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Demonstration Program to Design, Manufacture and Test an Autonomous Electro-Hydrostatic Actuator to Gimbal Large Booster-Class Engines

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This paper discusses the trade studies performed, the design of the selected actuator and the status of building and testing of an electro-hydrostatic actuator that could be used to gimbal a large booster-class liquid propellant rocket engine. This paper will describe the three actuator types traded, the advantages of the chosen electro-hydrostatic actuator as compared to existing electro-hydraulic (using either an autonomous or centralized hydraulic power supply) and electro-mechanical linear actuators. Benefits of the chosen actuator include the simplification of the whole system (power source and actuator); system cost reduction; system efficiency increase to 0.6 compared to 0.3-0.35 for the best hydraulic systems; and the reduction of the total system mass. The development of the schematic and design of the electro-hydrostatic actuator, the program to manufacturing and assembly of the experimental actuator and the program of an autonomous testing of the actuator itself and its components will be discussed.

Nomenclature

EHS	=	Electo-Hydrostatic Actuator
TVC	=	Thrust Vector Control

I. Introduction

Arsenal-207 in cooperation with Aerojet conducted a comparison analysis of three main types of actuators to control rotational position of the gimalled mass of a liquid rocket engine in the booster thrust class. The three types of linear actuators evaluated, shown in Figure 1, are:

Type I – electro-hydrostatic actuator –an autonomous electro-hydraulic actuator (closed-loop self-contained hydraulic pump) with an electric power source;

Type II - an electro-mechanical actuator with an electric power source;

Type III – an electro-hydraulic actuator with a centralized hydraulic power supply system.

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As a result of this comparative analysis using mass, power and specific power as figures-of-merit; the electro-hydrostatic actuator with an electric power source was chosen for further design work. The schematic is well-known and is widely used in Europe and U.S. advanced hydraulic actuators research and development work for control systems in airplane applications.

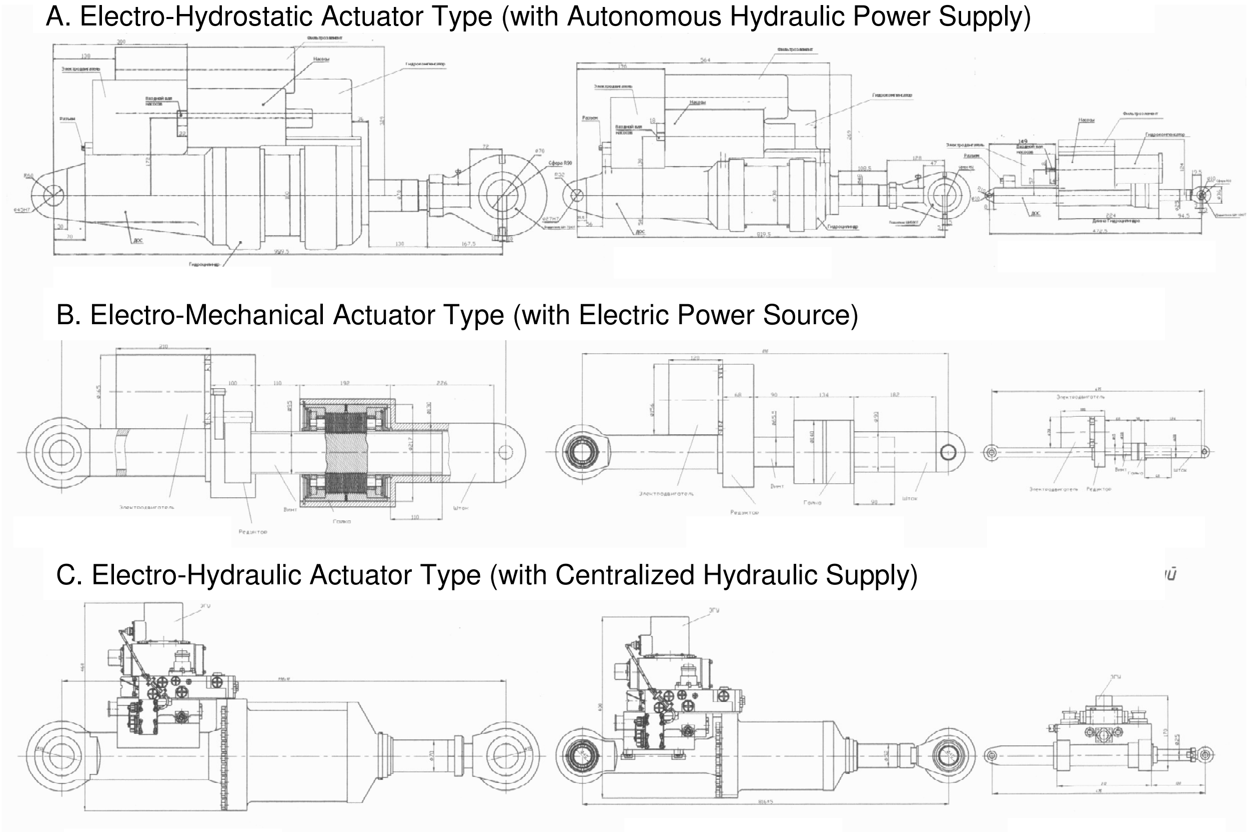


Figure 1. Comparison of Different Linear Actuator Types for Three Different Actuator Power Outputs – A. Electro-Hydrostatic, B. Electro-Mechanical, C. Electro-Hydraulic

The comparisons of the three types of actuators' volume/weight vs. force are shown in Figure 2 for an actuator velocity of 300 mm/sec. The comparison of the specific power vs. power output for the various actuator types are shown in Figure 3.

The trades indicated that the best actuator was electro-hydrostatic actuator for the power ranges evaluated. The system advantages of this actuator type included; the lowest system production cost, a simplified vehicle interface, no external hydraulic system, lowest engine thrust vector control system weight, higher TVC system efficiency (due to lesser parasitic losses), higher reliability and simplified maintenance since there is no external mechanical or hydraulic ground support equipment required to for actuator maintenance. The overall system efficiency for the electro-hydrostatic actuator was determined to be 0.6 as compared to the current state-of-the-art electro-hydraulic actuator efficiencies of 0.3-0.35.

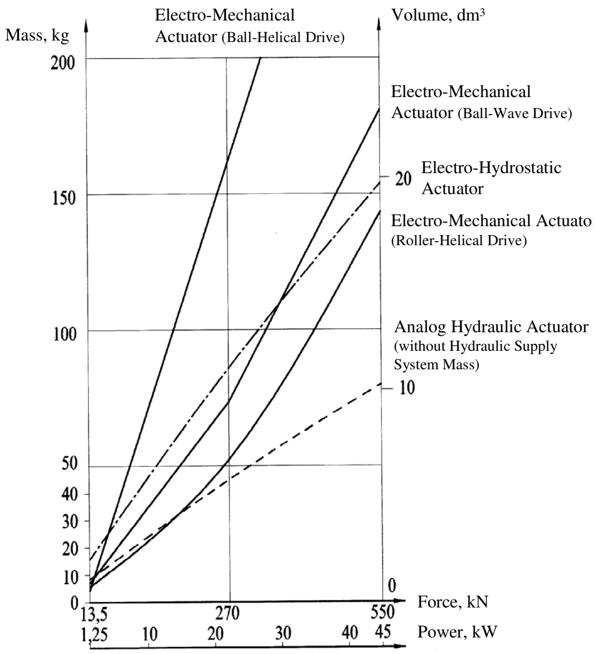


Figure 2. Actuator Volume and Weight vs. Actuator Force for Three Actuator Types (Actuator Velocity of 300 mm/sec)

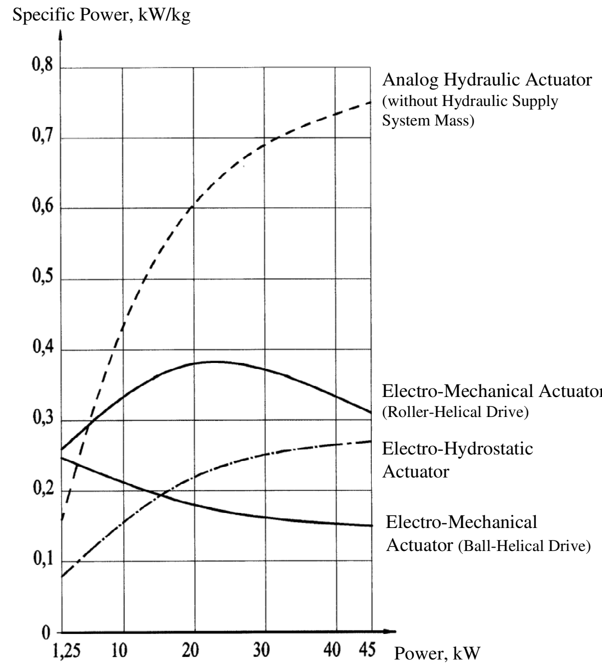


Figure 3. Comparison of Specific Power vs. Power Output of Various Actuator Types

This preliminary design includes further development of the electro-hydrostatic actuator with an autonomous hydraulic supply source and electric power source, consisting of a pump-type hydraulic assembly with a subassembly of main reverse pumps and an auxiliary pump, hydraulic compensator and a subsystem of control valve, hydraulic cylinder with the mechanical link; an electro-mechanical module, consisting of brushless direct-current electric motor, and an engine electronic control block, including power transistors, and internal feedback loops for current, speed and position.

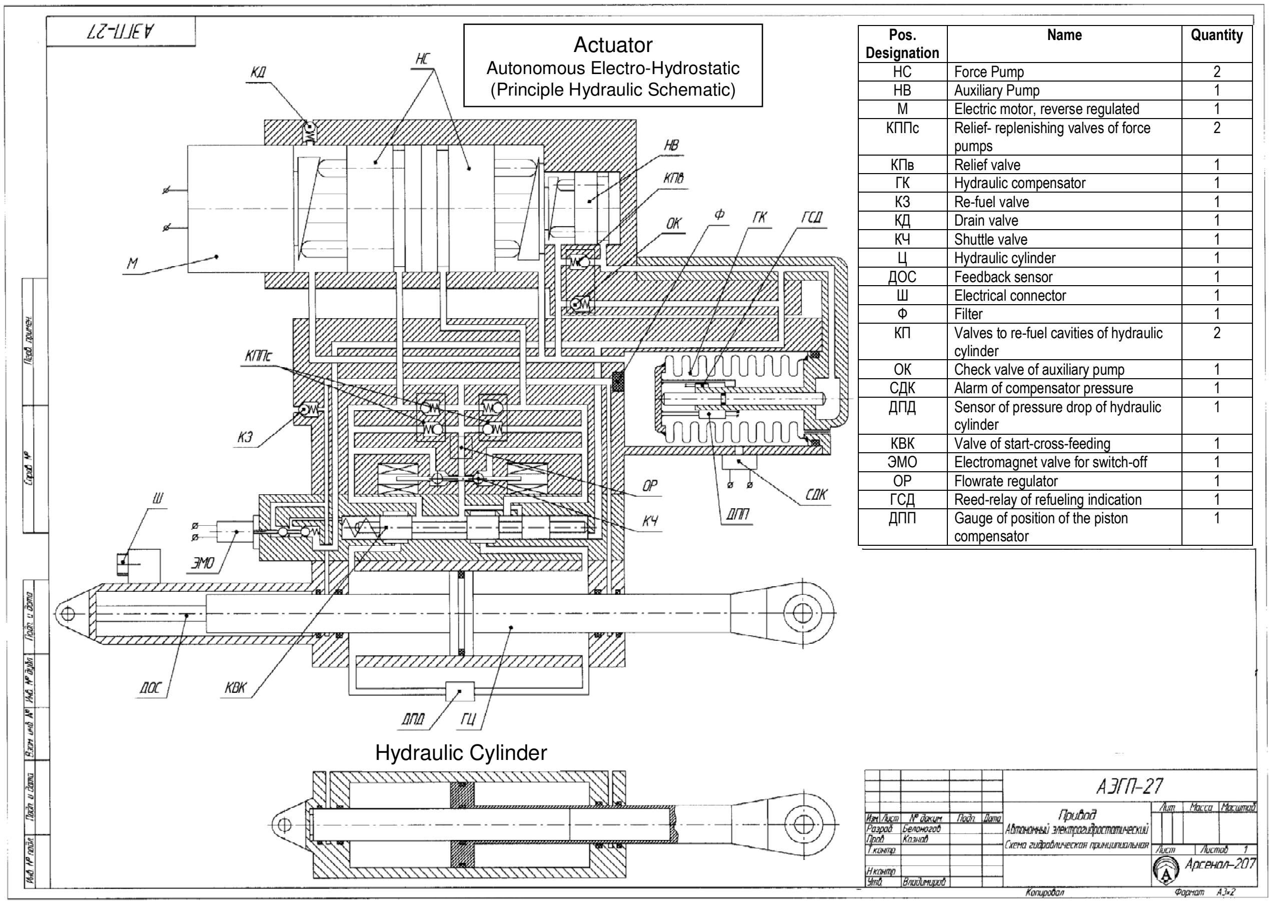
The following types of work were conducted during the preliminary design phase:

1. Design calculation and evaluation of main parameters of basic components and actuator itself, particularly: the subassembly of hydro-pumps, tank-compensator, and shuttle valve.
2. Analysis of power sufficiency of the actuator and the main requirements for electric motor characteristics.
3. Design calculations and requirements for the electro-mechanical module and schematic (electric motor plus electronic module).
4. Preliminary study of the electric motor, electronic module, subassembly of power electronics and program software.
5. Actuator reliability prediction.
6. Actuator mathematical model developed and used to calculate static, dynamic and power characteristics.
7. Design and analyses on the basic components; i.e. pump module, hydraulic cylinder, hydraulic compensator, starting-cross feeding valve, shuttle control valve, pump replenishing valves, and dual valve for the force pump.

II. Principals of Operation of the Electro-Hydrostatic Actuator

A general schematic is presented in Figure 4 explaining the operational principal of the electro-hydrostatic actuator with a dual valve-type pump and shuttle valve. The schematic also shows the passive cavity switching of a hydraulic cylinder to a compensator-tank, from which the working liquid goes to the suction piping of the active pump. The electrical motor attaches to the dual pump. There are a set of valves shown for the distribution of the working liquid to the hydraulic cylinder. Each of the pumps provides liquid supply to one of the cavities of the hydraulic cylinder. Another cavity of the hydraulic cylinder is connected through the shuttle valve with the compensator-tank cavity through a filter. Suction piping of both pumps is connected to the compensator cavity. Pressure in the compensator-tank cavity is supported with an auxiliary pump installed on the common shaft with main pumps and a head valve releasing excessive liquid into the working cavity of the compensator-tank.

The actuator motor is a regulated, reversible, brushless, direct-current electric motor using 270 volts with



Pos. Designation	Name	Quantity
НС	Force Pump	2
НВ	Auxiliary Pump	1
М	Electric motor, reverse regulated	1
КППс	Relief- replenishing valves of force pumps	2
КПв	Relief valve	1
ГК	Hydraulic compensator	1
КЗ	Re-fuel valve	1
КД	Drain valve	1
КЧ	Shuttle valve	1
Ц	Hydraulic cylinder	1
ДОС	Feedback sensor	1
Ш	Electrical connector	1
Ф	Filter	1
КП	Valves to re-fuel cavities of hydraulic cylinder	2
ОК	Check valve of auxiliary pump	1
СДК	Alarm of compensator pressure	1
ДПД	Sensor of pressure drop of hydraulic cylinder	1
КВК	Valve of start-cross-feeding	1
ЭМО	Electromagnet valve for switch-off	1
ОР	Flowrate regulator	1
ГСД	Reed-relay of refueling indication	1
ДПП	Gauge of position of the piston compensator	1

Figure 4. Simplified Schematic of Electro-Hydrostatic (EHS) with Self-Contained Auxiliary Pump

permanent rare-earth magnets inside the three-winding rotor. The identified windings are controlled with a force electronic amplifier-inverter with power transistors commutating depending on the rotation angle of the direct current motor. The rotation angle of the electric motor rotor is measured with a special sensor installed on the shaft. Consecutive switching of the stator windings and formation of the electro-magnetic forces rotates the motor along with the attached pump rotor. Switching the power transistors in a prescribed sequence is conducted with a micro-computer embedded into the actuator. A view of the electric motor with the power electronics is shown in Figure 5.

The mechanical layout of an actuator with an output power of 225 kN that would be applicable for a booster-engine in the 1,500-1,800 kN thrust class is shown in Figure 6. The electric motor, pump and shuttle valve are located in the upper cylinder; the hydraulic cylinder is the middle cylinder; and the compensator-tank in the lower cylinder.

Figure 5. General View of Electrical Motor

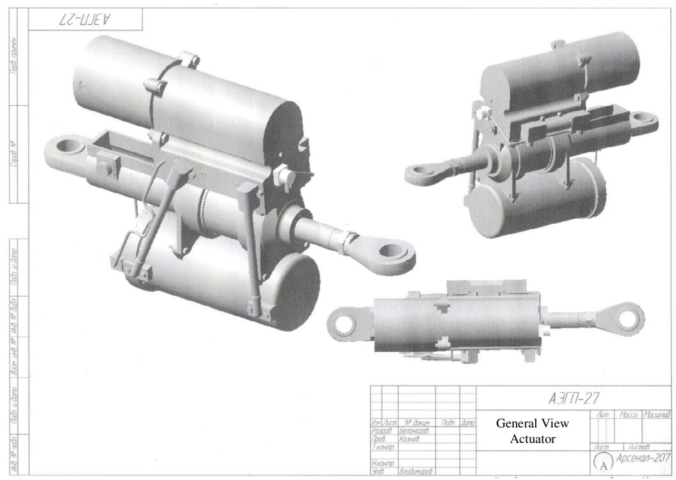


Figure 6. General View of EHS with an Output Power of 225 kN

The closed-loop frequency phase and gain response versus the requirements are shown in Figure 7 when using position feedback loop only. The design meets the stated requirement with minimum margin at one resonance point for the gain response and was low margin over the lower phase response requirement. By introducing velocity and differential pressure feedback, the gain and phase response is significantly reducing system resonance and improving phase response as compared to the requirements, as shown in Figure 8. These feedbacks loops will be selected for the actuator during the fabrication and testing phase to validate the design analyses.

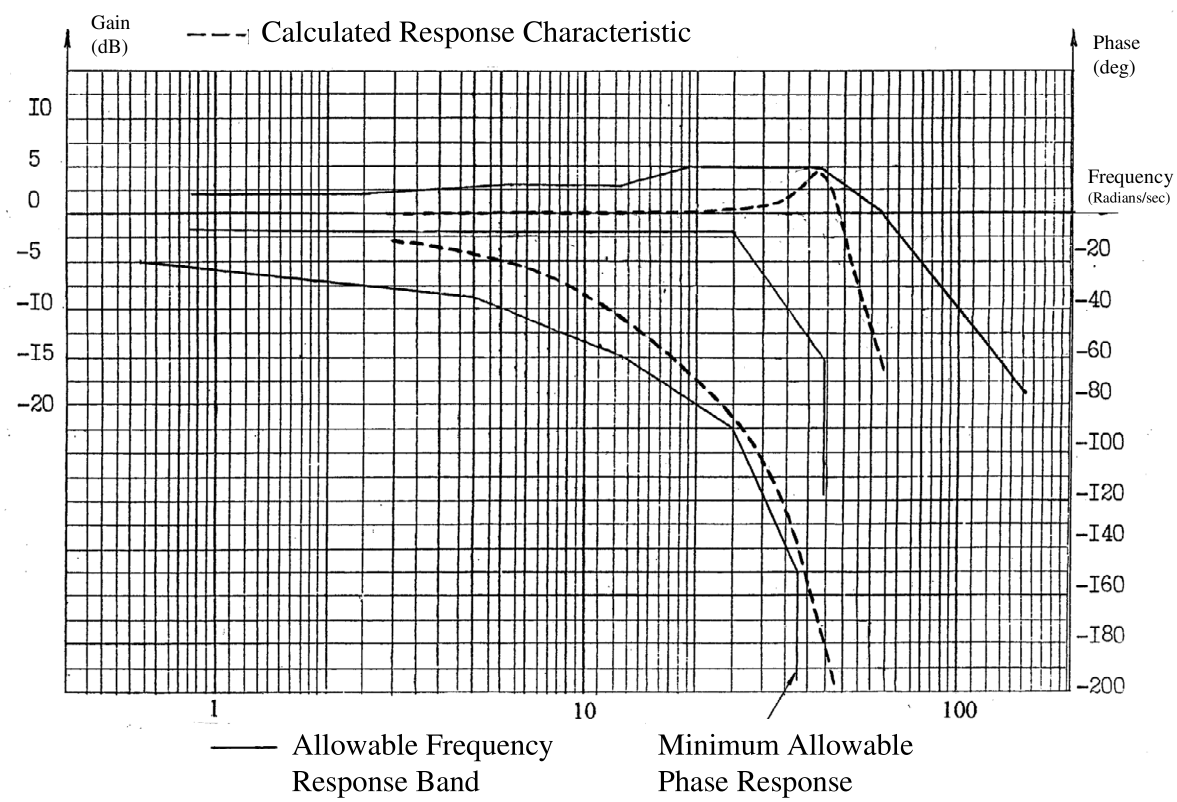


Figure 7. Closed-Loop Frequency Response without Additional Feedback Control (Position Feedback Only)

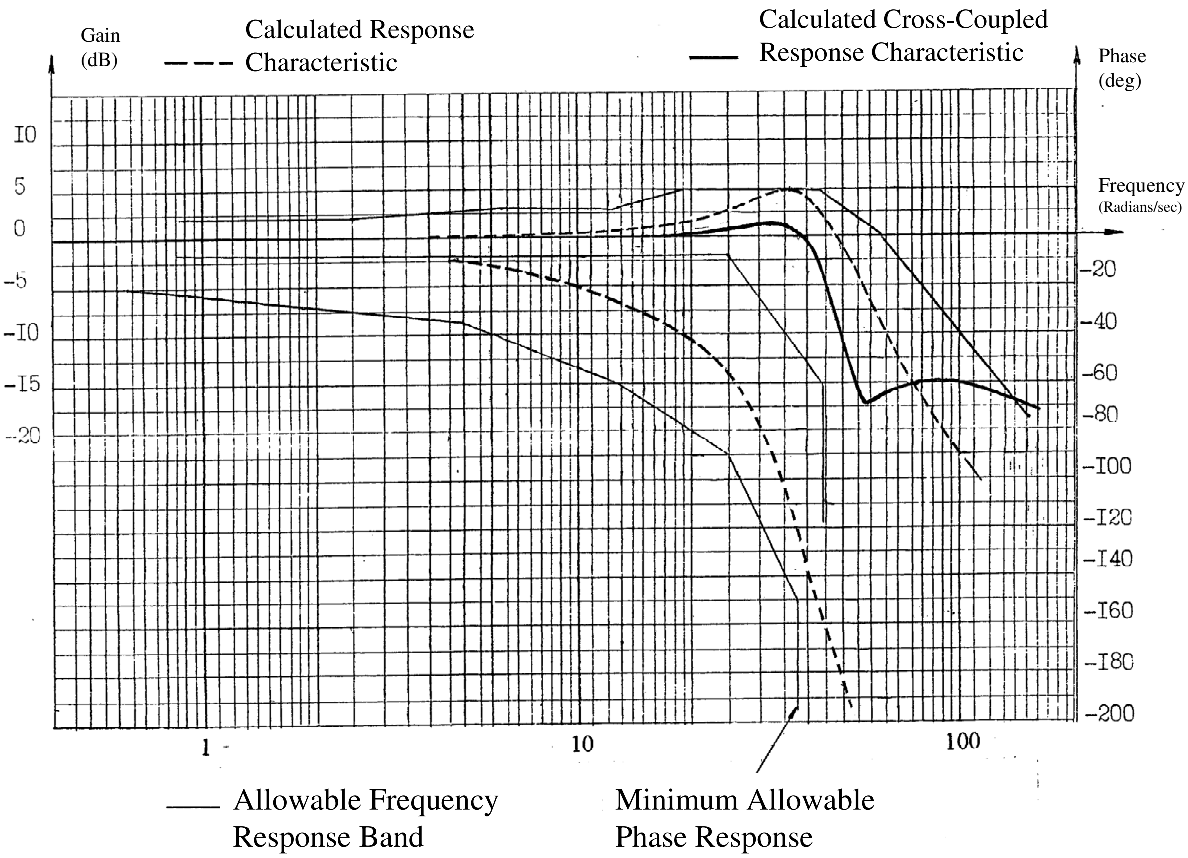


Figure 8. Simplified Closed-Loop Frequency Response Including Additional Feedback Control (Velocity, Differential Pressure, etc)

III. Current Status and Future Plans

The long-lead material for the actuator motor and the power electronics are being purchased in parallel with the assembly of the hydraulic pump assembly (auxiliary pump, main pump and valve components). The delivery of the electric motor is scheduled for October 2006. The full actuator assembly is planned to be complete by December 2006. The actuator testing is planned to be completed by March 2007 with the final report and a fully assembled actuator to be delivered to Aerojet by July 2007.

IV. Conclusion

The trade studies that were conducted demonstrate the benefits of the chosen EHS actuator type. These benefits include system cost reduction, system efficiency increases, and the reduction of the total system mass. In addition, the vehicle interface simplification increases the operability of the TVC system. Electro-hydrostatic actuators show clear benefits and Aerojet's and Arsenal-207 is planning for using these actuator types for future applications of reusable and expendable launch vehicles for liquid propellant rocket booster engines.