Analysis of Modeling Techniques for Low-Cost Actuators

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Low-cost actuators are equipped on small uninhabited aerial vehicle platforms to displace the control surfaces and maneuver the aircraft. The control laws, models, and even a complete description of the actuator output are typically unavailable from the manufacturer. This is a concern because many of these aircraft are used to perform flight control research. Models of the actuator system is required in order to accurately run simulations and develop flight controls. The Unmanned Aerial Vehicle Research Group at the University of Minnesota is comparing various approaches to actuator modeling to determine which yields the appropriate fidelity level required in flight control applications. Development time may be reduced when a low fidelity model can be implemented instead of a high fidelity model. This paper compares three types of models: a black box first order equivalent system, a black box second order equivalent system, and a grey box first order equivalent system. These models were constructed based on data recorded from an actuator equipped with sensors that measure angular deflections, angular rates, back electromotive force, and current consumption. Future research will determine the best model to use for flight control research.

Nomenclature

θ	Angular Deflection, deg
$\dot{\theta}$	Angular Rate, deg/s
$\ddot{\theta}$	Angular Acceleration, deg/s^2

I. Introduction

Over the past decades, small uninhabited aerial vehicles (SUAVs) have been widely researched and implemented for both military and civilian operations. They are frequently used in applications such as reconnaissance, research and development, weather data collection, and environmental monitoring. More recently, low-cost UAV platforms have been developed to study more high risk flight-control applications, such as loss-of-control behavior, fault-detection and isolation, and modeling at the boundaries of the traditional flight envelope. Since these applications are high risk and may cause damage to the aircraft, it is important to implement a low-cost approach to the entire platform in order to minimize research expenses. Low-cost actuators are used, not only in high risk applications, but in all low-cost flight research. One of the key tasks in developing such a platform is obtaining accurate models for the components that make up the UAV. However, models for low-cost components (such as the sensors and actuators) are typically unavailable from the manufacturers. The goal of this research is to test various modeling techniques for low-cost actuators to determine the fidelity level required for flight control applications.

The UAV Research Group at the University of Minnesota is a group that focuses on flight control and navigation research with low-cost SUAVs. An example of a test vehicle is shown in Figure 1. It has a

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conventional fixed-wing geometry, with aileron, rudder, and elevator control surfaces. This aircraft uses Hitec 5645MG servos.[1] Accurate models of these actuators would allow the research group to develop a more accurate aircraft model to be implemented in their flight control and navigation research which would decrease simulation development time.

Figure 1. UAV Research Group's Ultra Stick 120

Recent research has focused on comparing various approaches to actuator modeling and the long term goal of this research is to determine which model provides the highest fidelity while minimizing model complexity. Currently, three separate models have been tested: a black box first order equivalent system, a black box second order equivalent system, and a grey box first order equivalent system. These three models are very basic and offer an initial insight into what kind of model is optimal for SUAV flight control and navigation research. These models are validated based on data obtained from a modified "smart" actuator, which was originally developed by researchers at MTA Sztaki: a computer and automation research institute at the Hungarian Academy of Sciences. Unlike a commercial actuator, which does not offer the ability to manipulate the control laws or accurately measure the output, this smart actuator allows custom control laws to be implemented in addition to providing the angular position, angular rate, back electromotive force (EMF) and current consumption[2] of the actuator.

Although there are many other models, the three tested in this paper provide a starting point and will direct the efforts of future research. Future research will focus on expanding the number of models compared in addition to varying the input for these models. By trying various models and inputs, the most appropriate model for flight control and navigation research can be identified.

II. Hardware Implementation

The UAV Research Group focuses on developing and implementing low-cost, open-source UAV technology with applications in guidance, navigation, and control. The UAV flight test platform is used on a variety of projects, such as navigation and estimation algorithms compatible with low-cost sensors, GPS way-point tracking algorithms, system identification, and fault detection and isolation. More information about the research group can be found on the research lab's website.[1] A current research project focuses on modeling actuators to identify the appropriate level of fidelity for a given application. More accurate models will enable improved flight control and fault detection algorithms. To facilitate this research, a low-cost actuator has been equipped with sensors and interfaced to Simulink.

Commercially available actuators offer little support to aid in system identification. It is highly likely that the user does not have knowledge of what controller an actuator is using and therefore higher level modeling is difficult. Obtaining accurate output data in order to test black box models is also difficult and often times has significant errors. The combined lack of controller knowledge and lack of output data offers little support for system identification. Researchers at MTA Sztaki: a computer and automation research institute at the Hungarian Academy of Sciences, developed a new "smart actuator" designed to allow system identification of low-cost actuators.

A. Position Feedback Control Actuator

The actuator used for this research is customized with position feedback control, allowing it to output the rotational position of the actuator shaft and export that data to the user. It also allows the user to tune the control laws. The actuator is a modified Futaba S3305 actuator with dimensions of 40x20x38mm,[3] which is small enough to comfortably fit into a hand, as shown in Figure 2. This specific model was chosen because of its high precision, large maximum torque, and its long lifespan.[2] MTA Sztaki disassembled the actuator leaving only the housing, gears, and motor. Despite the advantages of a core-less motor (free of torque disturbances leading to linear magnetic fields), the non-coreless motor from Futaba was not replaced. The actuator power and measurement electronics were replaced with custom electronics housed inside the actuator casing. These custom electronics consisted of a sensor for angle measurement, a circuit to measure the induced voltage on the motor, another circuit to measure the current inside the motor, and a MOSFET bridge, which allowed the motor to be controlled using a driving circuit. These components allow the user to measure motor EMF signals, current consumption, and receive data through a serial peripheral interface bus (SPI) from a magnetic encoder. The encoder used in the actuator is an Austria Micro Systems A5045 encoder, which measures the position of the shaft and speed with a bit resolution precision of 0.0875 degrees.

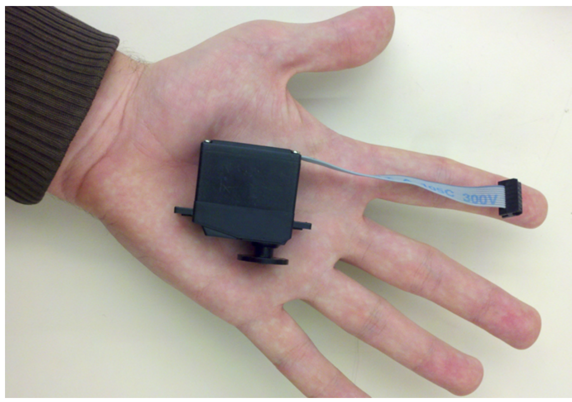

Figure 2. The modified Futaba S3305 actuator

The actuator is attached to an actuator management board which is a custom board that regulates the control algorithm and digitization of analog signals.[2] It also sends commands to the actuator motor using pulse width modulation (PWM) signals. The board utilizes a Freescale S12XF FlexRay microcontroller to manages SPI communication from the encoder, sample analog signals, implement control algorithms, and control the power electronics. Control and measurement of the actuator shaft position is done at 250 Hz. The PWM signals used to command the actuator are 1kHz. The actuator management board is connected to the communication board through a controller area network environment (CAN) bus.

The communication board, or the AVR Stamp board, is connected to the MATLAB/Simulink through a virtual COM port.[2] It receives and decodes serial packets from Simulink and sends the commands through the CAN bus to the Actuator Management board. Simulink is used to collect data recorded from the actuator, and to configure parameters in the control laws. It uses Real Time Windows Target, at a rate of 50 Hz, for real-time serial port access as it sends packets to the communication board. Having measurements of the actuator deflection readily available allows for identification of the motor model. A diagram summarizing the communication is shown in Figure 3. A photograph of the actual boards can be seen in Figure 4.

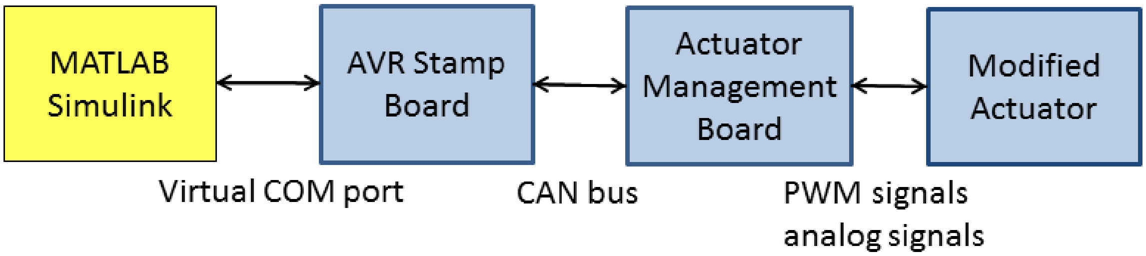

Figure 3. Layout of the hardware components

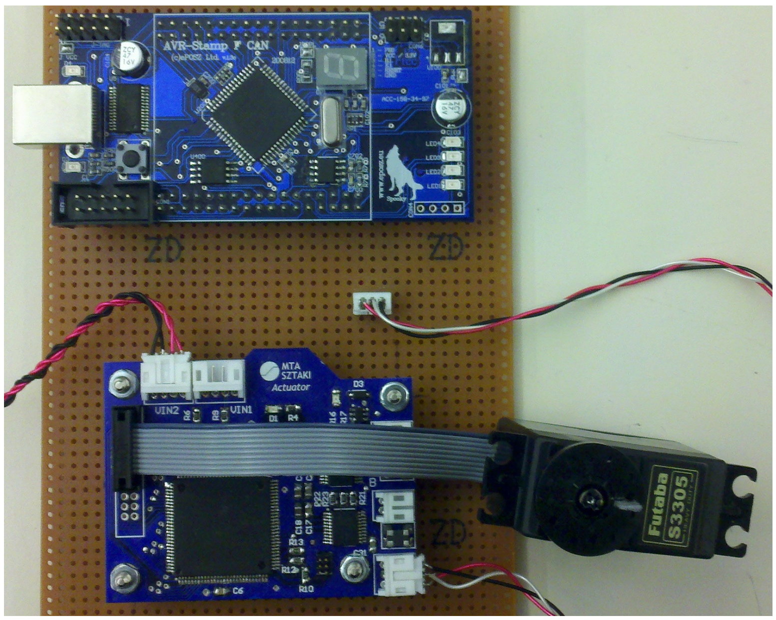

Figure 4. Layout of the hardware components

Following the chart above, Simulink sends packets to the AVR Stamp Board through the virtual COM port. The AVR Stamp Board unpacks these packets which contain the controller parameters and commands for the actuator. The parameters and commands are sent to the S12XF actuator management board through a CAN bus. The actuator management board uses the controller to construct the control law for the actuator. It also sends the actuator commands through PWM signals to the actuator. As the actuator deflects, the measured angle and angular rate of the shaft, back EMF, current consumption, and received PWM commands are recorded and sent back through the actuator management board and AVR Stamp boards and finally to Simulink, where the data is recorded in the MATLAB workspace.[2]

B. Control Algorithm Implemented on Actuator

MTA Sztaki built the actuator with a closed-loop control system. There are three separate parts in the closed-loop system: a control algorithm, motor model, and gear ratio (shown in Figure 5). The control algorithms accept commands, modifying the commands to increase the desired result of the command, and then push the new command to the motor. Control algorithms can be rewritten, however, the control laws used in this research were developed at MTA Sztaki. The motor model acts as a representation of the mechanical system and takes the commands and produces a change in shaft position. The gear ratio takes the shaft position of the motor and accounts for the various gears inside the actuator which drive the shaft of the actuator. Combined, these three parts making up the closed-loop system are able to convert a command into produce motion.

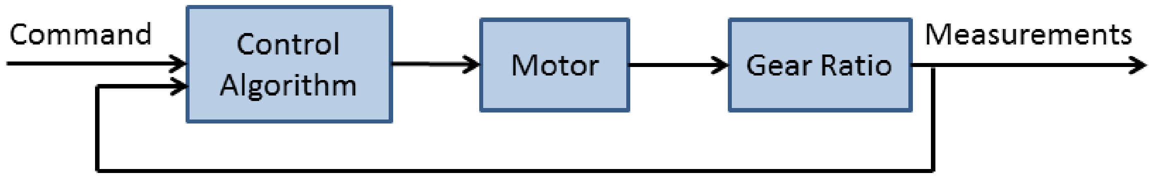

Figure 5. Layout of actuator components

The closed-loop system uses an inner-loop and an outer-loop control algorithm. The inner-loop is characterized by angular rate and is a PI controller. This controller is input into Simulink as a discretized transfer function, but for the model the controller was converted to continuous time and takes the form of Equation (1). The integrator gain was chosen by engineers at Sztaki to have a pole zero cancellation at 0.1318. To avoid saturation, the steady state gain was chosen to be ten. The outer-loop is characterized by position feedback and is a simple P controller with a gain of eight. After the command is sent through the control algorithms, it enters the motor which outputs a motor shaft displacement.

$$F(s) = \; 10\,\frac{1+0.1318s}{0.13182s} \tag{1}$$

Finally, the motor shaft displacement enters the gear ratio. The gear ratio allows factors like backlash, gear flex, and shaft flex to be taken into consideration. These factors need to be accounted for when modeling mechanical objects to avoid errors from propagating through the data. However, since the actuator is not under load there is minimal stress and strain on physical components. Therefore, for the purposes of this research, those gear ratio parameters are considered negligible.

III. Model Structure and Identification Techniques

There are multiple approaches to modeling the dynamics of actuators and future research will expand the number of tested models, however, this paper explores the fidelity of three unique methods. The three models tested include (in order from least to most complex) a black box first order equivalent system, a black box second order equivalent system, and a grey box first order equivalent system. These models were chosen because of their simplicity and each approach presents a different level of expected accuracy. After more models are test, they can be compared against each other, conclusions can start to be made regarding which model provides the appropriate fidelity level needed for flight control applications. This minimizes the work needed to determine models for actuators. The output-error identification method in the time-domain is used to determine parameters in the model structure[4].[5]

Besides testing a variety of models, it is important to test a variety of inputs. Several data sets were collected at various magnitudes and frequencies including: steps, ramps, chirps, sine waves, and 3-2-1-1. All of the data sets can be found on the UAV Research Group's website.[6] For the first input, it was decided to use step functions to determine the rate limit.

Because of the test setup, a time delay was introduced. After visually matching the actuator and model output, the delay was calculated to be 0.0175 seconds. This allows the command signal and measured output to be synced and a more accurate depiction of the actuator dynamics to be viewed.

A. First Order Equivalent System

Using a low order equivalent system (LOES),[7] a black box first order equivalent model is approximated as a single transfer function plus a time delay with rate and positions limits. It is shown in Figure 6. By visually matching the model to the actuator output, the single gain that defines the first order transfer function was determined. The pole of the first order system, labeled as Gain in Figure 6, was found to be 30 rad/sec. This corresponds to a low pass filter with bandwidth of 4.78 Hz.

Saturations were introduced to account for physical limitations of the actuator. The two saturations introduced on either side of the integrator accounted for the physical limits of the actuator. A mechanical system cannot move instantaneously, as the commands do, hence a rate limit was introduced. The rate limit prevents the model from moving at a faster rate than a physical actuator would allow. The rate limits were calculated to be 240 deg/s as the actuator approached the step, and -350 deg/s as it left the step. It is not entirely understood why the rate limits differ in one direction than the other. The second saturation accounts for limit of rotation of a actuator. The actuator has a physical deflection limit of 180 degrees, which is why the saturation was set to 180 degrees and -180 degrees to allow the model actuator to exhibit the same limits as the physical actuator.

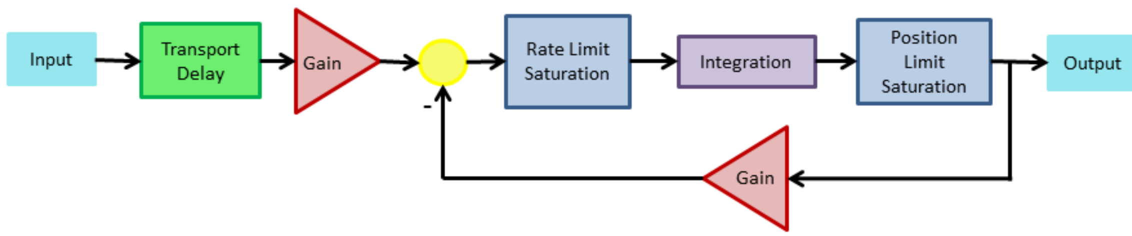

Figure 6. First order system transfer function with time delay and saturations

B. Second Order Equivalent System

The black box second order equivalent system is more complex than the black box first order system. It accounts for the acceleration and velocity. This model is also simplified using a LOES. The model is shown in Figure 7. This model was also visually matched and the inner loop gain B was determined to be 54 while the outer loop gain A was determined to be 900. Again, this models a low-pass system with 4.775 Hz bandwidth and some high damping.

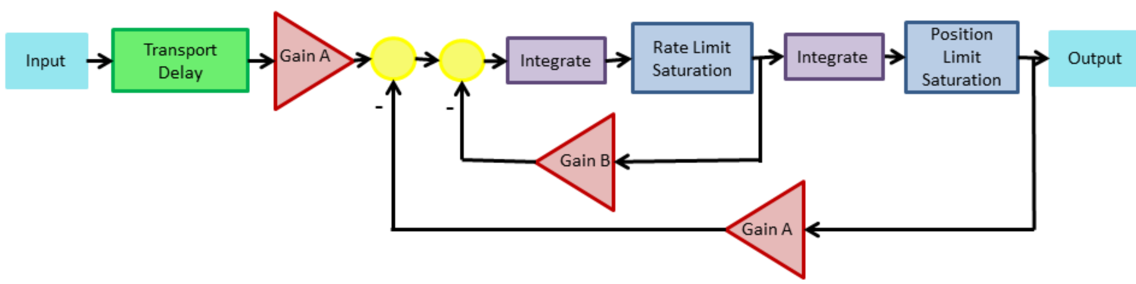

Figure 7. Second order system transfer function with time delay and saturations

C. Grey Box Model

The grey box first order model is also a LOES model. The controllers have already been described, but the motor model needed to be identified. A motor model was identified by MTA Sztaki as a first order linear model, but re-identified through testing at the UAV Research Group. To identify the model, researchers at the UAV Research Group visually matched the actuator output to the model. This model was defined with a PWM input (%) and angular velocity (deg/sec) output. The model is represented by a first order transfer function and is show in Equation (2),[2] which is the same as the transfer function found by MTA Sztaki. It is also important to note that in addition to the time delay and the saturations, this model included an anti-windup to prevent overshooting. This was represented as a gain to offset the accumulated error in the integral. The entire grey box first order equivalent model can be seen in Figure 8.

$$G(s) = \frac{2.836}{s + 7.586} \tag{2}$$

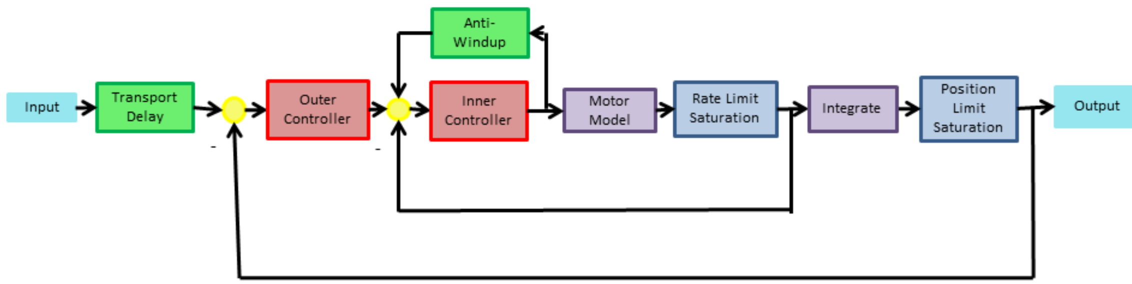

Figure 8. Grey box first order transfer function with controllers, time delay, and saturations

IV. Model Validation

Each model was tested on two separate step inputs: constant pulse and variable step. Figure 9 shows that the black box first order equivalent system model is very accurate when compared to the actuator output for a constant step input. The grey line shows five different actuator model outputs. This allows the viewer to compare a variety of test runs against the black box first order equivalent system. A major difference between the actuator output and the model output appears at approximately 3.2 seconds, and this inflection in the actuator output can be attributed to the custom control algorithm used in the actuator. Further research will verify this assumption.

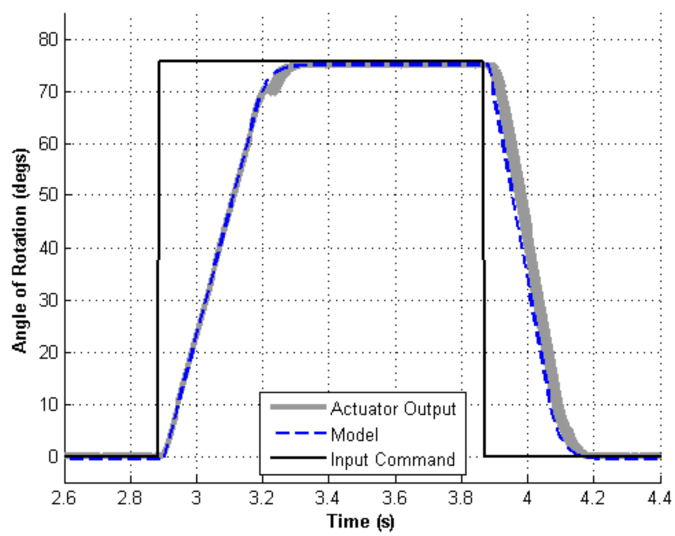

Figure 9. Simulink graph of First Order System with a constant step input

It is important to note that the actuator is rate limit driven. As the actuator approaches the step and leaves the step, it reaches the rate limit and becomes nearly linear. This was replicated by the model. The saturation prevents the rate from increasing above the physical limits and so the model becomes nearly linear, just like the actuator.

This can also be seen in Figure 13, where the input is variable step. When using a variable step input, some of the steps are too large for the actuator to physically follow, so there are large discrepancies in the input and output of the actuator. However, the first order equivalent system follows the actuator model with some accuracy. Generally, the black box first order equivalent system overshoots the actuator output while maintaining the general shape.

The same main differences that appear in the black box first order equivalent system appear in the black box second order equivalent system. The model for a constant step input in shown in Figure 10. Again, the grey line represents five separate data sets which allows the viewer to see an average of the actuator output results. The system remains rate limit driven.

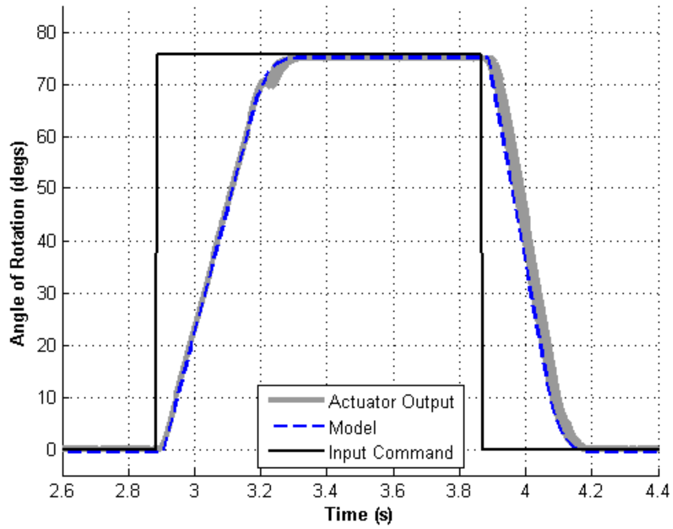

Figure 10. Simulink graph of black box second order system with constant step input

The black box second order equivalent system was also subjected to a variable step input and like the black box first order equivalent system, this system overshot the actuator output. The second order equivalent system actually overshot the actuator output more frequently and with a higher magnitude, which can also be seen in Figure 13.

Neglecting the time delay, rate limits, and angle limits the transfer functions are compared using a Bode plot. The blue line is the first order transfer function while the second order transfer function is in red. From visually inspecting the Bode Plot shown in Figure 11 it can be seen that they capture similar dynamics. Both models identify a bandwidth at 4.775 Hz.

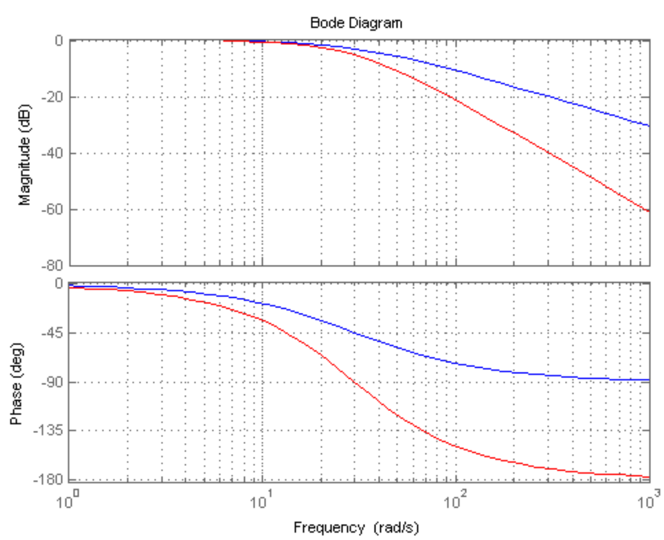

Figure 11. Bode Plot of black box models

Figure 12 shows the grey box first order model. Again, the grey line is composed of five separate data sets. It is an acceptable model when compared to the actuator output. The aforementioned remarks regarding the encoder error and integrator wind-up still hold true. The model follows the rise of the measured actuator data and employs its anti-windup gain to better follow the measured data. However, it oscillates when it reaches the peak and overshoots when it decends back to zero.

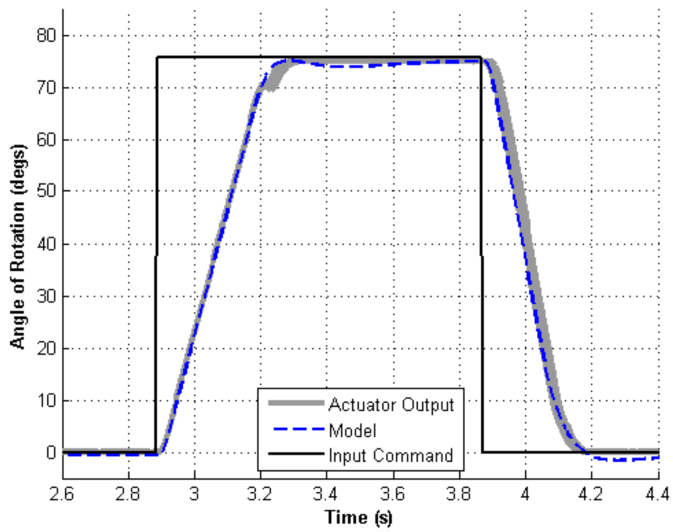

Figure 12. Simulink graph of the grey box first order model

This model was also tested with a variable step input, which can be seen in Figure 13. This test showed that the grey box first order equivalent model has significant overshoot errors, far exceeding the previous models. This model also fails to follow the curvature of the actuator output as closely as the previous models.

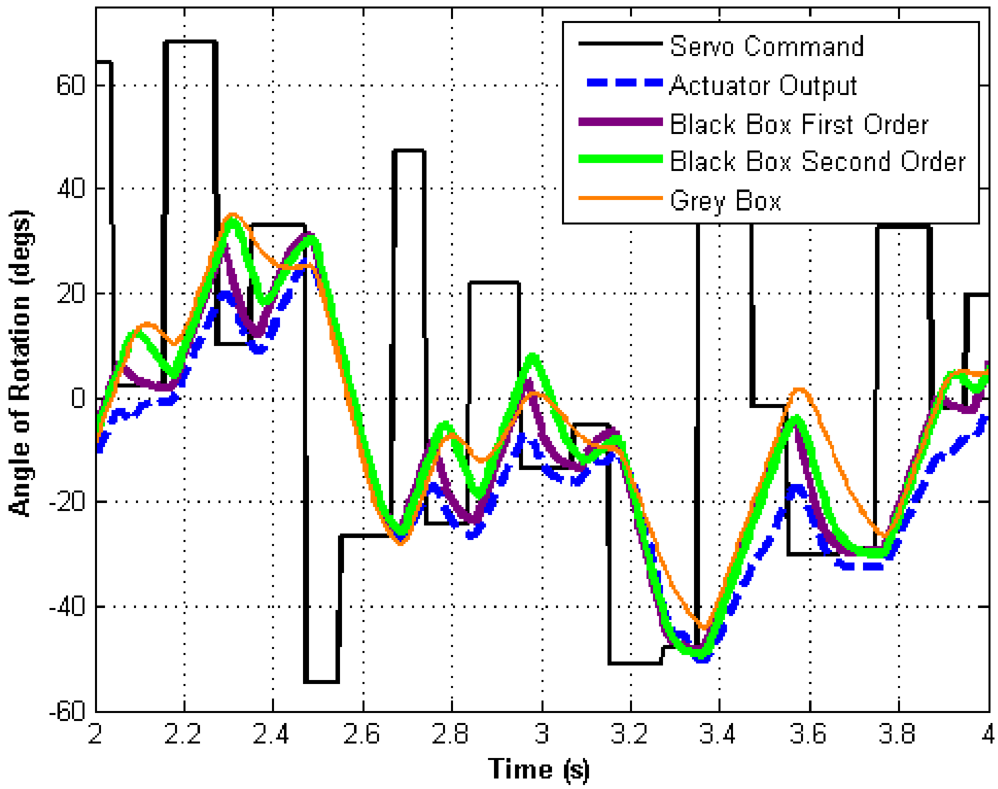

Figure 13. Simulink graph of all three models with variable step input

V. Conclusion

Low-cost actuators are implemented on many research vehicles throughout the world. Obtaining an accurate model of these systems increases the reliability and decrease the simulation time of aircraft models used for flight control and navigation research. Commercially available actuators offer a limited means to model actuator dynamics, so the development of a "smart" actuator has given researchers the ability to make accurate actuator models. This research has taken one of these new actuators and provided data sets in order to determine which modeling technique can provide the least complex and the correct fidelity model for the application. Despite only three different models being tested, these studies show that low-cost actuators can be accurately modeled with a variety of techniques.

As this research continues, more complex models will be tested. In addition to various models, a variety of inputs will be tested, varying from step to sine wave, and ramps to 3:2:1:1. It is important to note that this research was conducted on an actuator which drove no loading. Future research may also consider comparing model characteristics between loaded and unloaded systems using a dynamometer or a wind tunnel to provide a constant load or variable, flight condition, load.

VI. Acknowledgments

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