A Survey of Subscale Aircraft Primary Flight Control Actuator Dynamic Response Characteristics

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Abstract— **This paper is intended to act as a reference document for subscale aircraft and aerospace system designers who are laying out primary flight control devices. Although a great deal of information exists on actuator deflections, moments, relatively little data is publicly available on actuator dynamics. Because aircraft dimensions and weights are growing ever smaller, aeromechanical modes are growing higher and higher in frequency. As a result, it is imperative that flight control actuators with high enough bandwidths to control these aircraft be specifid, modeled, integrated and flown. The paper begins with a brief overview of seveal major flight control actuator classes which are suitable for subscale aircraft flight control and a fundamental history of each. Following the historical overview, a survey of i.) conventional electromagnetic servoactuators, ii.) pieoelectric and iii.) pneumatic subscale flight control actuators are made. The study concludes with a side-by-side comparison of the dynamics of subscale flight control actuators with corner frequencies ranging from 0.5 to 460 Hz.**

Keywords: Flight Control, Subscale, MicroFlight, UAV, MAV, Servoactuator, Piezoelectric

I. BACKGROUND

For many thousands of years, humans have been contemplating the idea of remote controlled projectiles. The first to appear in (pre-) history is ascribed to Homer as he laid out the properties of Athena's guided arrows.[1] Among Jules Verne's many prophetic predictions, he anticipated both torpeodes and guided missiles [2]. Although a visionary, some of Jules Verne's creative musings were realized before he died in 1905. Indeed, the first radio-controlled electromechanical servoactuator manipulated device which was made by man was built by the research team of the fabled visionary Nikola Tesla himself as shown in Figure 1.[3],[4].

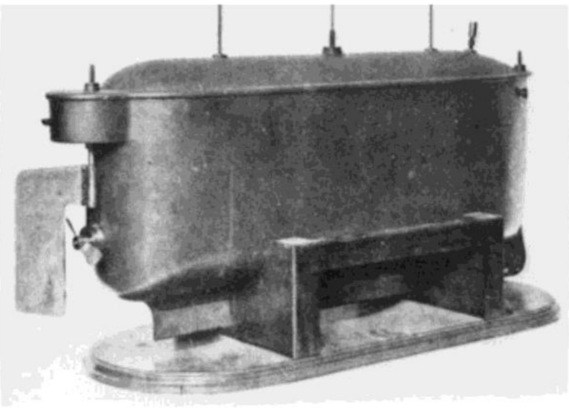

Figure 1. Nikola Tesla's Radio Controlled Teleautomation First Publicly Demonstrated in 1898,[4]

At the core of Tesla's earth shattering invention was the world's first deployed, demonstrated and fully remote controlled electromechanical servoactuator. This clearly marked a milestone in machine remote control and guidance. Electromechanical servoactuators increased steadily in capabilities and speed while becoming ever more compact and efficient through today.

While Tesla, Verne and others mused about remote controlled devices of many scales for many purposes, the famed Pierre and Jacques Curie, Lipmann and other scientists in Europe were discovering the principles of piezoelectricity.[5-8] The reason why the principles of piezoelectricity are so important is that they would eventually be used quite successfully as driving materials for some of the world's smallest aircraft. If one examines the many incarnations of piezoelectric flight control mechanisms, it is easy to see that missiles, munitions, bullets, uninhabited aerial vehicles and micro aerial vehicles have all employed piezoelectric actuators for flight control over the past 21 years. Starting with the seminal work of Crawley's lab at MIT in the 1980's, grounding work was made which firmly established the parameters which allowed piezoelectric elements to actively manipulate plates and basic flight control surfaces.[9]-[13]

These basic moving plate elements were rapidly recast into aerodynamic shapes and integrated into helicopter rotor blades in the late 1980's and early 1990's. These adaptive rotor blades would be actively twist, bent, pitched and otherwise mechanically manipulated with a host of solid state actuators and materials and proven quite successfully in flight.[14]-[18]

While demonstrating that basic helicopter vibration

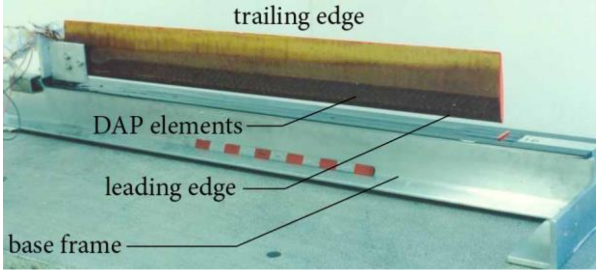

Figure 2 The World's First Piezoelectrically Actuated Helicopter Rotor Blade, [14]

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reduction could be achieved via methods such as higher harmonic control (HHC) and individual blade control (IBC), the task of full blown flight control was achieved in "Gamera" in September of 1996.

Parallel efforts were being conducted on fixed-wing aircraft of a number of configurations. In 1990 the first piezoelectric missile fin was invented and tested over the following three years.[19-23] The team at Purdue headed by Professor Terry Weisshaar would then follow with active flexible trailing edge flight control using monolithic piezoelectric actuator elements.[24-26] With deflection levels suitable for flight control, the trailing edge actuators were shown to be suitable for certain types of flight load manipulations. With closer examination, $c_{h\alpha}$ and $c_{h\delta}$ coupling lead to challenges involving aeromechanics and never-before-seen flight dynamics modes. Ways around strong control derivative coupling were developed for missiles, munitions and UAVs and extensively wind tunnel and flight tested.[27]-[32]

Although these programs yielded a series of well evolved, mature flight control actuators, greater deflection levels given a certain design volume was constantly being sought. In 1997 a major breakthrough was achieved by the team of Lesieutre at Pennsylvania State University. These approaches would come to drive otherwise linear piezoelectric actuators deep into the nonlinear range and allow for deflection levels which were nearly an order of magnitude greater while maintaining the full range of blocked force and moment capability.[36,37] Lesieutre's fundamental breakthrough enabled a host of other innovations which lead to far greater performance adaptive flight control actuators for missiles, munitions and UAVs.[38]-[44]

Although many innovations in flight control actuation were being made for missiles, hard-launched munitions and UAVs, separate efforts were underway for gravity weapons of a number of calibers. Tail kit, canard and wing actuation schemes were being developed from a variety of adaptive actuator materials.[45]-[46] Some of the most important testing conducted at this time was related to lightning strike. Figure 3 shows the overall configuration of the "Weapon Integration and Design Technology" (WIDT) canard assembly prior to lightning strike testing. Among the important tests which were conducted was a tactically-configured lightning strike test on the entire assembly. The tests were important for the field of adaptive flight control actuation not only because they showed that the actuators could survive, but that the performance of the actuators actually *increased* after the lightning strike event by approximately 3%.

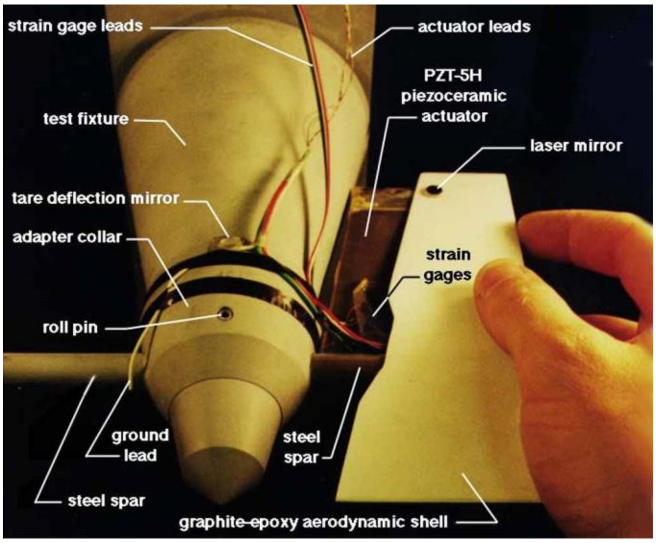

Figure 3 Adaptive Canard Actuator During Mounting, prior to Lightning Strike Testing [45]

Because the actuator configurations of gravity weapon nose kits were designed to be completely integrated into the flight control surfaces themselves (without occupying any space within the aircraft fuselage), they were highly amenable to being integrated into self-actuated flight control surfaces which could be placed adjacent to critical flight assemblies such as rocket motors and penetrators.[45]-[46].

While the actuators for the WIDT and many other programs were well underway for uninhabited aircraft, a separate program was being conducted for primary flight control of certified aircraft. By using natural examples, the world's highest mass-specific actuator energy density actuator class was being developed as shown in Figure 4.[47-50] By using Pressure Adaptive Honeycomb (PAH), it was shown that the amount of work achieved per kg added to the aircraft for flight control can be maximized if pressure adaptive honeycomb actuators are used. Because these actuators use only FAR-25 certifiable materials operating strictly in the "infinite life" stress-strain zone on S-n curves, they are inherently built to be compatible with certifiable aircraft. As with all actuators classes, the PAH actuators have limitations and are shown to be highly compatible with secondary flight control type applications. While they are well suited for primary flight control of certain aircraft types, their limited bandwidth due to pneumatic manipulation makes them better suited for secondary flight control. Still, the PAH flight control actuators have been constructed on several different scales ranging from just 15cm to nearly 2m in chord and wind tunnel tested at representative flow speeds and dynamic pressures. Because the actuator deflection levels can be coupled to both dynamic pressure and angle of attack, it has been shown that PAH flight control actuators are ideal surfaces to be designed into wings, canards and stabilizers that must inherently reject gust loading.

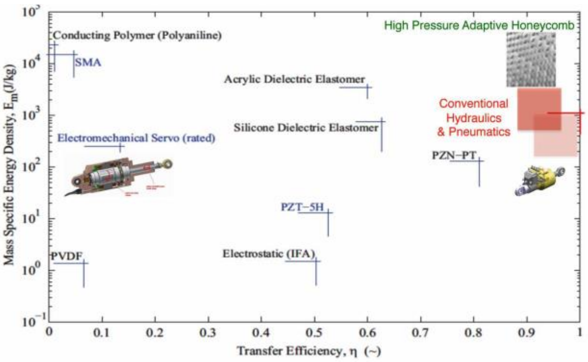

Figure 4 Mass Specific Energy Density and Transfer Efficiency Comparison of Aerospace Grade Actuator Materials [50]

II. OVERVIEW OF SUBSCALE FLIGHT CONTROL ACTUATOR SALIENT CHARACTERISTICS

A. Conventional Subscale Electromechanical Servoactuators

The first class of actuators which have steadily evolved to be compatible with smaller and smaller aircraft are conventional electromagnetic servoactuators. Starting in the 1950's, an evolving spectrum of radio control transmitters, receivers and servoactuators has continually evolved which have brought flight down to smaller and smaller sizes and into the hands of the every-day enthusiast. There are, literally, hundreds of types of electromagnetic servoactuators on the open market today. They are comparatively inexpensive, have good deflection and power consumption characteristics and are "plug and play" compatible with radio control receivers. Several representative samples of these actuators will be examined for the purposes of this study. These represent flight control actuators which are capable of controlling scale aircraft through micro aerial vehicles (MAVs).

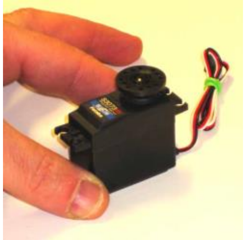

Fig. 5 Futaba S3073HV

Futaba S3003

This "standard" type of actuator is widely used and representative of some of the most ubiquitous forms of flight control on the planet. It is often found in aircraft as small as 60cm span trainers through 2m sail planes through trim tabs on giant scale aircraft.

Futaba S3073

With a form factor very similar to the Futaba S3003, the S3073 is designed to handle voltage levels produced by two lithium cells. Accordingly, it represents an incrementally more modern incarnation of the standard servoactuator that the industry has relied upon for nearly a half-century.

JR DS 368

This digital servoactuator is frequently used in slightly smaller aircraft including helicopters. Because it is digital, its rates and trim states can be programmed ahead of time to give pilots the exact "feel" they desire in the aircraft.

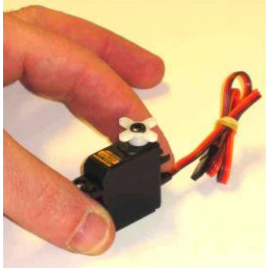

Fig. 6 JR DS 368

Cirrus CS-10BB

This type of servoactuator was one of the first sub-submicro-servoactuators on the market. It was known for its low weight and high actuation speeds. Following its introduction, many other manufacturers started manufacturing their own servoactuators on a similar scale. In a departure from most other manufacturers, Cirrus began manufacturing the CS-10 in a variant which had "ball bearing" races supporting the main shaft in an effort to improve robustness and reliability while reducing stiction, friction and slop. It was this very type of servoactuator which was used in some of DARPA's very first Micro Aerial Vehicles, dating to 1997.

HiTec HS-55

This servoactuator possessed many of the same characteristics as the Cirrus CS-10, but is a more modern build with mechanical fasteners joining the halves rather than adhesive-backed strips.

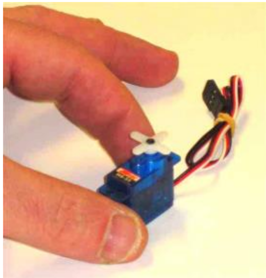

Fig. 7 HiTec HS-55

Tower Nano TS-5

This device represents a strong entry into the sub-submicro-servoactuator market by one of the largest R/C distributors in the US. It has many of the same kinds of mechanical features as the HS-55 with similar performance. This class of actuator has since been used in many park flyers and subscale rotorcraft.

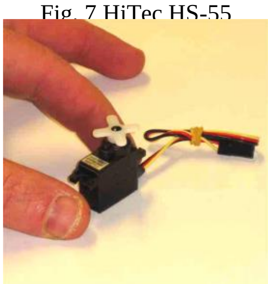

Fig. 8 Tower Nano TS-5

HiTec HS 5065MG

In a bid to further increase quality, reduce the debilitating effects of stiction, friction, slop and backlash while maintaining high pointing accuracy, the HS-5065MG employs metal gears (the genesis of the MG designator) to bring these positive characteristics. The servos are known for being more robust than most of the sub-submicroservoactuators on the open market today and yet still within a reasonable price range.

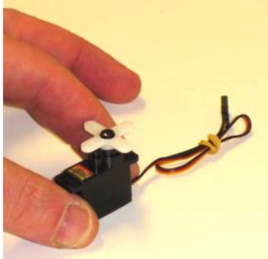

Fig. 9 HS 5065MG

If one examines the overall salient characteristics of these servoactuators, it can be seen that speed is inversely related to size of actuator and that the overall torque is much more directly related to the total mass of the actuator. The reader will note blank spaces in the Tables I and II. These represent conditions for which the servoactuators are not rated; accordingly, no data was taken at those points.

TABLE I. SALIENT CHARACTERISTICS OF SELECTED CONVENTIONAL R/C SERVOACTUATORS (MEASURED)

	Cirrus CS-10BB	**HiTec HS 5065**	**HiTec HS-55**	**Tower Nano TS-5**
Rate (@4.8V, deg/s to 60deg):	1000	429	333	545
Rate (@6V, deg/s to 60 deg):		545	429	667
Torque @ 4.8V (n-cm):	4.94	17.64	10.73	11.78
Torque @ 6V (n-cm):	0.00	21.87	12.70	14.68
Mass (g):	5.2	11.4	7.6	9.3
L (mm):	22.9	23.4	22.6	21.8
W(mm):	9.4	11.4	11.4	10.9
H(mm):	15.5	23.9	23.9	19.8

TABLE II. SALIENT CHARACTERISTICS OF SELECTED CONVENTIONAL R/C SERVOACTUATORS (MEASURED)

	JR DS368	**Futaba S3003**	**Futaba S3073HV**
Rate (@4.8V, deg/s to 60deg):	286	261	
Rate (@6V, deg/s to 60 deg):		316	300
Torque @ 4.8V (n-cm):	37.40	57.00	
Torque @ 6V (n-cm):	14.68	30.34	30.34
Mass (g):	21.8	39.5	39.5
L (mm):	27.9	40.9	40.9
W(mm):	13.0	20.1	20.1
H(mm):	30.0	36.1	36.1

B. *Piezoelectric Subscale Flight Control Actuators*

There are many forms of piezoelectric flight control actuators that have evolved over the past 20 years. Although most were benchtop demonstrators, several have been flying quite successfully for decades. Among the most noteworthy accolades that this class brags is that DARPA's first Micro Aerial Vehicle was actually enabled by a Tip-Joint Flexspar piezoelectric stabilator in 1997. Dozens of unclassified aircraft and flight control mechanisms have been built around piezoelectric sensors and actuators over the past 20 years.[51] The actuators selected below represent just a small sampling of the total volume, but are representative of many of the actuators which have been used to control the flight of subsonic aircraft.

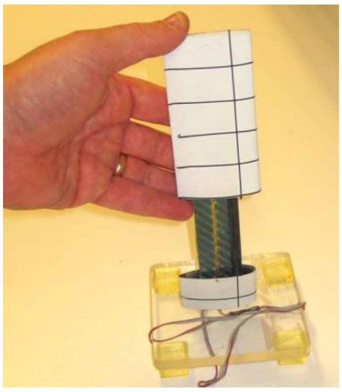

Fig. 10 Free-Spar Piezoelectric Torque-Plate Fin

Free-Spar Torque Plate Actuator

This configuration of piezoelectric actuator represents one of the earliest incarnations of piezoelectric flight control mechanisms ever to fly. With roots stretching back to 1989, this configuration of actuator has been applied to small aircraft, missiles and munitions for more than a quarter-century.[16,51] As can be seen in Fig. 10, the twisting Directionally Attached Piezoelectric (DAP) elements twist from root-to-tip to drive the aerodynamic shell in pitch around a strong main spar. The Free-Spar family of piezoelectric torque-plate actuators were the first aerodynamically and inertially balanced piezoelectric flight control assemblies publicly disclosed. The properties of aerodynamic and inertial balance made the structures essentially impossible to flutter and decoupled hinge moments from both deflection and angle of attack changes in attached flow flight regimes. Because of this basic insensitivity to flow angularities, stable flight was proven on a number of missiles, munitions and UAVs through the entire subsonic flight regime.[51]

Flexspar Actuator

The most widely used group of piezoelectric flight control actuators is the Flexspar family. These were first employed in the famous "Mothra" aircraft of 1994 which was the first UAV to fly with all piezoelectric flight controls.[51] ,Because the overall design could be tailored between very low speed (and dynamic pressure) flight regimes and high dynamic pressures, it has proven quite useful. Indeed, several families of Flexspar actuators have been successfully flown on a variety of subsonic and transonic systems and used as flutter test surfaces. Figure 11 shows a transonic flutter test surface being assembled for NASA's Rotationally Active Flutter Test Surface (RAFTS) program of 1998.[51]

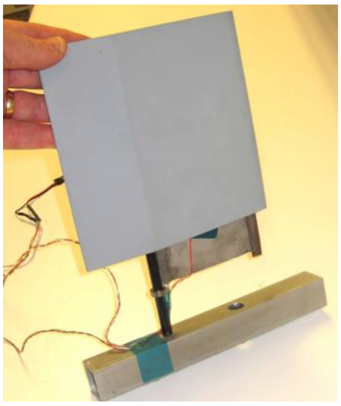

Fig. 11 Shell-Joint Flexspar Piezoelectric Actuator

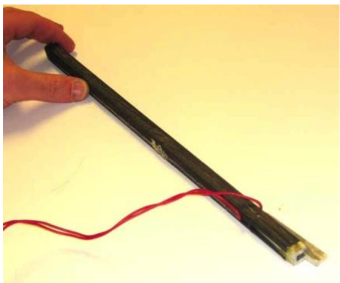

Fig. 12 HITT Piezoelectric Switchblade Actuator

Piezoelectric Switchblade Actuators

By far the fastest piezoelectric flight control actuators ever produced were made for the US Army Space and Missile Defense Command's (SMDC) Hypersonic Interceptor Test Technology (HITT) program. Figure 12 shows the actuator core of the piezoelectric switchblade actuator. Although designed for full 10 deg. deflections with deployment time constants under 5ms, the actuator and blade itself was so powerful that it could resist and overpower full hypersonic airloads.

C. *Pneumatic Subscale Flight Control Actuators*

Pneumatic subscale flight control actuators are among both the oldest and most modern actuators known. They have been used in FAR-23 certified aircraft for more than 50 years.

Brittain Industries Pneumatic Actuators

In the early 1950's a series of flight control actuators were matured for the aerospace industry which would take

Fig. 13 Brittain Industries BI707 Pneumatic Boost Flight Actuator

advantage of differentials in bleed compressor air. Figure 13 shows a pneumatic Brittain BI707 rudder-boost servoactuator which is used to certify the Beechcraft King Air. These types of actuators respond very quickly to feed line changes and are limited in bandwidth mostly by the gas dynamics of the gas supply system rather than the inertial characteristics of the actuator itself.

1m Pressure Adaptive Honeycomb Pneumatic Flap

In 2007 a new form of pneumatic actuator was conceived and reduced to practice. Unlike the cylindrical actuators of the 1950's this actuator class would take a well-characterized aerospace grade material and rotate it 90 deg. to achieve actuation. These Pressure Adaptive Honeycombs (PAH) would eventually be shown to have the highest mass-normalized energy densities of any aerospace grade actuators yet made, as seen in Fig. 4. A series of tests on 1m PAH actuated flap sections would prove critical for the nascent field of actuation.[47]-[49]

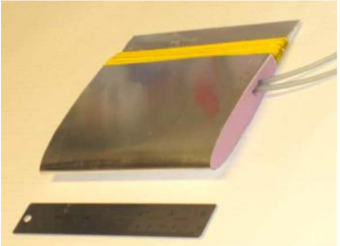
Fig. 14 Pressure Adaptive Honeycomb (PAH) 15cm Semispan Proof-of-Concept Demonstrator

15cm Pressure Adaptive Honeycomb Pneumatic Flap

Although the 1m chord PAH wing section would prove to be quite useful in establishing the performance of such actuator elements, a smaller test apparatus would prove necessary to bring the benefits to smaller aircraft such as missiles, munitions and UAVs. Figure 14 shows the overall arrangement of the 15cm chord, 15cm semispan NACA 0012 PAH actuator based on biomimetic trailing edge flap manipulation. This class of actuator would prove to be useful not only for flight control, but most importantly for its inherent gust-rejection properties. because many classes of aircraft are challenged by high frequency gusts, the PAH configuration offers an elegant and highly effective form of semi-active gust rejection. By tailoring the total and differential pressures in the flap actuator section, it was shown that the slope of the lift curve itself could be manipulated from that of a completely rigid airfoil all the way to negative values.

III. TEST GOALS

The reader is encouraged to read through the many references in this document. While interesting designs and configurations will come to the fore, one consistently missing set of data for all of these actuators is related to actuator dynamic response. Because professional aircraft flight control system and aircraft design engineers need this data, it is the purpose of this study to measure and report on the dynamic responses of all of these actuator classes in a side-by-side comparison so that choices in flight control actuation may be professionally executed in the future and control systems may be designed with confidence.

IV. TEST APPARATUS

The basic test apparatus used to evaluate most of these systems was structured on a rotational measurement and indication system within a temperature controlled environment. The flight control actuator was firmly attached to the indicator spar of the test device. Rotational deflections were transferred to the outside of the test box. Rotational deflections were measured with a rotary potentiometer which was calibrated to 0.1 deg of rotational deflection accuracy through 90 deg of rotation at a sampling rate of 1kHz. For the purposes of this study all tests were conducted between a controlled temperature range of 20 and 22 deg. C. Figure 16 shows how the typical servoactuator was mounted within the box (showing a Futaba S3073HV). For actuators which were fully integrated within their aerodynamic surfaces (like the PAH flap actuators), dynamic testing was conducted on the entire assemblies themselves. For the fastest actuators, laser reflection techniques were used so as not to corrupt the modal dynamics of the flight control surface.

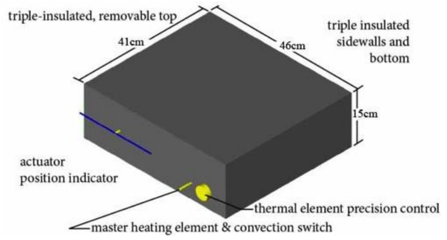

Fig. 15 Flight Control Servoactuator Environmental Chamber and Test Box Geometry

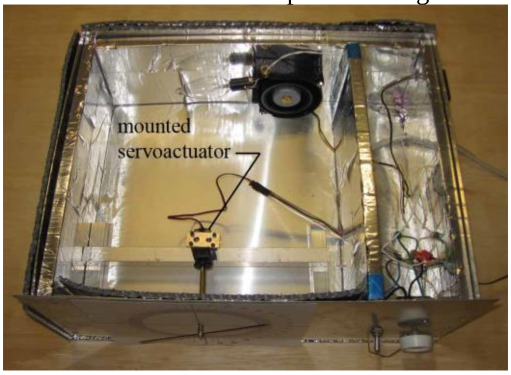

Fig. 16 Typical Servoactuator Mounting Arrangement for Dynamic Testing within Test Chamber (Futaba S3073 mounted as an example)

V. TEST RESULTS

The reader will note that the extensive reference collection almost uniformly contains a great deal of deflection data, but is devoid of dynamics accordingly, this study is centered on recording the dynamic response of the actuators described herein. Because the speeds of the flight control actuators varied considerably, the data reduction techniques were tailored to suit the speeds considered. For speeds below 10 Hz, the Test Chamber of Fig. 16 was used. Above 15 Hz, laser reflection techniques were employed. Flash recording of no less than 100 cycles were taken at 16 bits for each frequency measured. All experiments were conducted at least three times so as to ensure repeatability. Figure 17 shows the results of all of the dynamic testing of all actuators under consideration.

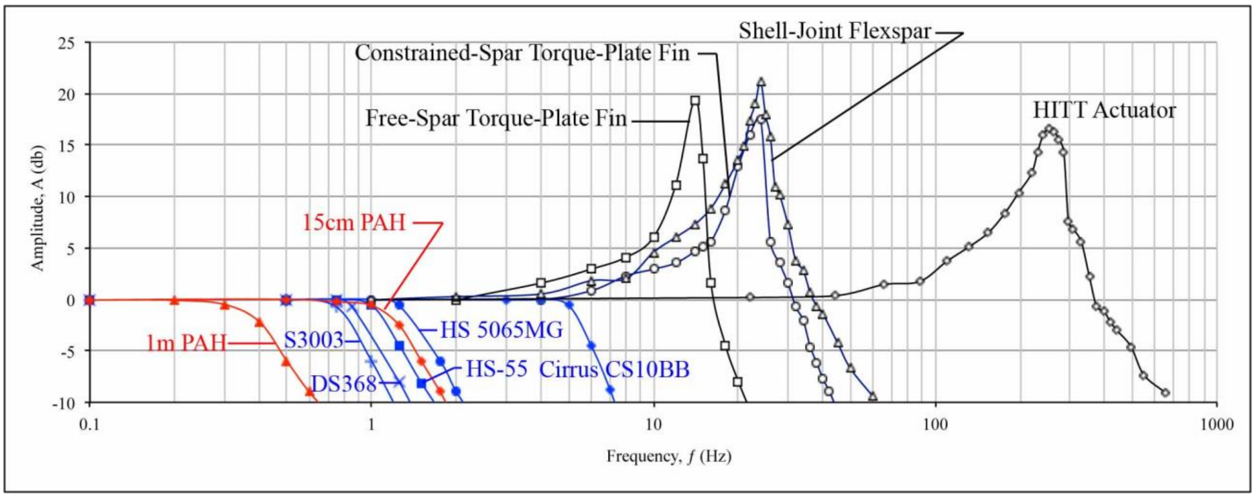

Fig. 17 Dynamic Responses of Subcale Conventional Electromagnetic Servoactuators, Piezoelectric Flight Control Actuators and Advanced Pneumatic Flight Control Actuators

VI. CONCLUSIONS

It can be concluded that there exists a wide variety of dynamic characteristics related to subscale flight control actuators. The highest speed fully proportional, repeatable flight control actuator family currently in existence in the technical community is centered on piezoelectric elements. These actuators regularly manipulate flight control surfaces at rates from 10 through 300 Hz. Conventional electromagnetic servoactuators, submicro servoactuators and sub-submicroservoactuators on the R/C scale exhibit dynamic responses from below 1 Hz through 6 Hz. Pressure adaptive pneumatic flight control actuators are capable of manipulating flight control surfaces from 1m through 15cm at rates below 1 Hz up through 2 Hz at nominal operating pressures of only 1.5 atmospheres of cell differential pressure. A summary of corner frequencies is shown in Table 3:

TABLE III. CORNER FREQUENCIES AND ACTUATOR TYPE

	Corner Frequency, *f*c (Hz)
1m PAH @ 1.5 atm	0.5
Futaba S3003	0.8
JR DS 368	1.0
HiTec HS-55	1.2
15cm PAH at 1.5 atm	1.3
HiTec HS-5065	1.5
Cirrus CS-10BB	5.8
Piezoelectric Free-Spar Torque-Plate Fin	18
Piezoelectric Constrained-Spar Torque-Plate Fin	36
Piezoelectric Shell-Joint Flexspar	42
Piezoelectric HITT Switchblade Actuator	463

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