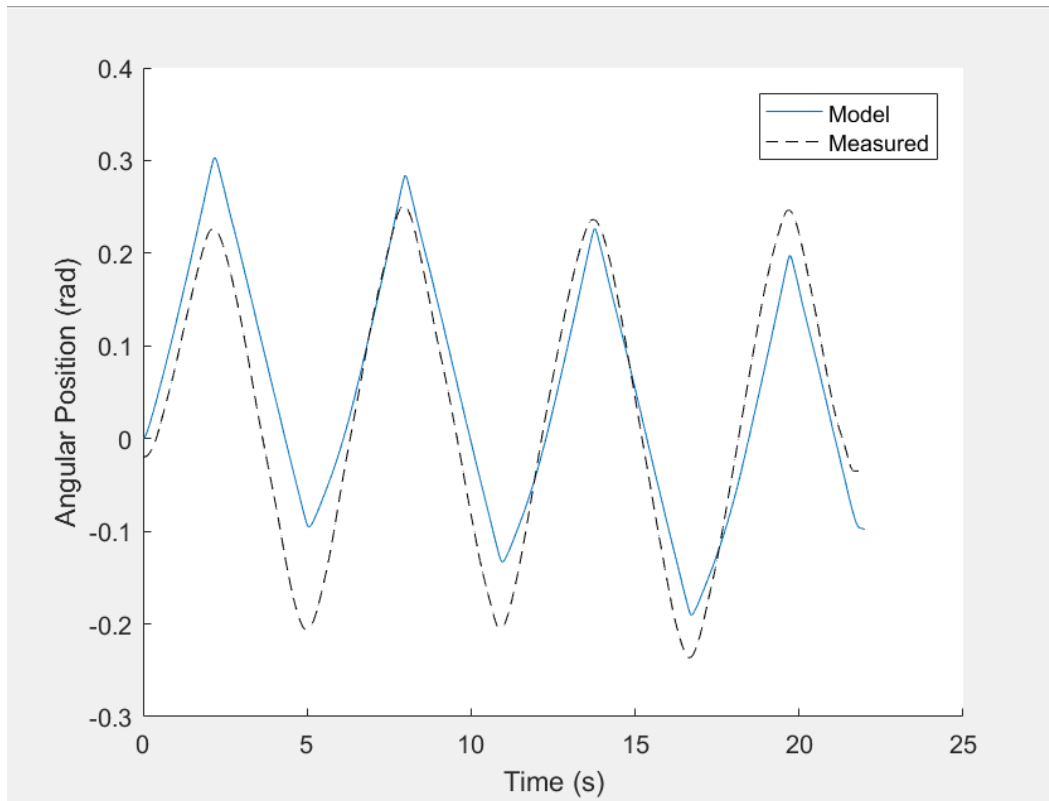


Figure 16. Hingeline Damping Test - Rig and Model Response

As was expected, considering the limitations of a linear model, the PEMAT rig's performance is not perfectly matched. While the model reproduces the basic characteristics of the rig well, there is some variation in the magnitude of the displacement. Since model was built based on a simplified version of the rig, particularly in the turnbuckle assemblies, some of this variation likely results from unmodeled effects related to the interplay of these simplified components. Additional variation could result from errors in the data acquisition on the rig; future experimentation could help characterize the source of this error and reduce it. The model response also shows a slight negative trendline: this is theorized to result from the method used to model the damping characteristics. Since the rig's

damping is not a linear characteristic, particularly when alternating between positive and negative rates of rotation, these variances would build up over time resulting in the model predicting a general negative trend where the rig did not experience one. Even with these sources of error, the model was able to reproduce the rig's dynamics with an RMSE of 0.06 rad, which was expected to be accurate enough to pose no issues for the continuation of this analysis, provided the testing is constrained to timescales for which the buildup of estimation errors is insignificant enough to prevent any major issues.

Free Response Test Results

As in the hingeline damping test, the model was configured to match the rig layout for the test, and the appropriate element values input, including the newly estimated hingeline and flex coupling damping coefficients. Once this had been accomplished, the same MATLAB process was used to evaluate the response of the model to the profile data from the test of the rig. In this case, the estimated parameters were the effective damping coefficient and effective inertia of the paired turnbuckle assemblies. Once the estimation algorithm had converged, the resulting model data was output and can be seen below, along with the PEMAT rig response data which it was intended to model.

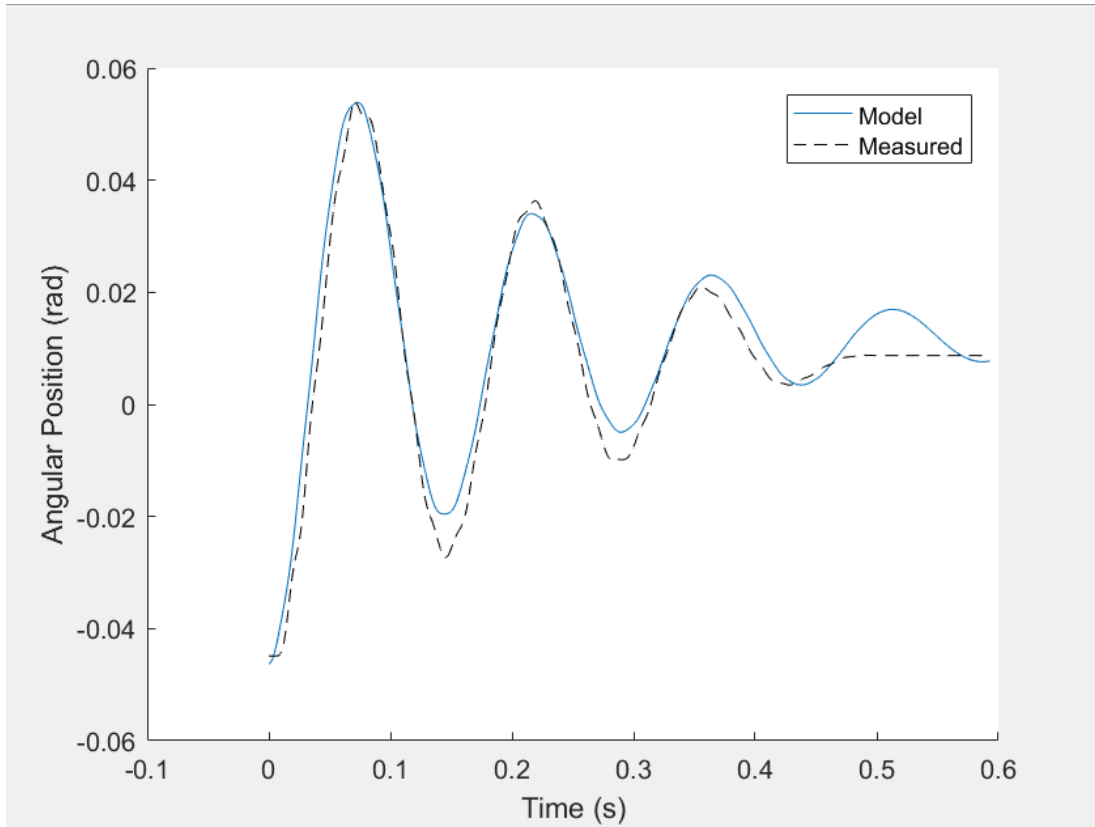


Figure 17. Free Response Test - Rig and Model Response

This set of test data, like the previous set, shows a good match between the test rig and the model, with an RMSE of 0.004 rad. Again, there are differences in the magnitude of the oscillations, but in this case, they are smaller than in the hingeline test data. This is likely a result of the estimated turnbuckle assembly inertia, as this parameter could compensate for errors in the model's representation of other elements. This set of data also shows variation in the damping characteristics, most easily seen at the end of the test. The rig data is consistent with a transition from dynamic to static friction as it comes to a rest, a characteristic which is not accounted for in the model, explaining the continued oscillation of the model

response after the rig had come to rest. This result suggests that in future tests, conditions which seek to evaluate the rig's performance at very low rates and magnitudes of oscillation should be avoided on the model, as they will likely be misrepresented. As these types of tests would be uncommon among those used for control surface actuator evaluation, this limitation, like the timescale limitation discussed above, should not pose any issues for this research.

The numerical values of the model elements, determined both through previous AFRL-conducted analyses and through the estimation procedures described above, are shown below.

Table 1. PEMAT Rig Model Parameters

Element	Value	Element	Value
Hingeline Inertia (each side) *	0.31 kg-m ²	Torsion Spring C Spring Coeff. *	2510 N-m/rad
Inertia Disk (each) *	5.22 kg-m ²	Torsion Spring D Spring Coeff. *	2498 N-m/rad
Effective Turnbuckle Inertia	2.77 kg-m ²	Hingeline Damping Coeff. (Left)	36.88 N-m-s/rad
Flex Coupling Spring Coeff. (Left) *	65575 N-m/rad	Hingeline Damping Coeff. (Right)	36.91 N-m-s/rad
Flex Coupling Spring Coeff. (Right) *	65065 N-m/rad	Flex Coupling Damping Coeff. (Left)	32867.7 N-m-s/rad
Torsion Spring A Spring Coeff. *	2544 N-m/rad	Flex Coupling Damping Coeff. (Right)	28440.4 N-m-s/rad
Torsion Spring B Spring Coeff. *	2504 N-m/rad	Effective Turnbuckle Damping Coeff.	21.26 N-m-s/rad

* [2]

Flight Test Data Modeling Results

With a validated model of the PEMAT rig, the capability to reproduce the load and position profiles for aircraft actuators could be evaluated. As previously discussed, this analysis utilized the data from an aileron reversal maneuver and a roll doublet on the NASA EPAD aircraft [22], with variable model elements (torsion springs and inertia disks) assembled in the various possible configurations to achieve the most accurate model response. Model response was evaluated for each of these configurations, and the resulting position data was output for comparison to the flight data.

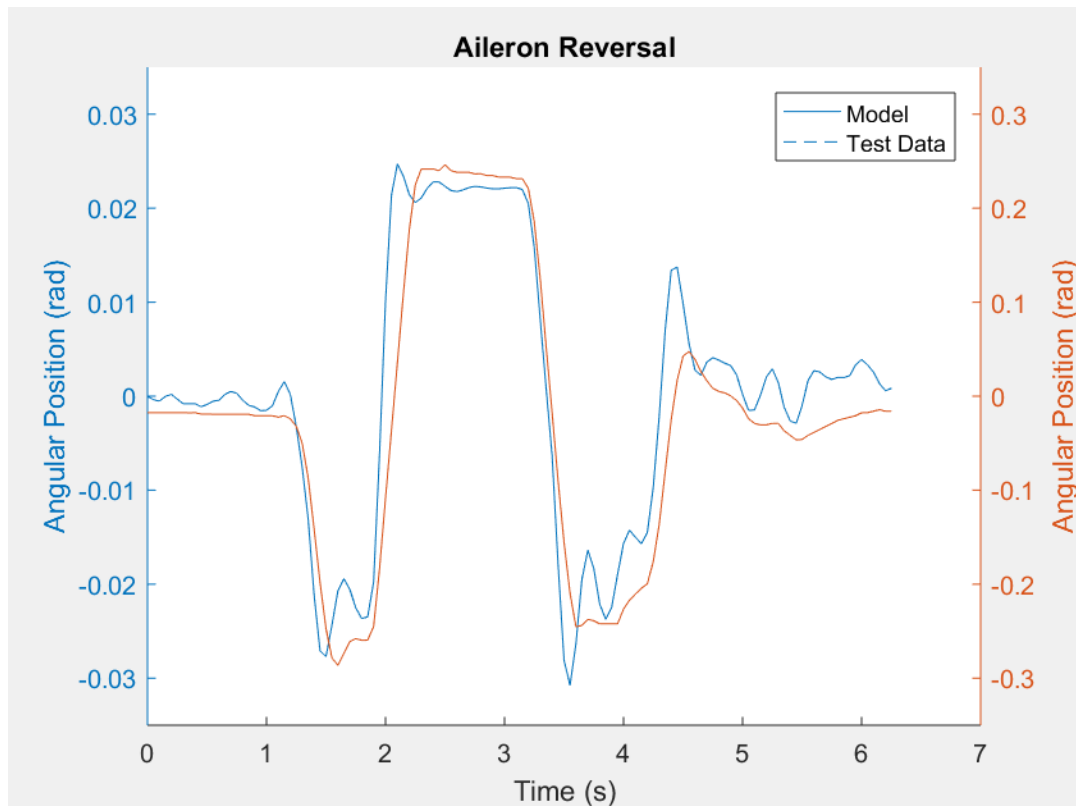


Figure 18. Aileron Reversal Maneuver - Actuator Flight and Model Data

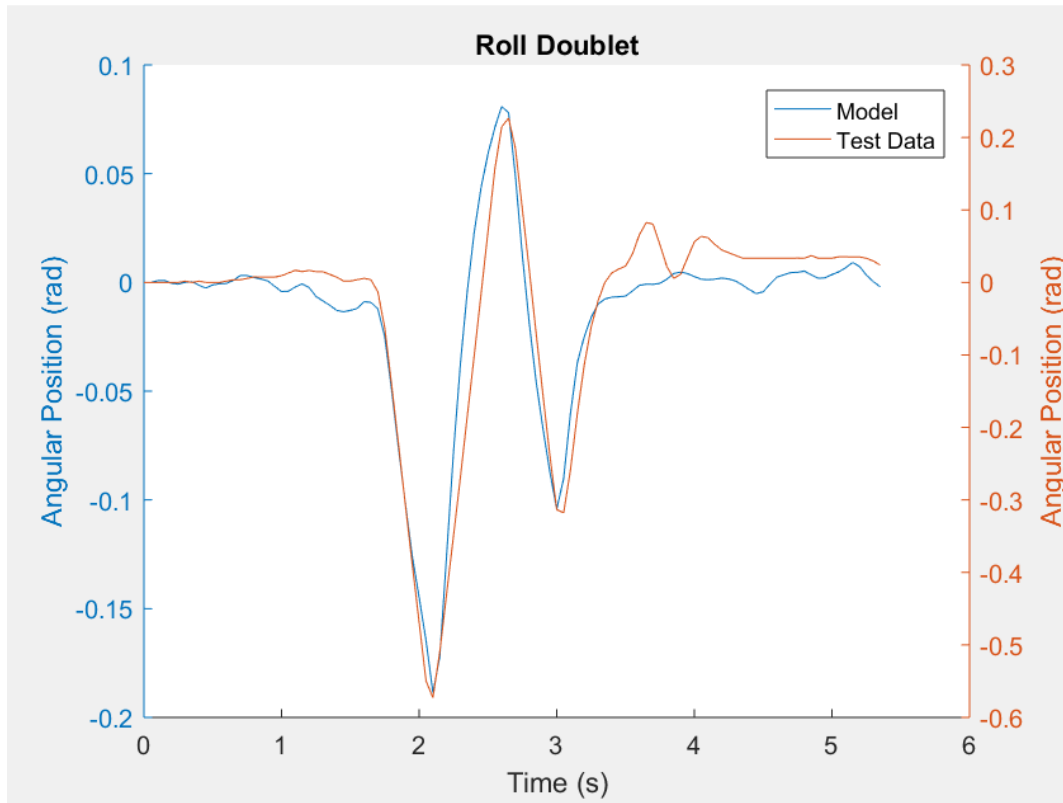


Figure 19. Roll Doublet Maneuver - Actuator Flight and Model Data

The best match for these maneuvers was achieved using both inertia disks and with torsion springs A and B on the north and south left sides of the rig, respectively. The model responses for this configuration, along with the flight test data, is shown in the preceding figures.

The best match for these maneuvers was achieved using both inertia disks and with torsion springs A and B on the north and south left sides of the rig, respectively. The model responses for this configuration, along with the flight test data, is shown in the preceding figures. The RMSE of the aileron reversal data was 0.059 rad, and for the roll doublet data was 0.048 rad.

Please note that in order to facilitate the comparison of the model and flight test responses, the model response was scaled up by a factor of ten for the aileron reversal, and by three for the roll doublet: the aircraft system and the test rig are of different scales, resulting in some of this variation, and flight conditions vary greatly during even a single flight, which could lead to the additional variation, but the linearity of the model allows this scaling – equivalent response magnitude could also be achieved by scaling the input torque by the same constant factor.

As was hypothesized, the linear model is able to reproduce the first order characteristics of the flight system well. Higher order variability can be seen as the model response exhibits more oscillation along the profile. While some of this variability may be the result of imperfect modeling between the hardware of the EPAD actuation system and that of the PEMAT rig, there are other effects to consider as well, as the data from a flight test will contain more uncontrolled variables than a laboratory test, and even more so than a model of a laboratory test. Significant among these would be effects of turbulent or simply inconsistent airflow across the control surface. While the relationship between load and deflection is nominally linear, and is represented as such in the model, fluctuations in the air through which the EPAD aircraft was flying would lead to variations in the load experienced by the actuator, and this effect would lead to inconsistencies like those seen in the above data when not accounted for in the model.

Despite these higher order variations, the desired fidelity of the model in reproducing flight actuator data was to the first order, and the results shown in the

figures above **Error! Reference source not found.** demonstrate this capability.

Based on this level of model performance, the PEMAT rig can be expected to provide the same capability.

Flight Test Data Reproduction Results

The final step in this research was to evaluate flight-representative profiles on the PEMAT rig hardware itself. Each of the profiles used for this purpose were derived by the same method as those in the model response testing: they were sourced from data gathered on the NASA EPAD program [8] [22], and scaled to fit the capabilities of the rig. As the available data was all gathered from the aileron actuator system, rig configuration was matched to that which provided the best performance on the model: both left and right inertia disks were used, as were torsion springs A and B on the north and south, respectively. With each profile representing the performance of the same actuator system, as wide a variety of maneuvers as possible were used to ensure the evaluation was not limited to a narrow scope of the possible flight envelope, and to provide information on performance in various regimes which could be experienced in other EMA applications. For each of these maneuvers, the position profile was used to determine a time history of each state related to that measurement, and MATLAB's "ode45" differential equation solver was used to determine the remaining states. This provided the load experienced by the model actuator, which is compared to the rig performance in the following figures.

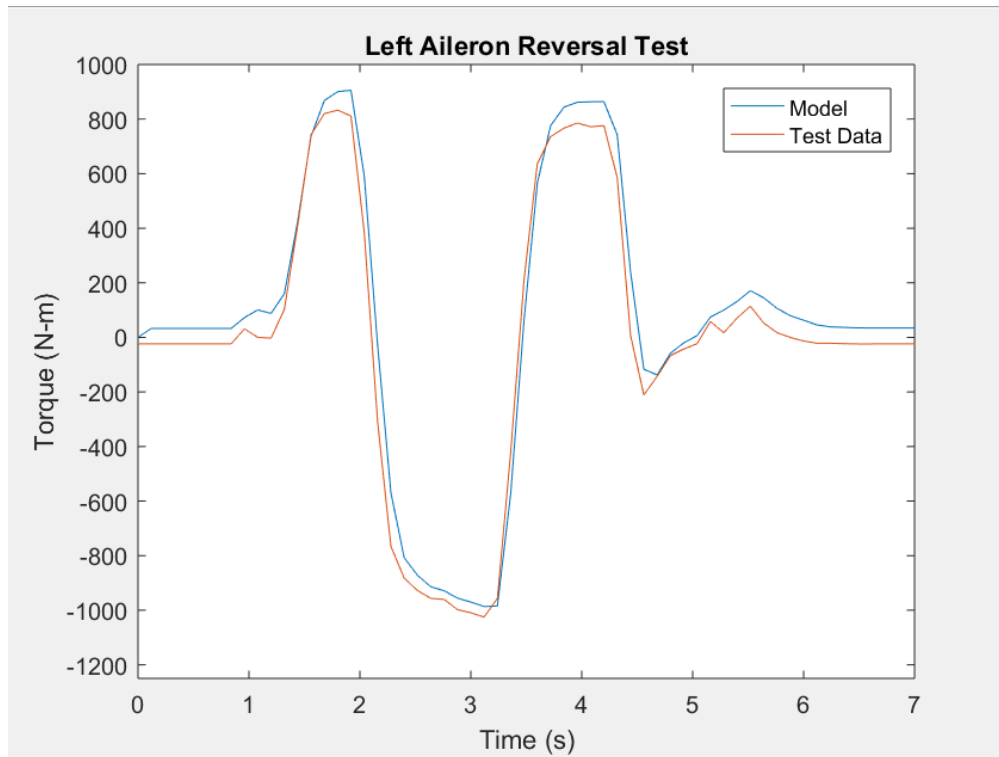


Figure 20. Aileron Reversal Load Profile - Rig and Model Response

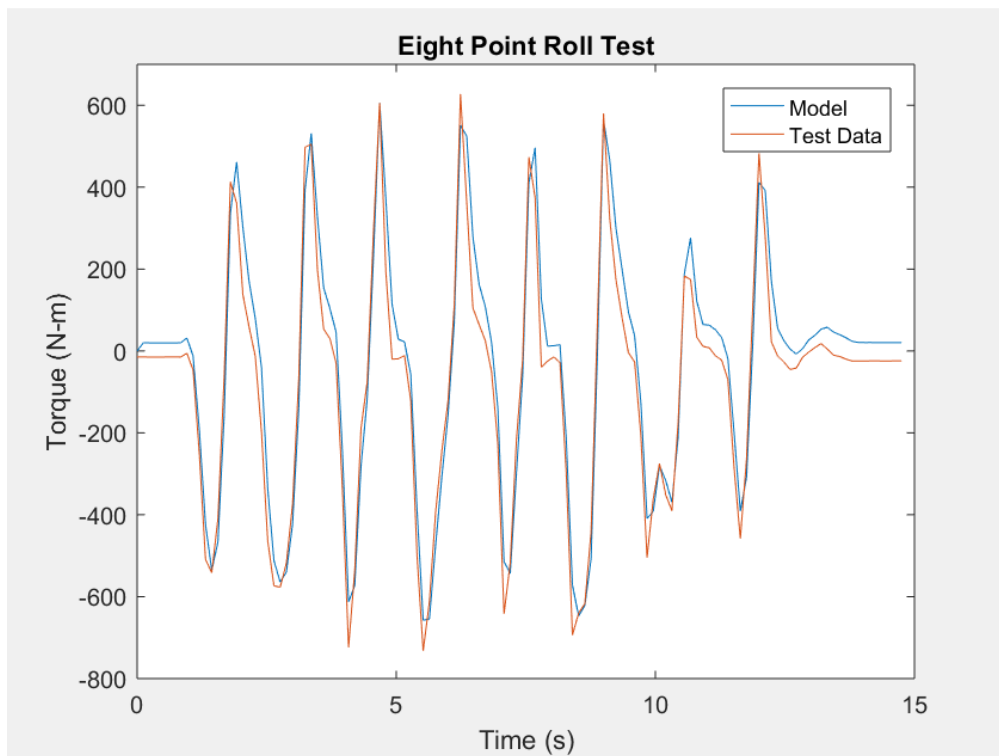


Figure 21. Eight Point Roll Load Profile - Rig and Model Response

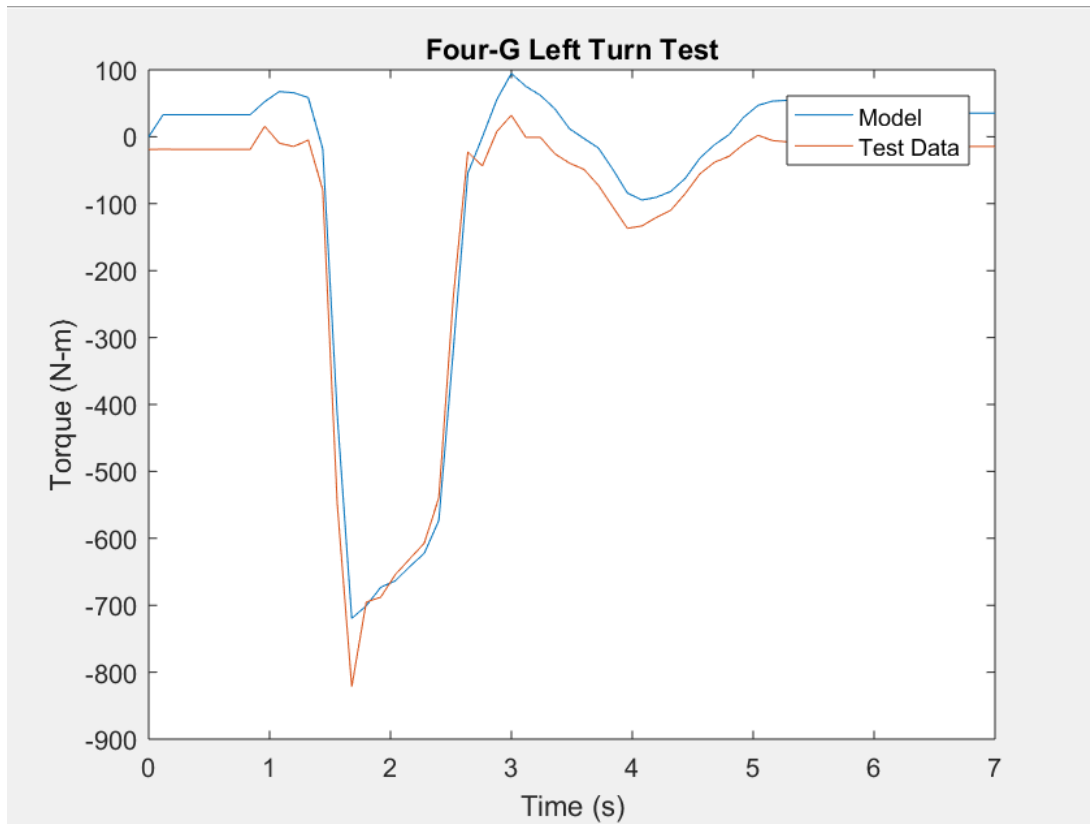


Figure 22. Four-G Left Turn Load Profile - Rig and Model Response

In each of these profiles, some slight variations can be seen. Most noticeably, the model response experiences an initial sharp movement, offsetting it from the rig response by a small amount which carries through to the end of the profile. This is expected to result from the initial torque provided by the actuator being insufficient to provide any initial deflection to the rig, whereas in the model, the lack of static friction allows for some motion. Since this affects the baseline condition for the remainder of each profile, it carries through the entire test. There are also some variations seen at inflection points along the profile, which can be expected from the capabilities of a linear model, but these are minor enough to present no

difficulties in applying the model. There is no significant performance difference seen between periods of rapid motion, repeated cycling, or high loads, which indicates a broad spectrum of applications should be available.

It is important to point out that, to this point, no direct comparison between the performance of the PEMAT rig and data from an actuator flight test has been drawn; many of the maneuver profiles used contained only the position information, and those which also included load required some manipulation to fall within the hardware limitations of the rig. As such, the torque resulting from the rig tests could not be compared to flight data. However, each of the profiles which were run on both the rig and the model thereof indicated an accurate representation of the rig characteristics, and validation conducted with the model showed that reproduction of flight systems can be done.

V. Conclusion

Conclusions

The overall goal of this research was determining the suitability of the PEMAT test rig for use evaluating electromechanical actuators for use in various aerospace applications: specifically, it was desired to determine whether the rig could reproduce the dynamics experienced by an EMA in a flight application. Due to the characteristics of the rig, with its passive loading, it was expected that it could match a flight system's first order characteristics. While this would omit some of the effects an actuator would experience in flight, it would include the most impactful characteristics, those important for the early phases of testing. The simplicity and cost-effectiveness of testing on the PEMAT rig would be a significant benefit over active test rigs and especially wind tunnel or flight testing. While data availability limited the scope of this research to the analysis of aircraft ailerons, the underlying dynamics of many control surfaces and other movable elements in a variety of applications are similar, and the conclusions herein should be generalizable to the extent of their precision. In pursuit of this end goal, several intermediate determinations needed to be made to provide enough information to judge the success of the project. Indeed, regardless of whether the future application of the PEMAT facility is as proposed, these intermediate conclusions can provide valuable information for assessing the rig's capabilities both qualitatively and quantitatively, as well as for developing the specific test profiles that are desired.

The first step was the development of a linear model of the rig. Since the rig was intended to capture the first order response of a flight system, a linear model was expected to provide a precise enough reproduction of the rig to evaluate the necessary characteristics. This model, as described above, was constructed as a spring-mass-damper system, with as many elements as possible defined from direct measurements taken by AFRL [2]. The final elements were estimated by comparing the model response to that of the rig for a pair of characterization tests. With the best attainable estimates of these elements, the model was able to reproduce the rig data to an RMSE of 0.06 rad and 0.004 rad, respectively. As noted previously, the performance of the model shows the most variation over longer timescales and over small and slow deflections. These limitations can be expected, considering the approximations necessary in the model development. Typical requirements of flight actuators would not be limited by performance in these regimes, and even so, the overall error of the model's response takes them into account. This level of performance was deemed sufficient, and the linear model was accepted as characterizing the rig to the degree necessary for continuation. The equations defining this model can be seen in Equations, with element values contained in Table 1.

With the model developed, the next step was to determine whether it could be used to replicate the dynamics of a flight system. Courtesy of the NASA EPAD program, aileron actuator torque and position data was available, and was thus utilized. It was then possible to compare this flight data with data from the model, manipulating the configuration of the rig's load springs and inertia disks to achieve

the most accurate reproduction. The best performance was achieved by using two springs, one on the north and one on the south, and both inertia disks. Since the sizes of the rig and its actuator do not match those of the aircraft, the magnitude of the response is different by a factor of ten, but when scaled up, the profiles match to within 0.06 RMSE, indicating that the dynamics of a control surface like this aileron can be captured by the model, and with the model determined to be an accurate representation of the rig, the same should be true of the latter.

The final element of this research was to determine the response of the rig itself to the type of maneuvers an EMA could experience during flight. Comparing this data to the response of the model to the same maneuvers would validate the match between the model and rig characteristics for such flight-representative profiles, indicating that, like the model, the rig would be capable of supporting testing of EMAs for flight applications. For this testing, the rig and model were kept in the configuration which earlier testing suggested was the most accurate representation of the aileron system used to develop the tests. Seven different profiles were run, covering a variety of maneuvers and flight conditions, ranging from slow, sustained maneuvers to repeated, cyclical actuation to abrupt, high-load maneuvers. With the variation between the rig and model profiles not exceeding 0.05 RMSE, the model can be confirmed as an accurate representation of rig performance, and the rig can be shown to accurately reproduce the dynamics of an aircraft control surface system.

With the demonstrated capability of the PEMAT rig to reproduce the load profile of an aileron for multiple maneuvers, this research has developed the capability to test EMAs for at least one type of aerospace application. Additional applications, particularly other aircraft control surfaces, but also those on rockets and other spacecraft, while not directly validated, can be expected to exhibit analogous dynamics, and their representation should thus also fall within the capabilities of the rig. With this capability, the PEMAT facility has its potential application expanded from its current use running simple test profiles for force-fight analysis to the analysis of any number of electromechanical actuators intended for use on aerospace vehicles in the future, as well as, by contributing to the body of knowledge regarding EMA systems in the course of these tests, aiding in the development of requirements and design parameters for aerospace EMAs in the future.

Future Work

There are several areas which present themselves as providing potential for future development. First, it may be possible to further enhance the accuracy of the model. The conceptually simplest possible improvement would be to further refine the model fidelity. In this research, the rig characteristics were reduced to a limited number of model elements, and the use of more elements would capture more of the dynamics, potentially leading to a more accurate representation. Another area for investigation is in the damping characteristics: the current linear model does not

account for static and dynamic friction independently, and this or other time dependencies in the damping lead to some variation between the model and the rig. Each of these suggestions would lead to increased model complexity, potentially compromising its linear nature; the benefit of these refinements would have to be weighed against the performance advantages of a linear model.

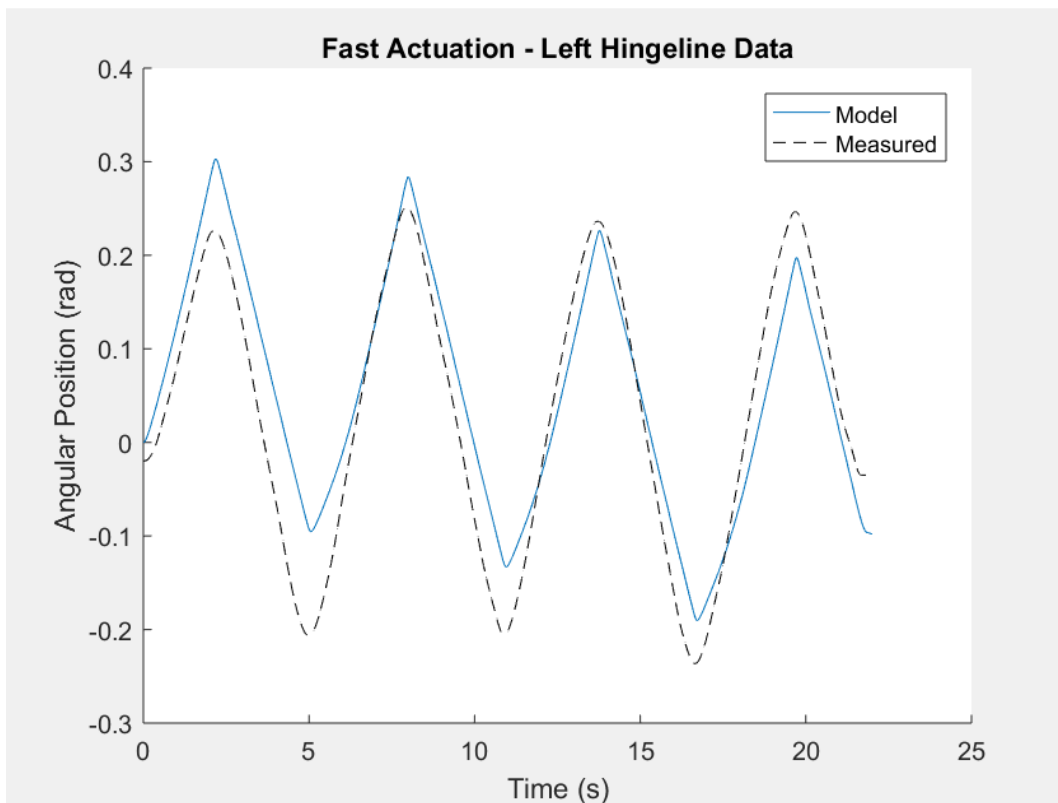
As this research involved comparing the model response to data from a single system, a logical continuation would be to compare data from additional systems, whether those would be other control surfaces, systems from additional aircraft, or systems from rockets or spacecraft. These comparisons would further verify the rig's representation capabilities, definitively demonstrating whether EMAs intended for the various actuator systems could be tested in the PEMAT facility. While the basic dynamic characteristics of these systems can be expected to mirror those of the aileron system used in this analysis, the rig in its current state has its configurability limited by the available load spring and inertia disk hardware. The representation of other systems may require configurations not available with this hardware. By comparing the rig response, through hardware testing or model simulation, to the load profiles of additional systems, it could be determined whether the current capability is sufficient, and if not, what additions or changes would need to be made to achieve effective system representation.

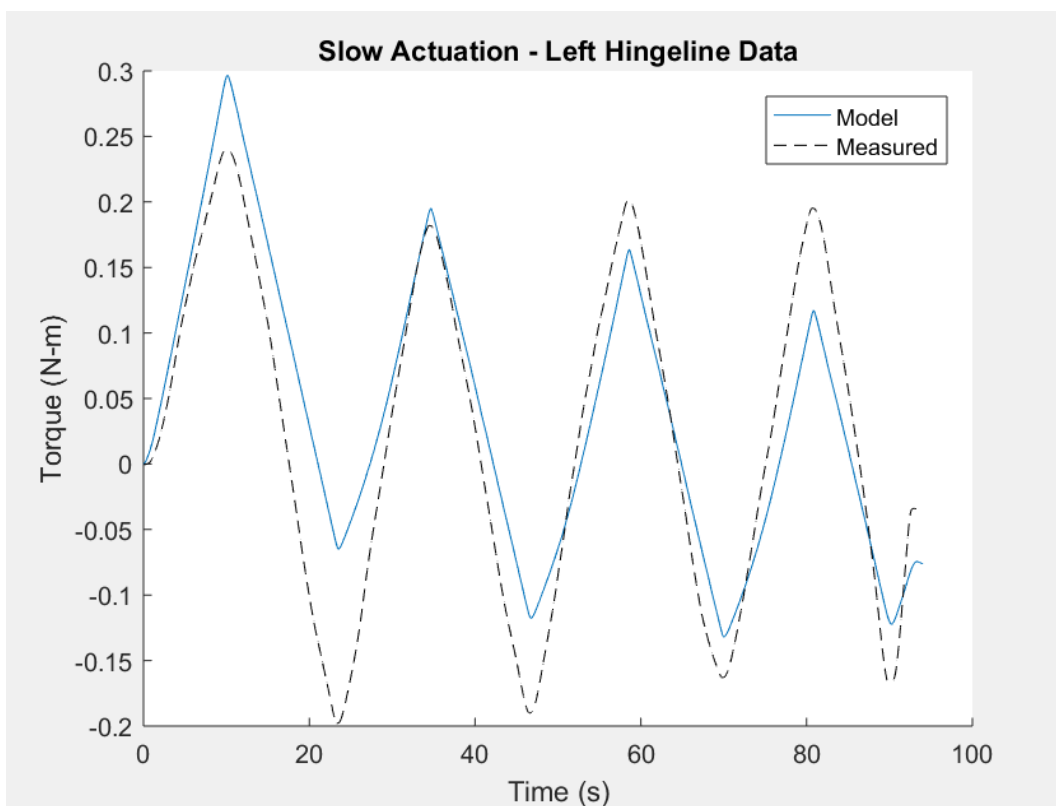
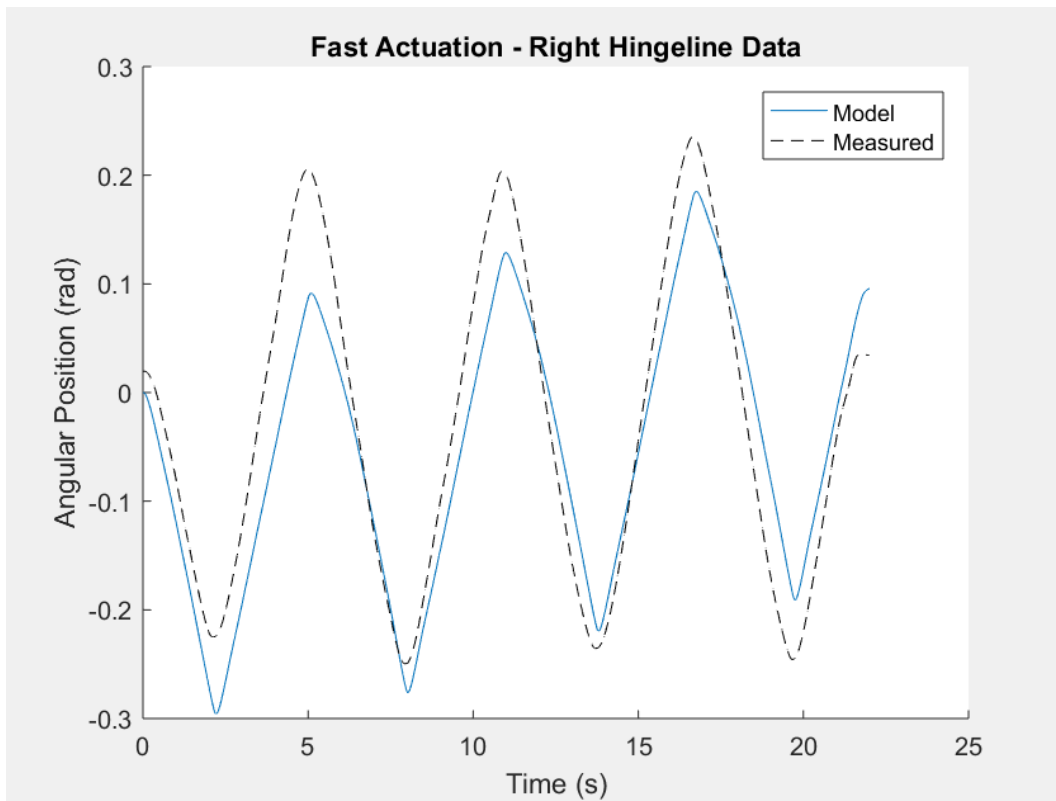
Finally, as the purpose of this research was to determine whether effective testing could be conducted on EMAs intended for flight, a desirable continuation would be to test such EMAs. This is a longer-term goal from the viewpoint of this

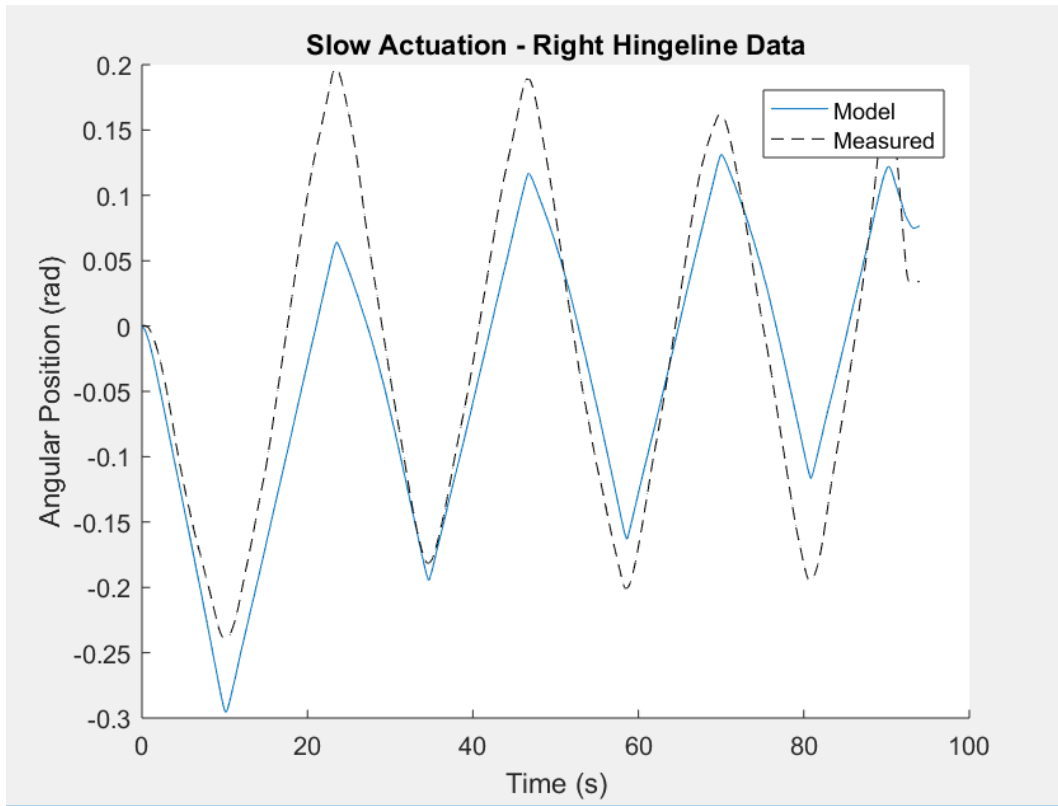
program, as it would require the identification of a system, either under development or legacy, which could benefit from EMA integration, verification of the PEMAT rig's capability to represent that particular system, and, considering the rig's limitation to representing first-order effects, the capability to conduct the necessary follow-on testing on the EMA prior to acceptance. However, with the capability development in this research and in the recommended future work above, this process would not need to start from zero: with the growing interest in integrating EMAs into a variety of aerospace applications, it is likely that a system matching the rig's representation capabilities would already be at some stage in development. For such a program, the PEMAT facility could provide significant benefit, as its use could significantly narrow the field of potential actuators, providing preliminary data on their performance for the desired role. This would reduce the necessity for development and conduction of more complex, actively-loaded, wind tunnel, or similar tests, saving both time and money.

Appendix A. Model Development Data

This appendix contains the plots of additional test data from the hingeline damping rig characterization tests. For the hingeline data, the “Fast Actuation” plots were produced using data from the test conducted at 0.35 rad/s, and the “Slow Actuation” plots using data from the 0.175 rad/s actuation test. The “Left Hingeline” plots show data from the sensors on the left side of the hingeline, and the “Right Hingeline” plots from the sensors on the right side. As could be expected, the performance of each side of the rig for the same test is nearly identical, with the data mirrored over the X-axis.

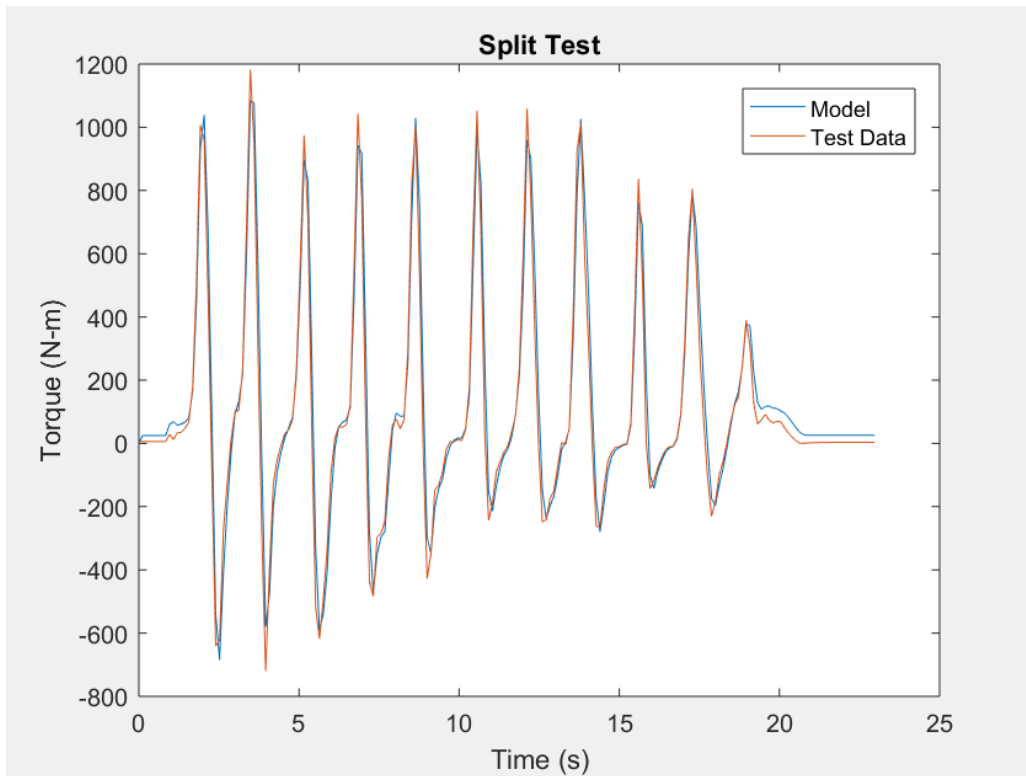


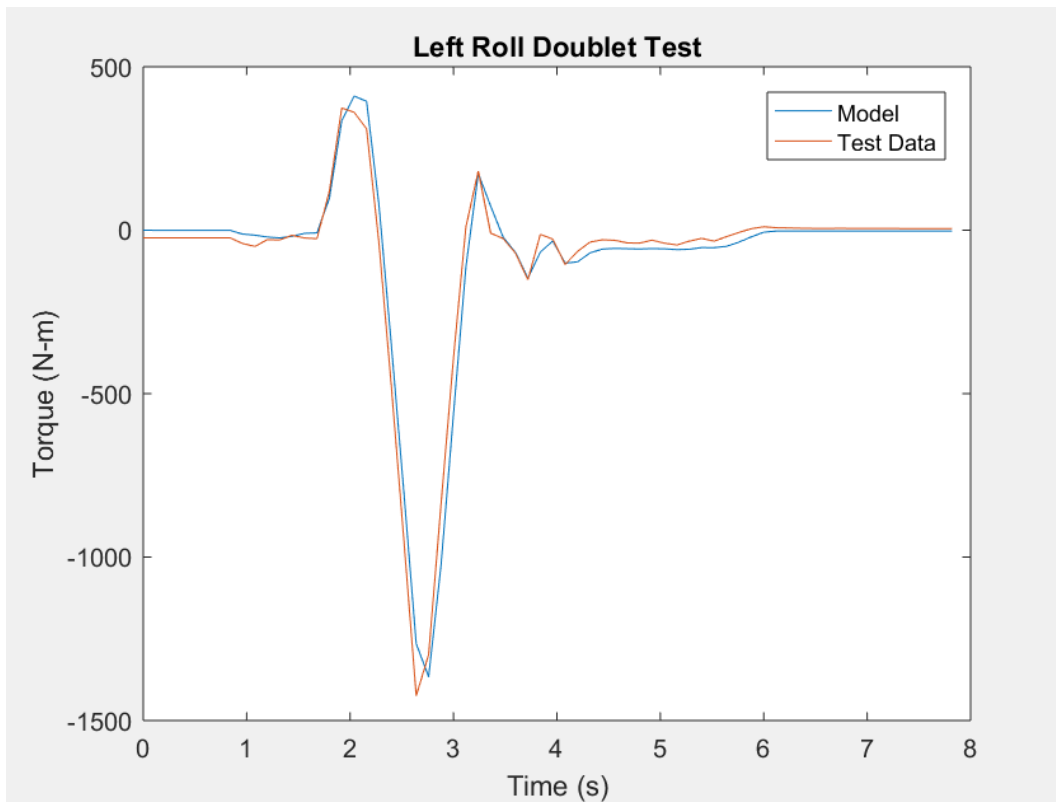
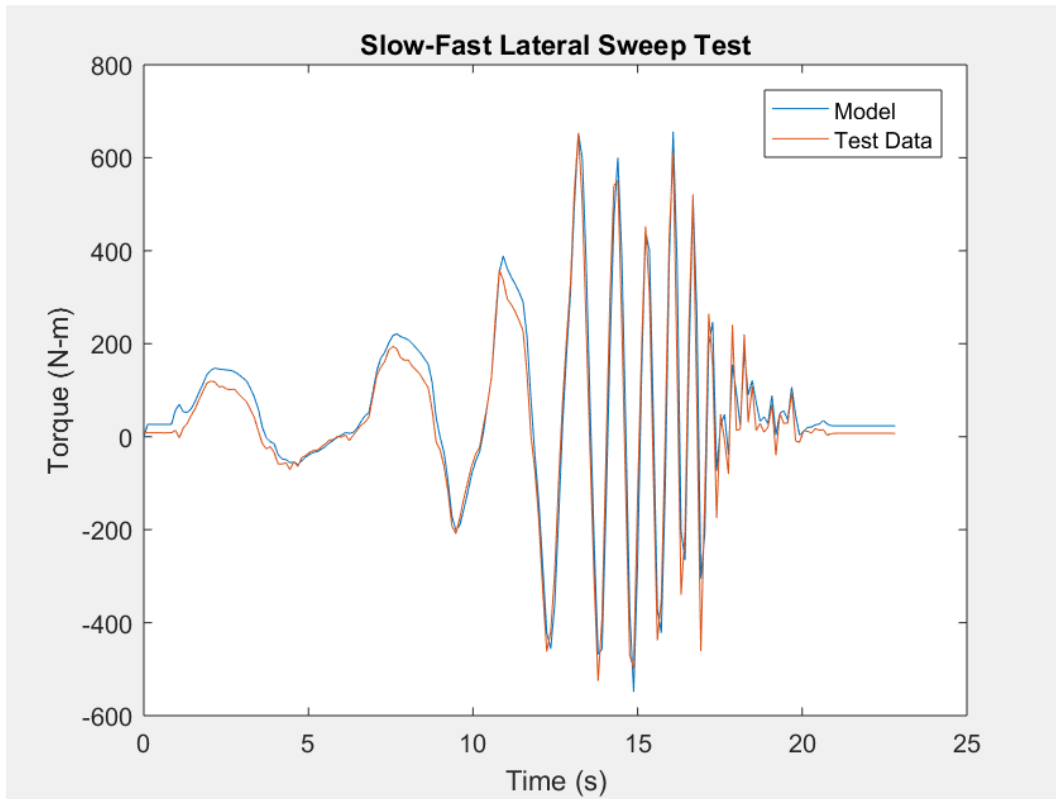


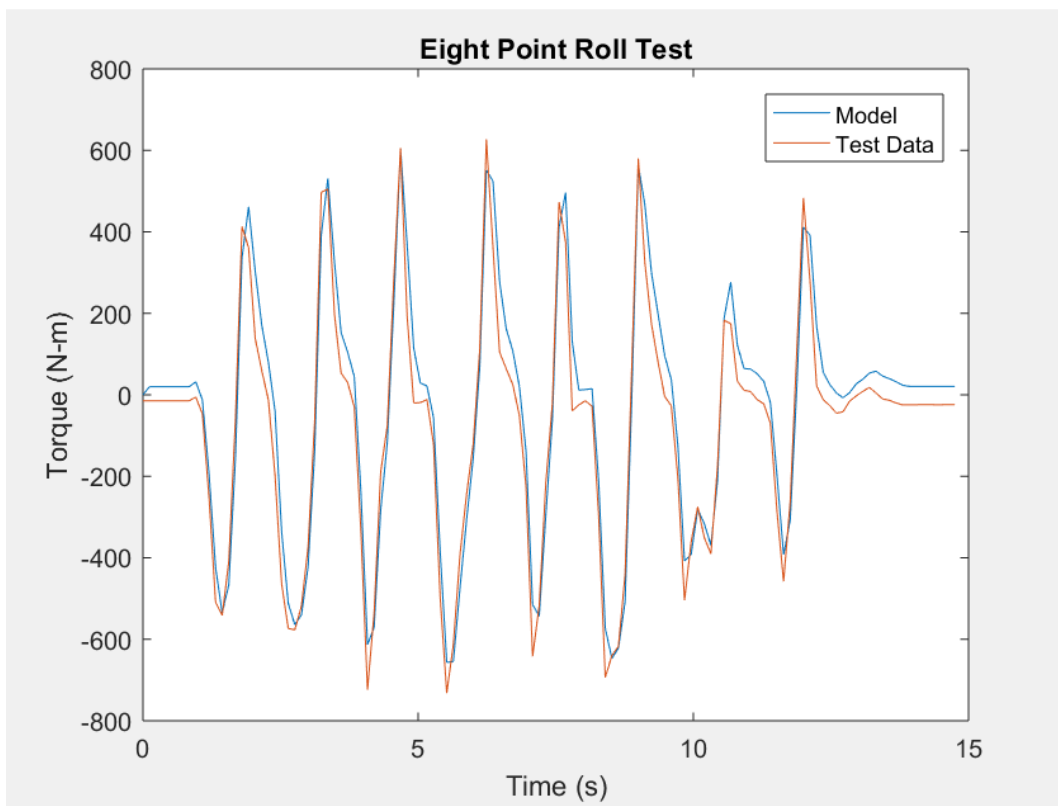
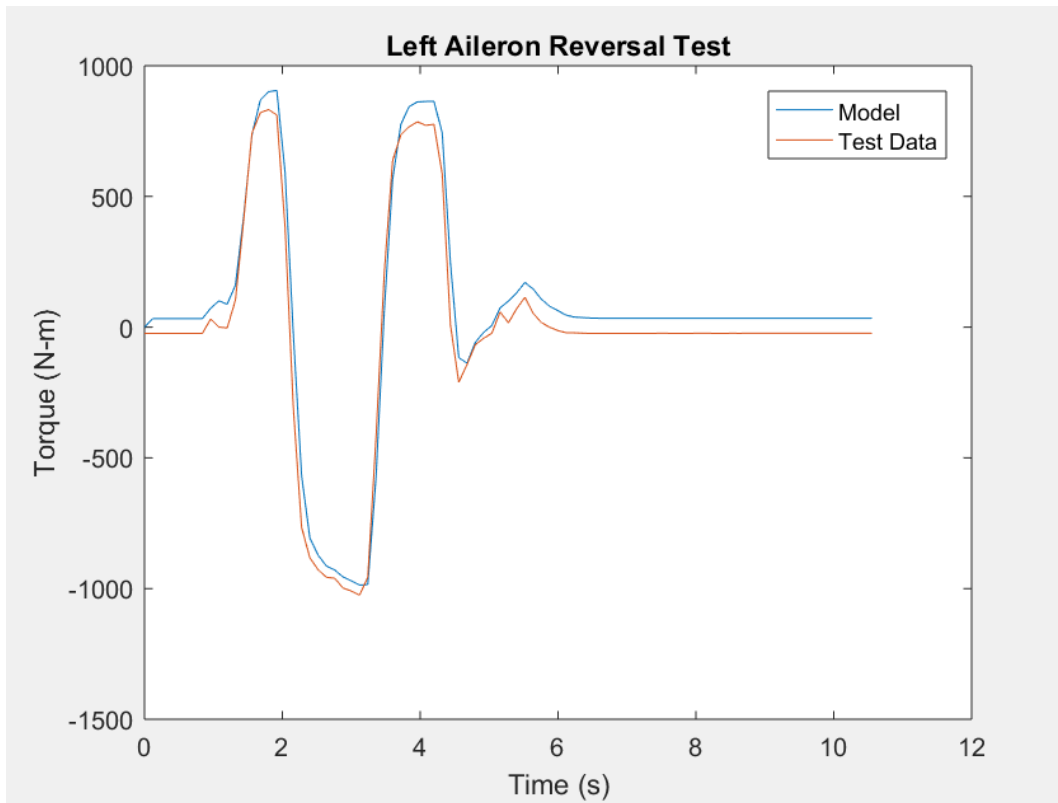


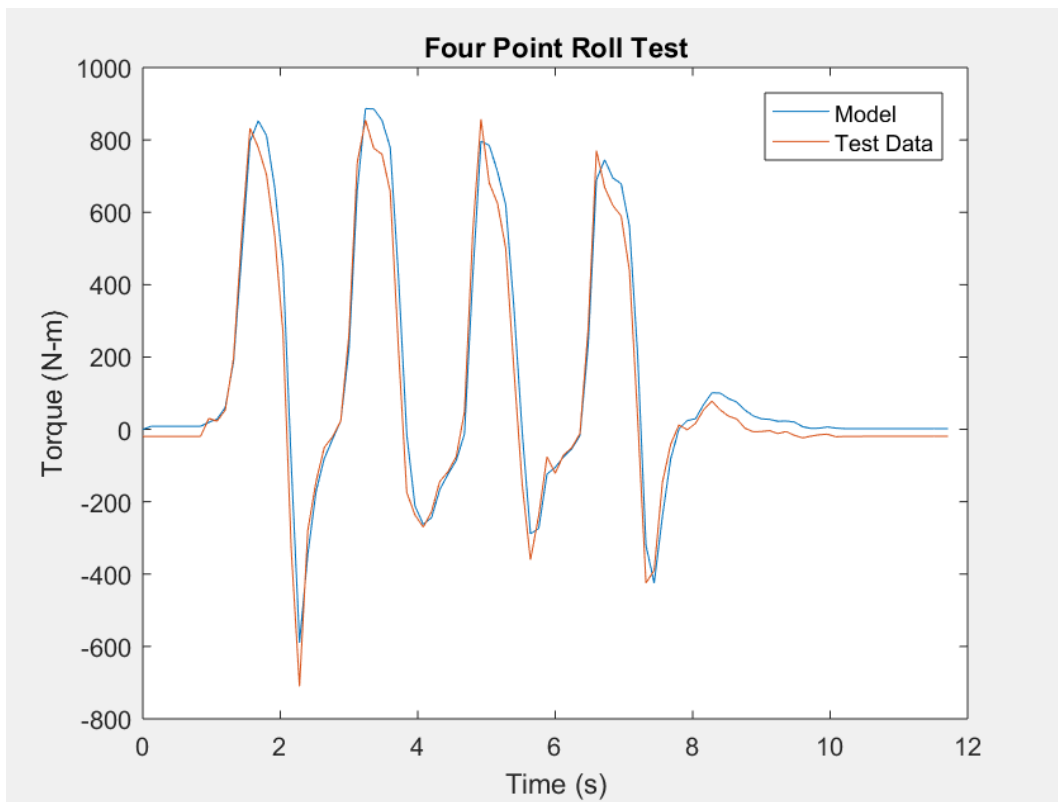
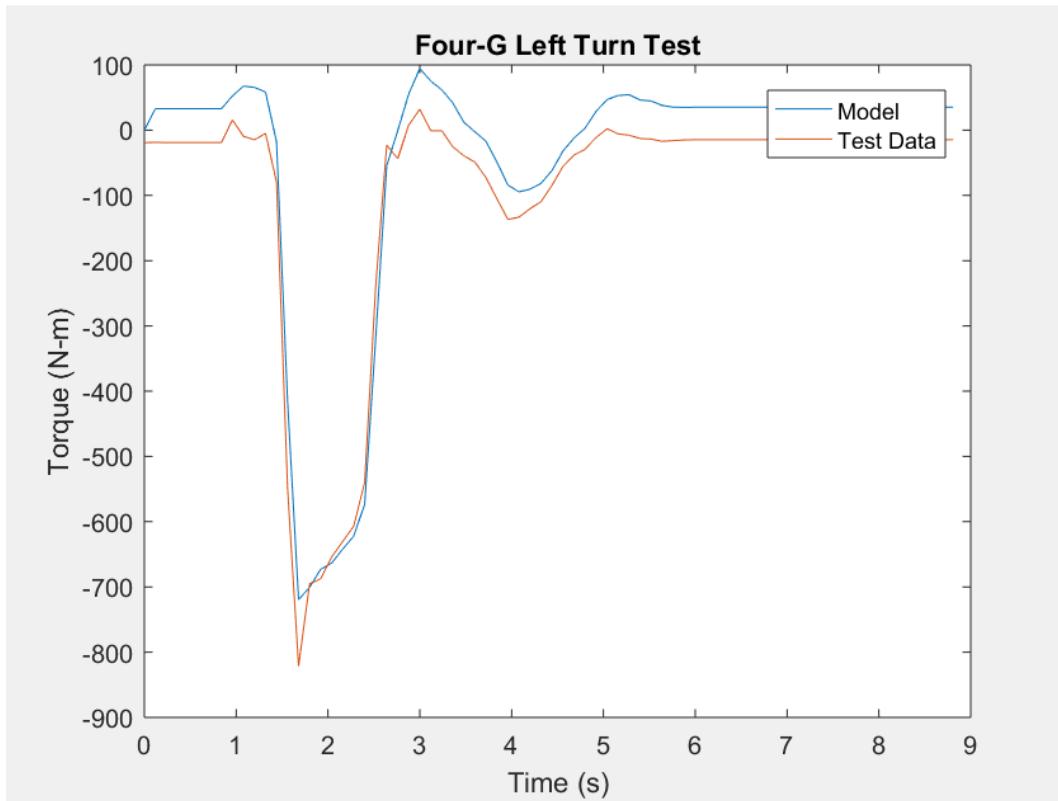
Appendix B. Rig and Model Comparison Data

The additional profiles, based on flight maneuvers, used to compare the performance of the rig and the linear model are contained in this appendix. Each figure includes the load response from the rig test as well as from the model simulation.









Appendix C. MATLAB Code

This appendix contains the MATLAB code used in the various analysis steps over the course of this research. Functions are grouped by which section of the analysis they were used for: the hingeline damping test, free response test, flight test data modeling, and flight test data reproduction.

Hingeline Damping Test

Hingeline.m

```
clear all; close all; clc;
%% Import data
fname = 'Hingeline Damping Test Data';

T1 = linspace(0,94,77492); %set time vectors
T2 = linspace(0,22,53732);

T_l1 = xlsread(fname,1,'B1502:B78993'); %read in torque (in-lbf)
    T_l1 = T_l1*0.112985; %convert to N-m
    T_l1 = T_l1-0.3809; %remove measurement offset
T_r1 = xlsread(fname,1,'C1502:C78993');
    T_r1 = T_r1*0.112985;
    T_r1 = T_r1+0.3868;
T_l2 = xlsread(fname,2,'B1502:B55233');
    T_l2 = T_l2*0.112985;
    T_l2 = T_l2-0.4909;
T_r2 = xlsread(fname,2,'C1502:C55233');
    T_r2 = T_r2*0.112985;
    T_r2 = T_r2+0.4889;

P_l1 = xlsread(fname,1,'D1502:D78993'); %read in position (deg)
    P_l1 = P_l1*(pi/180); %convert to rad
P_r1 = xlsread(fname,1,'E1502:E78993');
    P_r1 = P_r1*(pi/180);
P_l2 = xlsread(fname,2,'D1502:D55233');
    P_l2 = deg2rad(P_l2);
P_r2 = xlsread(fname,2,'E1502:E55233');
    P_r2 = deg2rad(P_r2);

%% Set system parameters
K_f1 = 1144.5*(180/pi); % N-m/rad
K_f2 = 1135.6*(180/pi); % N-m/rad
I_f = 0.80; % kg-m^2
I_h = 0.31; % kg-m^2
```

```

C_f1 = 500; % N-m-s/rad          %%% FIT %%%
C_f2 = 500; % N-m-s/rad          %%% FIT %%%
C_h1 = 50;          %%% FIT %%%
C_h2 = 50;          %%% FIT %%%

%% Optimize Fast Left Parameters
[x_l2,fval1] = fminsearch(@(x)
Lerror(K_f2,I_f,I_h,T_l2,T2,P_r2,x),...
[C_f2,C_h2]); %perform estimation
C_f2 = x_l2(1); %pull off estimated values
C_h2 = x_l2(2);

%% Plot Optimized Left Model Fast Response
A2 = [0 1 0 0;-K_f2/I_f -C_f2/I_f K_f2/I_f C_f2/I_f;...
      0 0 0 1;K_f2/I_h C_f2/I_h -K_f2/I_h -(C_f2+C_h2)/I_h]; %set
model elems
B2 = [0;1/I_f;0;0];
C2 = [1 0 0 0];
D2 = [0];

Sys2 = ss(A2,B2,C2,D2); %build state space model

[Y22,X22] = lsim(Sys2,T_l2,T2); %simulate system response

figure(1)
hold on
xlabel('Time (s)')
plot(T2,Y22)
plot(T2,P_r2,'k--')
ylabel('Angular Position (rad)')
legend('Model','Measured')
title('Fast Actuation - Left Hingeline Data')

%% Optimize Fast Right Parameters
[x_r2,fval2] = fminsearch(@(x)
Rerror(K_f1,I_f,I_h,T_r2,T2,P_l2,x),...
[C_f1,C_h1]); %perform estimation
C_f1 = x_r2(1); %pull off estimated values
C_h1 = x_r2(2);

%% Plot Optimized Right Model Fast Response
A1 = [0 1 0 0;-K_f1/I_f -C_f1/I_f K_f1/I_f C_f1/I_f;...
      0 0 0 1;K_f1/I_h C_f1/I_h -K_f1/I_h -(C_f1+C_h1)/I_h]; %set
model elems
B1 = [0;0;0;-1/I_f];
C1 = [-1 0 0 0];
D1 = [0];

Sys1= ss(A1,B1,C1,D1); %build state space model

[Y21,X21] = lsim(Sys1,T_r2,T2); %simulate system response

figure(2)
hold on
xlabel('Time (s)')

```

```

plot(T2,Y21)
plot(T2,P_l2,'k--')
ylabel('Angular Position (rad)')
legend('Model','Measured')
title('Fast Actuation - Right Hingeline Data')

%% Optimize Slow Left Parameters
[x_l1,fval4] = fminsearch(@(x)
Lerror(K_f2,I_f,I_h,T_l1,T1,P_r1,x),...
[C_f2,C_h2]); %perform estimation
C_f4 = x_l1(1); %pull off estimated values
C_h4 = x_l1(2);

%% Plot Optimized Left Model Slow Response
A4 = [0 1 0 0;-K_f2/I_f -C_f4/I_f K_f2/I_f C_f4/I_f;...
0 0 0 1;K_f2/I_h C_f4/I_h -K_f2/I_h -(C_f4+C_h4)/I_h]; %set
model elems
B4 = [0;1/I_f;0;0];
C4 = [1 0 0 0];
D4 = [0];

Sys4 = ss(A4,B4,C4,D4); %build state space model

[Y12,X12] = lsim(Sys4,T_l1,T1); %simulate system response

figure(3)
hold on
xlabel('Time (s)')
plot(T1,Y12)
plot(T1,P_r1,'k--')
ylabel('Angular Position (rad)')
ylabel('Torque (N-m)')
legend('Model','Measured')
title('Slow Actuation - Left Hingeline Data')

%% Optimize Slow Right Parameters
[x_r1,fval3] = fminsearch(@(x)
Rerror(K_f1,I_f,I_h,T_r1,T1,P_l1,x),...
[C_f1,C_h1]); %perform estimation
C_f3 = x_r1(1); %pull off estimated values
C_h3 = x_r1(2);

%% Plot Optimized Right Model Slow Response
A3 = [0 1 0 0;-K_f1/I_f -C_f3/I_f K_f1/I_f C_f3/I_f;...
0 0 0 1;K_f1/I_h C_f3/I_h -K_f1/I_h -(C_f3+C_h3)/I_h]; %set
model elems
B3 = [0;0;0;-1/I_f];
C3 = [-1 0 0 0];
D3 = [0];

Sys3= ss(A3,B3,C3,D3); %build state space model

[Y11,X11] = lsim(Sys3,T_r1,T1); %simulate system response

figure(4)

```

```

hold on
xlabel('Time (s)')
plot(T1,Y11)
plot(T1,P_11,'k--')
ylabel('Angular Position (rad)')
legend('Model','Measured')
xlabel('Time (s)')
title('Slow Actuation - Right Hingeline Data')

```

Lerror.m

```

%% Left Error Function
function err = Lerror(K_f,I_f,I_h,Tor,Time,Pos,x)
C_f = x(1); %pull estimated parameters
C_h = x(2);

A = [0 1 0 0;-K_f/I_f -C_f/I_f K_f/I_f C_f/I_f;...
     0 0 0 1;K_f/I_h C_f/I_h -K_f/I_h -(C_f+C_h)/I_h]; %set model
elems
B = [0;1/I_f;0;0];
C = [1 0 0 0];
D = [0];

Sys = ss(A,B,C,D); %build state space model

[Y,X] = lsim(Sys,Tor,Time); %simulate system response

err = rms(Y-Pos); % calculate root mean square error
end %function

```

Rerror.m

```

%% Right Error Function
function err = Rerror(K_f,I_f,I_h,Tor,Time,Pos,x)
C_f = x(1); %pull estimated parameters
C_h = x(2);

A = [0 1 0 0;-K_f/I_f -C_f/I_f K_f/I_f C_f/I_f;...
     0 0 0 1;K_f/I_h C_f/I_h -K_f/I_h -(C_f+C_h)/I_h]; %set model
elems
B = [0;0;0;-1/I_f];
C = [-1 0 0 0];
D = [0];

Sys= ss(A,B,C,D); %build state space model

[Y,X] = lsim(Sys,Tor,Time); %simulate system response

err = rms(Y-Pos); %calculate root mean square error
end %function

```

Free Response Test

Freeresponse.m

```
clear all; close all; clc
%% Load Data
fname = '02072017 Free Response';

Time = xlsread(fname,2,'A16317:A17799'); %data sample times, s
Time = Time-6.50757590464977; %normalized sample
times, s
Tor_l = xlsread(fname,2,'B16317:B17799'); %left torque, in-lb
Tor_l = Tor_l.*0.112984829; %left torque, N-m
Tor_r = xlsread(fname,2,'C16317:C17799'); %right torque, in-lb
Tor_r = Tor_r.*0.112984829; %right torque, N-m
Ang_l = xlsread(fname,2,'H16317:H17799'); %left angle, deg
Ang_l = Ang_l*(pi/180); %left angle, rad
Ang_r = xlsread(fname,2,'I16317:I17799'); %right angle, deg
Ang_r = -Ang_r*(pi/180); %right angle, rad
AngV_l = xlsread(fname,2,'O16317:O17799'); %left angular velocity,
deg/s
AngV_l = AngV_l*(pi/180); %left angular velocity,
rad/s
AngV_r = xlsread(fname,2,'N16317:N17799'); %right angular velocity,
deg/s
AngV_r = -AngV_r*(pi/180); %right angular velocity,
rad/s

%% Set Parameters
I_c = 0.80; % kg-m^2
I_ns = 0.08; % kg-m^2
m_ns = 9.37; % kg
c_ns = 0.0587*(180/pi); % N-m-s/rad
k_n = 44.4*(180/pi); % N-m/rad
k_s = 43.7*(180/pi); % N-m/rad

c_fr = 547.48; % N-m-s/rad
c_fl = 629.21; % N-m-s/rad
k_fr = 1135.6*(180/pi); % N-m/rad
k_fl = 1144.5*(180/pi); % N-m/rad

c_hr = 36.91; % N-m-s/rad
c_hl = 36.88; % N-m-s/rad
I_hrl = 0.31; % kg-m^2

%% Optimize Parameters
I_tb = 0.5; %kg-m^2/rad %%%%%%%%% FIT %%%%%%%%%
c_tb = 10; %N-s/rad %%%%%%%%% FIT %%%%%%%%%

Tor_i = (Tor_r-Tor_l); %set parameters based on right actuation
Ang_o = Ang_l;
k_f = k_fr;
c_f = c_fr;
c_h = c_hr;
```

```

[x,fval] = fminsearch(@(x)
FRMError(I_ns,I_c,c_ns,k_n,k_s,k_f,c_f,c_h,...
    I_hrl,Tor_i,Time,Ang_o,x),[I_tb, c_tb]); %perform estimation
I_tb = x(1); %pull off estimated values
c_tb = x(2);

%% Plot Optimized Model Response
FRMsys =
FRMbuild(I_ns,I_c,I_tb,c_ns,c_tb,k_n,k_s,k_f,c_f,c_h,I_hrl);
    %build state space model

Y = lsim(FRMsys,Tor_i,Time,[-2.65*(pi/180);0;-2.73*(pi/180);0]);
    %simulate model response

figure(1)
hold on
xlabel('Time (s)')
plot(Time,Y,Time,Ang_o,'--k')
ylabel('Angular Position (rad)')
legend('Model','Measured')

```

FRMerror.m

```

%% Error Function
function err =
FRMError(I_ns,I_c,c_ns,k_n,k_s,k_f,c_f,c_h,I_h,Tor_i,Time,Ang_o,x)
I_tb = x(1); %pull out estimations
c_tb = x(2);

FRMsys = FRMbuild(I_ns,I_c,I_tb,c_ns,c_tb,k_n,k_s,k_f,c_f,c_h,I_h);
%model

Y = lsim(FRMsys,Tor_i,Time,[-2.65*(pi/180);0;-2.73*(pi/180);0]);
%simulate response

err = rms(Y-Ang_o); %find RMSE
end %function

```

FRMbuild.m

```

%% Build Model
function FRMsys =
FRMbuild(I_ns,I_c,I_tb,c_ns,c_tb,k_n,k_s,k_f,c_f,c_h,I_h)
% Define Effective Parameters
I_eff = 2*I_ns + I_c + I_tb;
c_eff = 2*c_ns + c_tb;
k_eff = k_n + k_s;

% Build Model
A = [0 1 0 0;-(k_eff+k_f)/I_eff -(c_eff+c_f)/I_eff k_f/I_eff
c_f/I_eff;...
0 0 0 1;k_f/I_h c_f/I_h -k_f/I_h -(c_f+c_h)/I_h]; %set model
elems

```

```

B = [0;1/I_eff;0;0];
C = [1 0 0 0];
D = zeros(1);

FRMsys = ss(A,B,C,D); %build state space model

end %function

```

Flight Data Modeling

Profile.m

```

clear all;close all;clc;
%% Define Parameters
I_eff = 2.77;
I_l   = 0.31+5.22;
I_r   = 0.31+5.22;
k_eff = 5047.8;
k_l   = 65575;
k_r   = 65065;
c_eff = 21.26;
c_l   = 32867.7;
c_r   = 28440.4;
c_hl  = 36.88+9.775;
c_hr  = 36.91+9.775;

%% Build Model
A = [0 1 0 0 0 0;...
     -(k_eff+k_l+k_r)/I_eff -(c_eff+c_l+c_r)/I_eff k_l/I_eff
     c_l/I_eff k_r/I_eff c_r/I_eff;...
     0 0 0 1 0 0;...
     k_l/I_l c_l/I_l -k_l/I_l -(c_l+c_hl)/I_l 0 0;...
     0 0 0 0 0 1;...
     k_r/I_r c_r/I_r 0 0 -k_r/I_r -(c_r+c_hr)/I_r]; %set model
elements
B = [0;0;0;0;0;0;1/I_r];
C = [0 0 1 0 0 0];
D = 0;

sys = ss(A,B,C,D); %build state space model

%% Read In Aileron Reversal Data
fid1 = fopen('Aileron Reversal.txt'); %read in data
Data1 = fscanf(fid1,'%f');
Tor1 = Data1(1:length(Data1)/2); %pull off torque data
Pos1 = Data1((length(Data1)/2)+1:end); %pull off position data
Time1 = 0:0.05:6.25; %set time vector

%% Run AR Simulation
Y1 = lsim(sys,Tor1,Time1); %simulate model response

figure(1)

```

```

hold on
yyaxis left
plot(Time1,Y1)
axis([0 7 -0.035 0.035])
ylabel('Angular Position (rad)')
yyaxis right
plot(Time1,deg2rad(Pos1))
axis([0 7 -0.35 0.35])
title('Aileron Reversal')
legend('Model','Test Data')
xlabel('Time (s)')
ylabel('Angular Position (rad)')

%% Read In Roll Doublet Data
fid2 = fopen('Roll Doublet.txt'); %read in data
Data2 = fscanf(fid2,'%f');
Tor2 = Data2(1:length(Data2)/2); %pull off torque data
Tor2 = (Tor2-38.48867); %remove offset
Pos2 = Data2((length(Data2)/2)+1:end); %pull off position data
Pos2 = Pos2-27.594673156738; %remove offset
Time2 = 0:0.05:5.35; %set time vector

%% Run Roll Doublet Simulation
Y2 = lsim(sys,Tor2,Time2); %simulate model response

figure(2)
hold on
yyaxis left
plot(Time2,Y2)
ylabel('Angular Position (rad)')
yyaxis right
plot(Time2,deg2rad(Pos2))
title('Roll Doublet')
legend('Model','Test Data')
xlabel('Time (s)')
ylabel('Angular Position (rad)')

```

Flight Test Data Reproduction

DecTestTor.m

```

clear all;close all;clc;
%% Define Parameters
I_eff = 2.77;
I_l = 0.31+5.22;
I_r = 0.31+5.22;
k_eff = 2544+2504;
k_l = 65575;
k_r = 65065;
c_eff = 21.26;
c_l = 32867.7;
c_r = 28440.4;
c_hl = 36.88+9.775;

```

```

c_hr = 36.91+9.775;

%% Split Test
%read data
fid1 = fopen('Split Test 1.txt');
Data1 = fscanf(fid1, '%f');

%process data
thr1 = deg2rad(Data1(2:57423)); %convert to radians
wri1 = diff(deg2rad(Data1(1:57424))); %find velocity
ari1 = diff(wri1); %find acceleration
len1 = length(ari1);

tor_ac1 = Data1(57425:114848); %set test load

time1 = Data1(114849:172272); %set time vector

j1 = 0;
for i1 = 1:len1 %normalize vector size
    wri1(i1,1) = 0.5.*(wri1(i1)+wri1(i1+1));

    if i1 == 1 || rem(i1,300) == 0 || i1 == len1
        j1 = j1+1;

        thr1(j1,1) = thr1(i1);
        wri1(j1,1) = wri1(i1);
        ari1(j1,1) = ari1(i1);

        tor_ac1(j1,1) = tor_ac1(i1);

        time1(j1,1) = time1(i1);
    end
end
tspan1 = 1:length(thr1);

%run model
[tout1,xout1] = ode45(@(t,x) torfindEOMS(x,t,thr1,wri1),tspan1,...
    [thr1(1);wri1(1);thr1(1);wri1(1)]); %find additional states
th1 = xout1(:,1); %pull out states
w1 = xout1(:,2);
thc1 = xout1(:,3);
wc1 = xout1(:,4);

%find torque and error
Tor1 = I_r.*ari1+c_r.*wri1+k_r.*thr1-c_r.*wc1-k_r.*thc1; %find model torque

err1 = rms(Tor1-tor_ac1); %Find error

%plot
figure(1)
plot(time1,Tor1,time1,tor_ac1)
xlabel('Time (s)')
ylabel('Torque (N-m)')
legend('Model','Test Data')

```

```

title('Split Test')

%% Slow-Fast Lateral Sweep Test
%read data
fid2 = fopen('Slow Fast Lateral Sweep Test 1.txt');
Data2 = fscanf(fid2, '%f');

%process data
thri2 = deg2rad(Data2(2:57071)); %convert to radians
wrii2 = diff(deg2rad(Data2(1:57072))); %find velocity
ari2 = diff(wrii2); %find acceleration
len2 = length(ari2);

tor_aci2 = Data2(57073:114144); %set test torque

timei2 = Data2(114145:171216); %set time vector

j2 = 0;
for i2 = 1:len2 %normalize vector length
    wri2(i2,1) = 0.5.*(wrii2(i2)+wrii2(i2+1));

    if i2 == 1 || rem(i2,300) == 0 || i2 == len2
        j2 = j2+1;

        thr2(j2,1) = thri2(i2);
        wr2(j2,1) = wri2(i2);
        ar2(j2,1) = ari2(i2);

        tor_ac2(j2,1) = tor_aci2(i2);

        time2(j2,1) = timei2(i2);
    end
end
tspan2 = 1:length(thr2);

%run model
[tout2,xout2] = ode45(@(t,x) torfindEOMS(x,t,thr2,wri2),tspan2,...
    [thr2(1);wr2(1);thr2(1);wr2(1)]); %find additional states
thl2 = xout2(:,1); %pull out states
wl2 = xout2(:,2);
thc2 = xout2(:,3);
wc2 = xout2(:,4);

%find torque and error
Tor2 = I_r.*ar2+c_r.*wr2+k_r.*thr2-c_r.*wc2-k_r.*thc2; %find torque

err2 = rms(Tor2-tor_ac2); %find error

%plot
figure(2)
plot(time2,Tor2,time2,tor_ac2)
xlabel('Time (s)')
ylabel('Torque (N-m)')
legend('Model','Test Data')

```

```

title('Slow-Fast Lateral Sweep Test')

%% Left Roll Doublet Test
%read data
fid3 = fopen('Left Roll Doublet Test 1.txt');
Data3 = fscanf(fid3, '%f');

%process data
thri3 = deg2rad(Data3(2:19551)); %convert to radians
wrii3 = diff(deg2rad(Data3(1:19552))); %find velocity
ari3 = diff(wrii3); %find acceleration
len3 = length(ari3);

tor_aci3 = Data3(19553:39104); %set test torque

timei3 = Data3(39105:58656); %set time vector

j3 = 0;
for i3 = 1:len3 %normalize vector length
    wri3(i3,1) = 0.5.*(wrii3(i3)+wrii3(i3+1));

    if i3 == 1 || rem(i3,300) == 0 || i3 == len3
        j3 = j3+1;

        thr3(j3,1) = thri3(i3);
        wr3(j3,1) = wri3(i3);
        ar3(j3,1) = ari3(i3);

        tor_ac3(j3,1) = tor_aci3(i3);

        time3(j3,1) = timei3(i3);
    end
end
tspan3 = 1:length(thr3);

%run model
[tout3,xout3] = ode45(@(t,x) torfindEOMS(x,t,thr3,wri3),tspan3,...
    [thr3(1);wr3(1);thr3(1);wr3(1)]); %find additional states
thl3 = xout3(:,1); %pull out states
wl3 = xout3(:,2);
thc3 = xout3(:,3);
wc3 = xout3(:,4);

%find torque and error
Tor3 = I_r.*ar3+c_r.*wr3+k_r.*thr3-c_r.*wc3-k_r.*thc3; %find model
torque

err3 = rms(Tor3-tor_ac3); %find error

%plot
figure(3)
plot(time3,Tor3,time3,tor_ac3)
xlabel('Time (s)')
ylabel('Torque (N-m)')
legend('Model','Test Data')

```

```

title('Left Roll Doublet Test')

%% Left Aileron Reversal Test
%read data
fid4 = fopen('Left Aileron Reversal Test 1.txt');
Data4 = fscanf(fid4, '%f');

%process data
thri4 = deg2rad(Data4(2:26383)); %convert to radians
wrii4 = diff(deg2rad(Data4(1:26384))); %find velocity
ari4 = diff(wrii4); %find acceleration
len4 = length(ari4);

tor_aci4 = Data4(26385:52768); %set test torque

timei4 = Data4(52769:79152); %set time vector

j4 = 0;
for i4 = 1:len4 %normalize vector length
    wri4(i4,1) = 0.5.*(wrii4(i4)+wrii4(i4+1));

    if i4 == 1 || rem(i4,300) == 0 || i4 == len4
        j4 = j4+1;

        thr4(j4,1) = thri4(i4);
        wr4(j4,1) = wri4(i4);
        ar4(j4,1) = ari4(i4);

        tor_ac4(j4,1) = tor_aci4(i4);

        time4(j4,1) = timei4(i4);
    end
end
tspan4 = 1:length(thr4);

%run model
[tout4,xout4] = ode45(@(t,x) torfindEOMS(x,t,thr4,wri4),tspan4,...
    [thr4(1);wr4(1);thr4(1);wr4(1)]); %find additional states
thl4 = xout4(:,1); %pull out states
wl4 = xout4(:,2);
thc4 = xout4(:,3);
wc4 = xout4(:,4);

%find torque and error
Tor4 = I_r.*ar4+c_r.*wr4+k_r.*thr4-c_r.*wc4-k_r.*thc4; %find model
torque

err4 = rms(Tor4-tor_ac4); %find error

%plot
figure(4)
plot(time4,Tor4,time4,tor_ac4)
xlabel('Time (s)')
ylabel('Torque (N-m)')
legend('Model','Test Data')

```

```

title('Left Aileron Reversal Test')

%% Eight Point Roll Test
%read data
fid5 = fopen('8 Point Roll Test 1.txt');
Data5 = fscanf(fid5, '%f');

%process data
thri5 = deg2rad(Data5(2:36879)); %convert to radians
wrii5 = diff(deg2rad(Data5(1:36880))); %find velocity
ari5 = diff(wrii5); %find acceleration
len5 = length(ari5);

tor_aci5 = Data5(36881:73760); %set test torque

timei5 = Data5(73761:110640); %set time vector

j5 = 0;
for i5 = 1:len5 %normalize vector length
    wri5(i5,1) = 0.5.*(wrii5(i5)+wrii5(i5+1));

    if i5 == 1 || rem(i5,300) == 0 || i5 == len5
        j5 = j5+1;

        thr5(j5,1) = thri5(i5);
        wr5(j5,1) = wri5(i5);
        ar5(j5,1) = ari5(i5);

        tor_ac5(j5,1) = tor_aci5(i5);

        time5(j5,1) = timei5(i5);
    end
end
tspan5 = 1:length(thr5);

%run model
[tout5,xout5] = ode45(@(t,x) torfindEOMS(x,t,thr5,wri5),tspan5,...
    [thr5(1);wr5(1);thr5(1);wr5(1)]); %find additional states
thl5 = xout5(:,1); %pull out states
wl5 = xout5(:,2);
thc5 = xout5(:,3);
wc5 = xout5(:,4);

%find torque and error
Tor5 = I_r.*ar5+c_r.*wr5+k_r.*thr5-c_r.*wc5-k_r.*thc5; %find model
torque

err5 = rms(Tor5-tor_ac5); %find error

%plot
figure(5)
plot(time5,Tor5,time5,tor_ac5)
xlabel('Time (s)')
ylabel('Torque (N-m)')
legend('Model','Test Data')

```

```

title('Eight Point Roll Test')

%% Four-G Left Turn Test
%read data
fid6 = fopen('4G Left Turn Test 1.txt');
Data6 = fscanf(fid6, '%f');

%process data
thri6 = deg2rad(Data6(2:22023)); %convert to radians
wrii6 = diff(deg2rad(Data6(1:22024))); %find velocity
ari6 = diff(wrii6); %find acceleration
len6 = length(ari6);

tor_aci6 = Data6(22025:44048); %set test torque

timei6 = Data6(44049:66072); %set time vector

j6 = 0;
for i6 = 1:len6 %normalize vector length
    wri6(i6,1) = 0.5.*(wrii6(i6)+wrii6(i6+1));

    if i6 == 1 || rem(i6,300) == 0 || i6 == len6
        j6 = j6+1;

        thr6(j6,1) = thri6(i6);
        wr6(j6,1) = wri6(i6);
        ar6(j6,1) = ari6(i6);

        tor_ac6(j6,1) = tor_aci6(i6);

        time6(j6,1) = timei6(i6);
    end
end
tspan6 = 1:length(thr6);

%run model
[tout6,xout6] = ode45(@(t,x) torfindEOMS(x,t,thr6,wri6),tspan6,...
    [thr6(1);wr6(1);thr6(1);wr6(1)]); %find additional states
thl6 = xout6(:,1); %pull out states
wl6 = xout6(:,2);
thc6 = xout6(:,3);
wc6 = xout6(:,4);

%find torque and error
Tor6 = I_r.*ar6+c_r.*wr6+k_r.*thr6-c_r.*wc6-k_r.*thc6; %find model
torque

err6 = rms(Tor6-tor_ac6); %find error

%plot
figure(6)
plot(time6,Tor6,time6,tor_ac6)
xlabel('Time (s)')
ylabel('Torque (N-m)')
legend('Model','Test Data')

```

```

title('Four-G Left Turn Test')

%% Four Point Roll Test
%read data
fid7 = fopen('4 Point Roll Test 1.txt');
Data7 = fscanf(fid7, '%f');

%process data
thri7 = deg2rad(Data7(2:29290)); %convert to radians
wrii7 = diff(deg2rad(Data7(1:29291))); %find velocity
ari7 = diff(wrii7); %find acceleration
len7 = length(ari7);

tor_aci7 = Data7(29292:58582); %set test torque

timei7 = Data7(58583:87873); %set time vector

j7 = 0;
for i7 = 1:len7 %normalize vector length
    wri7(i7,1) = 0.5.*(wrii7(i7)+wrii7(i7+1));

    if i7 == 1 || rem(i7,300) == 0 || i7 == len7
        j7 = j7+1;

        thr7(j7,1) = thri7(i7);
        wr7(j7,1) = wri7(i7);
        ar7(j7,1) = ari7(i7);

        tor_ac7(j7,1) = tor_aci7(i7);

        time7(j7,1) = timei7(i7);
    end
end
tspan7 = 1:length(thr7);

%run model
[tout7,xout7] = ode45(@(t,x) torfindEOMS(x,t,thr7,wri7),tspan7,...
    [thr7(1);wr7(1);thr7(1);wr7(1)]); %find additional states
thl7 = xout7(:,1); %pull out states
wl7 = xout7(:,2);
thc7 = xout7(:,3);
wc7 = xout7(:,4);

%find torque and error
Tor7 = I_r.*ar7+c_r.*wr7+k_r.*thr7-c_r.*wc7-k_r.*thc7; %find model
torque

err7 = rms(Tor7-tor_ac7); %find error

%plot
figure(7)
plot(time7,Tor7,time7,tor_ac7)
xlabel('Time (s)')
ylabel('Torque (N-m)')
legend('Model','Test Data')

```

```
title('Four Point Roll Test')
```

torfindEOMs.m

```
function xdot = torfindEOMs(x,t,thr,wr)
I_eff = 2.77;
I_l   = 0.31+5.22;
I_r   = 0.31+5.22;
k_eff = 5047.8;
k_l   = 65575;
k_r   = 65065;
c_eff = 21.26;
c_l   = 32867.7;
c_r   = 28440.4;
c_hl  = 36.88+9.775;
c_hr  = 36.91+9.775;

A = [0 1 0 0;...
     -k_l/I_l -(c_l+c_hl)/I_l k_l/I_l c_l/I_l;...
     0 0 0 1;...
     k_l/I_eff c_l/I_eff -(k_eff+k_l+k_r)/I_eff -
     (c_eff+c_l+c_r)/I_eff];
B = [0;0;0;(k_r.*thr(round(t))/I_eff)+(c_r.*wr(round(t))/I_eff)];

xdot = A*x+B;

end
```

Bibliography

- [1] Rosero, J.A., J.A. Ortega, E. Aldabas, and L. Romeral. "Moving Towards a More Electric Aircraft," *IEEE A&E Systems Magazine* (March 2007)
- [2] Wroble, Dan. *Force Fight Evaluation in a Dual Electromechanical Actuator Configuration*. MS thesis. University of Dayton, Dayton OH, 2017.
- [3] Jänker, P. et al. "New Actuators for Aircraft and Space Applications," *11th International Conference on New Actuators*. Bremen, Germany: June 2008.
- [4] Davis, Mark A. "Electromechanical Actuation for Launch Vehicles," *37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*. Salt Lake City, UT: July 2001.
- [5] van den Bossche, Dominique. "'More Electric' Control Surface Actuation, a Standard for the Next Generation of Transport Aircraft," *Control 2004* (September 2004). University of Bath, UK.
- [6] Niedbalski, Nick, AFRL Mechanical Engineer. "Hingeline Dynamic Friction Test," Presentation, Air Force Research Laboratory, Wright-Patterson AFB OH, 2016.
- [7] Budinger, Marc. *Preliminary Design and Sizing of Actuation Systems*. Ph.D. dissertation. University of Toulouse, Toulouse FR, 2014.
- [8] Jensen, Stephen C., Gavin D. Jenney, Bruce Raymond, and David Dawson. "Flight Test Experience with an Electromechanical Actuator on the F-18 Systems Research Aircraft," *19th Digital Avionics Systems Conference*. Philadelphia, PA: October 2003.
- [9] Diaz Puebla, Alejandro and Raghu Chaitanya Munjulury. "Sizing of Actuators for Flight Control System and Flaps Integration in RAPID," *Aerospace Technology Congress*. Solna, SE: October 2016

- [10] Federal Aviation Administration. *Pilot's Handbook of Aeronautical Knowledge*. Washington: GPO, 2016
- [11] Reed, John G. et al. "Performance Efficient Launch Vehicle Recovery and Reuse," *AIAA SPACE 2016*. Long Beach, CA: 2016
- [12] Lu, Hao, Yunhua Li, and Chenglin Zhu. "Robust Synthesized Control of Electromechanical Actuator for Thrust Vector System in Spacecraft," *Computers and Mathematics with Applications*, 64: 699-708 (2012).
- [13] Sutton, George P. and Oscar Biblarz. *Rocket Propulsion Elements* (9th edition). Hoboken, New Jersey: Wiley, 2017
- [14] "Thrust Vector Control Systems." *MOOG Aerospace*. 2017. Retrieved on 2 January 2018.
- [15] Cowan, J. R. and Rae Ann Weir. "Design and Test of Electromechanical Actuators for Thrust Vector Control," *27th Aerospace Mechanisms Symposium*. 349-366. May 1993.
- [16] Hagen, Jeff, Landon Moore, Jay Estes, and Chris Layer. "The X-38 V-201 Flap Actuator Mechanism," *37th Aerospace Mechanisms Symposium*. 377-390. May 2004.
- [17] "fminsearch." *MathWorks*. Retrieved on 12 February 2018.
- [18] Lagarias, J. C., J. A. Reeds, M. H. Wright, and P. E. Wright. "Convergence Properties of the Nelder-Mead Simplex Method in Low Dimensions." *SIAM Journal of Optimization*. Vol. 9, No. 1: 112–147 (1998).
- [19] "ode45." *MathWorks*. Retrieved on 12 February 2018.
- [20] Shampine, L. F. and M. W. Reichelt, "The MATLAB ODE Suite," *SIAM Journal on Scientific Computing*, Vol. 18: 1–22 (1997).
- [21] "lsim." *MathWorks*. Retrieved on 12 February 2018.

- [22] Navarro, Robert. *Performance of an Electro-Hydrostatic Actuator on the F-18 Systems Research Aircraft*. NASA/TM-97-206224. Edwards, CA: Dryden Research Center, October 1997
- [23] Bennet, John W., Barrie C. Mecrow, Alan G. Jack, and David J. Atkinson. "A Prototype Electrical Actuator for Aircraft Flaps," *IEEE Transactions on Industry Applications*, Vol. 46, No. 3 (May/June 2010).
- [24] Norton, William J. *Advanced Electromechanical Actuation System (EMAS) Flight Test*. AD-A176148. Wright-Patterson AFB, OH: Air Force Wright Aeronautical Laboratory, June 1986.
- [25] Calzada, Ruby. "F-18 Systems Research Aircraft (SRA)." *National Aeronautics and Space Administration*. 18 November 2008. Retrieved on 6 June 2017.
- [26] Barnett, Street A. *Laboratory Test Set-Up to Evaluate Electromechanical Actuation System for Aircraft Flight Control*. MS thesis. University of Dayton, Dayton OH, 2015.
- [27] Tuplin, S., M.C. Best, and J. Wang. "Design and Control of a Linear Electromagnetic Actuation System for Active Vehicle Suspensions," *Proceedings of the 9th International Symposium on Advanced Vehicle Control (AVEC)*, Vol 1. 373-378. Kobe, Japan: October 2008.

REPORT DOCUMENTATION PAGE				<i>Form Approved</i> <i>OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 23-03-2018		2. REPORT TYPE Master's Thesis		3. DATES COVERED (From - To) 19-10-2016 - 23-03-2018	
4. TITLE AND SUBTITLE Passive Load Testing for Evaluation of Electromechanical Actuators				5a. CONTRACT NUMBER JON 18Y424	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Hoffman, Jeremiah R, 2LT Palazotto, Anthony N, Dr. Niedbalski, Nicholas P, Dr.				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way, Building 640 WPAFB OH 45433-8865				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFRL Aerospace Systems Directorate POC: Dr. Quinn Leland 1950 5 th St. B20018A RA213, WPAFB, OH 45433-7251 quinn.leland@us.af.mil 937-255-3060				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Distribution Statement A. Approved for Public Release; Distribution Unlimited					
13. SUPPLEMENTARY NOTES This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.					
14. ABSTRACT While aircraft control surfaces traditionally use hydraulic actuators, electromechanical actuators (EMAs) are interesting as they have potential to be lighter, lower maintenance, and more robust. However, EMAs require more research regarding force-fight characteristics, power requirements, performance specifications, and more. The Air Force Research Laboratory is conducting some of this research, and operates a test rig which provides a passive load to a pair of EMAs. This rig is designed for simple test profiles for investigating force-fight; if it could be used to represent actual flight profiles, the rig could accommodate a wider variety of tests. The focus of this project is to evaluate the test rig's suitability for such profiles by developing a rig model, comparing data from this model to flight data, and finally by comparing test rig data to both flight and model data. The model that was developed was able to reproduce several profiles representative of those an aileron control actuator would experience during flight. Validation of these profiles on the test rig has shown accurate replication of flight data with rig hardware and rig test data with the model, indicating that the test rig would be useful for actuator characterization and design.					
15. SUBJECT TERMS Electromechanical actuation, Passive load testing, Control surface actuation					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 99	19a. NAME OF RESPONSIBLE PERSON Dr. Anthony Palazotto
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER 937-255-3636 x4599