

DESIGN AND TESTING OF PIEZOELECTRIC-HYDRAULIC ACTUATORS

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Abstract

This paper describes design methodologies for construction of an actuator that uses smart materials to provide hydraulic fluid power. In the class of actuators described, hydraulic fluid decouples the operating frequency of the output cylinder from the drive frequency of the piezoelectric or other smart material. This decoupling allows the piezoelectric to be driven at high frequency, to extract the maximum amount of energy from the material, and the hydraulic cylinder to be driven at low frequencies to provide long stroke. However, due to fluid compressibility and structural compliance, the fundamental impedance match between the fluid and the piezoelectric make it difficult to convert energy from the piezoelectric into pressurized hydraulic fluid flow. The basic design tradeoffs and major technical issues are discussed in the areas of materials, mechanical design, and fluid-mechanical interface. Prototype devices and component measurements are presented. Test methods are described, and test results quantifying pump pressure and flow, and actuator force and velocity are summarized. The series of tests show the potential of these devices for high force long stroke devices powered by smart materials.

Keywords: Piezoelectrics, smart materials, piezohydraulic, actuation, power by wire, pumps

Introduction

Smart materials such as piezoelectrics, magnetostrictives and electrostrictives have a long history of use in precision control applications. Because of their limited shape change capability, these materials are not normally used in actuators requiring large linear motion. Over the last several decades there have been dozens of designs that achieve increased motion from smart material cores by various techniques. Among the common ones are mechanical amplification or transformation, for example those using lever and pivots,¹ and step-and-repeat types, for example the Inchworm™.² More recently, researchers have recognized the potential of integrating smart materials and fluids, making the pump a fundamental element to be exploited for linear actuation.³⁻⁸ This newer approach holds promise for high power actuation with long stroke.

The piezoelectric-hydraulic or “piezohydraulic” actuation brings advantages and disadvantages compared to other types of actuation, including conventional servo-hydraulic and various electromagnetic types.⁹ The primary advantage compared to traditional hydraulics is the power-by-wire aspect, i.e. the elimination of hydraulic distribution lines. Compared to electromagnetic methods including motor-driven ball screws, the piezohydraulic actuation provides the high force of hydraulics and a potentially more rapid response time. The new class of actuators has disadvantages compared to conventional hydraulics in the areas of heat distribution and tolerance for fluid loss. Compared to electromagnetic actuators, the new class, despite the small amount of fluid used, still requires both electrical and hydraulic integration. Many of these features of piezohydraulic actuation are common to electrohydraulic actuators (EHAs), such as those used on the Joint Strike Fighter. Where piezohydraulic actuation has a potential advantage over other EHAs is in the energy density of the piezoelectric material itself. Extracting this energy is a difficult task, and this paper attempts to describe some of the many challenges in a current development effort.

The overall design goal is to convert power input from a piezoelectric stack element, through various stages, to mechanical power delivered by an actuator output cylinder to an external load. The design starts with the piezoelectric smart material, extends to the piezoelectric-fluid interface, through valves, and finally to the output cylinder. Electronic drive of the actuator is also a consideration, though it is discussed elsewhere.⁹ Like many systems, the overall design is an integrated and iterative one, where individual components can be designed, but then require redesign to work well with other subsystems. Testing at the component, subsystem and system level aids in

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this process. Tests can be conducted to characterize individual elements, their interaction, and their collaboration. Measurement and maximization of total mechanical output of the device (force, velocity, or power) is the ultimate goal.

The remainder of the paper describes basic concepts in solid-fluid actuation, illustrating operation and highlighting limitations. The actuator design concept is presented next, and various key subsystems are described. Important properties of piezoelectrics for this application are considered. Design of the pressurization chamber is addressed and prototype devices are described. The various test approaches, for partial or complete device characterization, are enumerated, with the value of each is highlighted. The paper concludes with test results and interpretation for multiple generations of piezohydraulic devices.

Solid-Fluid Hybrid Actuation

In more general terms, piezoelectric-hydraulic or smart material-hydraulic actuation can be termed “solid-fluid hybrid” actuation. Energy sent to the smart material produces pressurized fluid. Then mechanical valves rectify the oscillating fluid pressure to create pressurized fluid flow. With hydraulic accumulators and another valve, the solid element can operate at a frequency different from the frequency required by the load. In general, the solid actuator operates at a frequency much higher than that required by the load, perhaps 100 times as high.

While theoretically attractive, practical limitations arise that limit the efficacy the solid-fluid hybrid actuation approach.⁸ In particular, fluid viscosity and compressibility combine with loss mechanisms inherent in the active material to limit the effective bandwidth of the driving actuator and the total actuator output power. Also, great care must be taken in design to match the characteristics of the driving actuator to the fluid transmission and output actuator if maximum power is to be available to drive the mechanical load.

Figure 1 illustrates the generic class of devices considered by the present development. As this figure shows, the device considered here comprises several elements: a solid-state element of stiffness k driving a piston of area A_1 to pressurize the working fluid, and fluid passages connecting the pressurization chamber with an hydraulic output cylinder and accumulator volume through four valves.

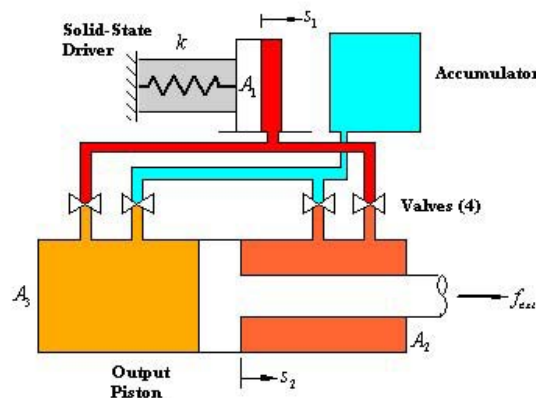


Figure 1: Hybrid solid-fluid actuator concept

Figure 2 shows the hybrid actuator's sequence of operation. Valve openings are timed to allow pressurized fluid into one of the output cylinder's chambers. During the stroke of the solid state actuator, the alternate output-piston chamber is ported directly to the accumulator volume to allow the output piston to displace different volumes in each chamber. Once the pressurization stroke has reached its limit, valve openings are adjusted to allow the pressurization chamber to take fluid in from the low-pressure volume of the output cylinder and the accumulator volume. This displacement of fluid from one side of the output piston to the other moves the piston in the direction opposite to the average fluid flow.

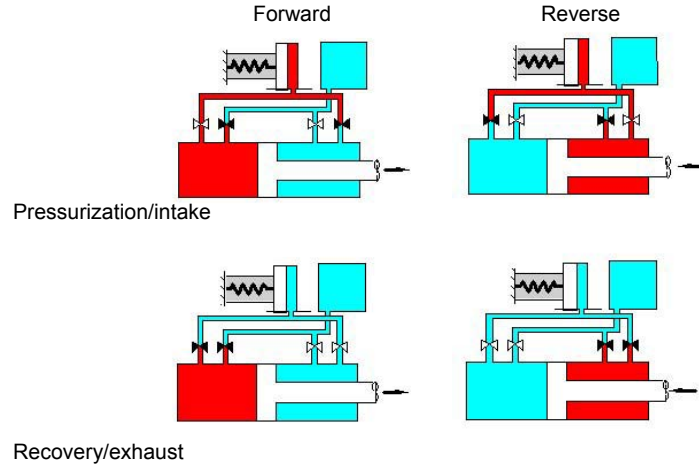


Figure 2: Sequences of hybrid actuator operation

The free-running output velocity of the device is the product of the volume of fluid displaced by the induced-strain actuator and the cyclic frequency of operation, divided by the output piston area. Chamber sizes and fluid properties may be adjusted to achieve a wide range of force-speed output characteristics for any given driving element. However, elementary consideration of the operating capability of the induced strain actuator will reveal that the maximum mechanical power that can theoretically be delivered by the solid-state actuator to the working fluid per cycle of operation at frequency $f = 1/T$ is

$$W_{MAX} = \frac{F_b \delta_{MAX}}{4T} = \frac{P_s \Delta V_{MAX}}{4TA_1^2} \quad (1)$$

where F_b is the actuator blocked-force rating, and δ_{MAX} is the actuator's maximum free induced stroke (P_s is the "stall" pressure – the pressure at which no fluid can be moved by the actuator, and $\Delta V_{MAX} = A_1 \delta_{MAX}$). This work quantity corresponds to the maximum-area rectangle that can be inscribed under the solid-state actuator's load line in force-displacement, or, equivalently, pressure-volume space, as illustrated in Figure 3. Consideration of compressibility of the working fluid dictates that the pressurization chamber acted upon by the solid-state actuator presents a finite fluid stiffness to the actuator. The stiffness of the pressurization chamber is $A_1^2 / \beta V_1$, where β is the fluid compressibility. The chamber fluid stiffness presents a loading to the actuator, as illustrated in Figure 3, which reduces the maximum achievable chamber pressure and power output, respectively, to

$$P_{MAX} = \frac{A_1^2 P_s}{\beta V_1 K + A_1^2}$$

$$W_A = \frac{P_s A_1}{4T} \left[\delta_{MAX} - \beta P_s \frac{V_1}{A_1} \right]$$

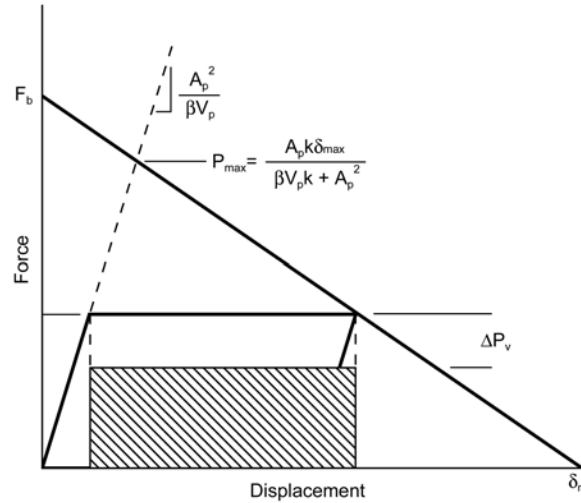


Figure 3: Explanation of hybrid-actuator work showing loss elements

The necessary pressure drop incurred to move fluid from the pressurization chamber to the output cylinder further reduces the available output of the integrated device:

$$W_o = \frac{(P_s - \Delta P_v) A_1}{4T} \left[\delta_{MAX} - \beta P_s \frac{V_1}{A_1} \right] \quad (2)$$

It is difficult to achieve in practice the output power predicted by Eq. 1. In practice, Eq. 2 provides guidance for maximization of output power for a given actuator. In particular, the valve pressure drop, fluid compressibility, and the effective height of the pressurization space (V_1/A_1) must be minimized, with various factors establishing a lower limit on the height. These goals are far from straightforward to accomplish, owing to the necessity of fluid passages, losses associated with viscous flow through these passages (included in ΔP_v), and the variable nature of fluid properties with temperature, entrained gas, etc.

It is possible to exercise the model based on the discussion above and other assumptions described in Ref. 8 to produce simulation results such as that of Figure 4. This graph shows the cyclic pressurization cycle of the piezoelectric and the resulting high and low pressure sides of the piston. It also shows the output actuator shaft position as it increases over time in an overall response that is slower than the piezo response by more than an order of magnitude.

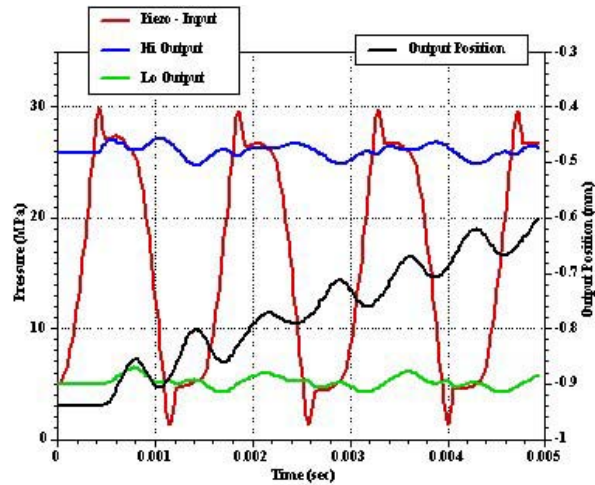


Figure 4: Pressure generated on startup by piezoelectric and at output location along with output displacement

The modeling effort shows fundamental limitations on the maximum actuation power available from a solid-fluid hybrid actuator include not only the inherent physical limitations of the solid driving element (e.g., stiffness, stroke, stable operating frequency), but also limitations imposed by the working fluid (e.g., compressibility, vapor pressure). The likelihood of fluid cavitation is the principal factor limiting the increase of output power with increasing operating frequency of the solid-state driving element.

Ref. 8 develops a simple expression to estimate the operating frequency at which maximum output power can be achieved:

$$f_{MAX} \approx \frac{A_{in}}{A_1 \pi \delta_{MAX} (2 + \pi)} \sqrt{\frac{2\bar{P}}{\rho}} \quad (3)$$

where $\bar{P}$ is the device charge pressure. Using typical values for device parameters, and $\bar{P}$ of 5 MPa (725 psi), a f_{MAX} is approximately 740 Hz. Cavitation-limited maximum output power of such devices also depends inherently on compressibility of the working fluid, and the external loading applied to the actuator.

There is a clear need for well-designed valves to rectify the high-frequency pressurization of the working fluid. Valves must operate at high frequency and, in particular, they must operate with sufficient speed and opening area to cause low pressure drop in the pressurization chamber's inlet passages. A series of valves and several methods of fluid pressurization have been tested in devices of the type described next.

Actuator Concept

The basic concept for the main portion of the smart material-hydraulic actuation is shown in Figure 1. This concept is shown in block diagram form in Figure 5, along with a photo of a design realized in hardware. From the external interface, the device receives electrical power and commands and sends back sensed quantity (e.g., load or displacement) status or health information. A microcontroller or low-end digital signal processor (DSP) performs the computations necessary to coordinate commands, process sensed information, and regulate drive and valve timing. A high power amplifier drives the main smart material actuator, and lower power amplifiers drive any active valves within the device. The main pressurizing actuator compresses fluid in the compression chamber, and the valves port this fluid rapidly in and out of the chamber, the accumulator, and the output device. The output actuator piston is driven at frequencies in the range of 1/100 to 1/50 of the internal actuator drive frequency. This actuator output drives a load, and global sensed quantities, such as flap angle, are made available to the embedded controller.

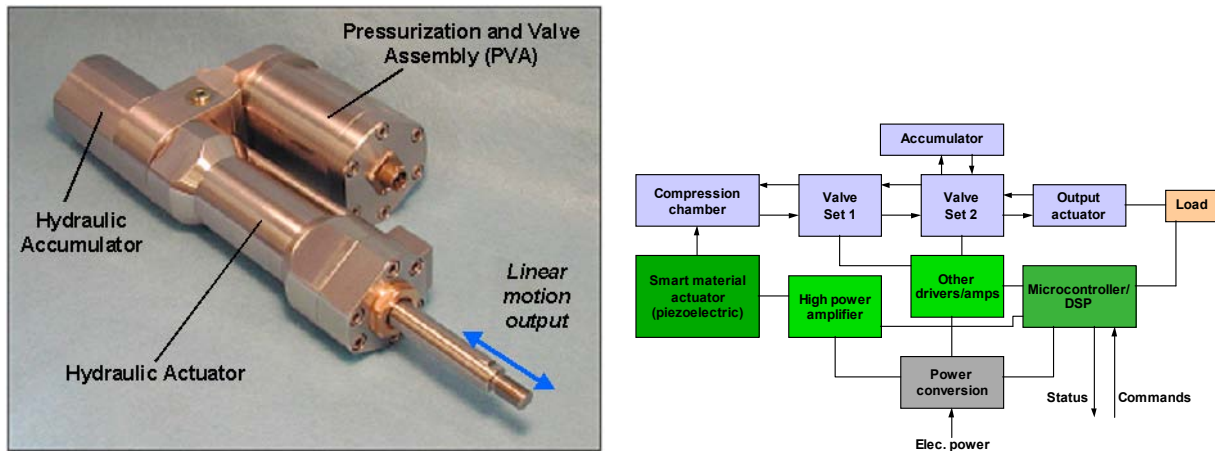


Figure 5: Basic architecture of the smart material-hydraulic hybrid actuator

The actuator is essentially a pump, sometimes called the pressurization and valve assembly (PVA), coupled to an output device. The coupling between these two subsystems is important, and design of the pump without consideration of the output actuator and the load will lead to inefficiencies. In the most general design, both the frequency and amplitude of the primary drive can be varied to regulate the flow and pressure through the system.

From an overall efficiency standpoint it is preferable to regulate this drive rather than deliberately restrict flow through valves, increasing pressure drop, and dumping energy as heat.

The mechanical housing performs the function of registering other components and holding and porting fluid. The housing must include allowance for fluid seals, and housing compliance must be minimized, particularly in the vicinity of the main fluid compression chamber. The housing also performs secondary functions in heat transfer and must include means of installation that may be application-dependent. An overall geometry that is not axisymmetric is acceptable, with the PVA and the hydraulic output device forming two assembly groups.

Clearly, the length of the internal fluid paths should be limited for high bandwidth operation, and the width or diameter of passages should also be minimized. A low volume in transfer passages is desirable, as is free flow, with little restriction and pressure drop. For a working fluid, high bulk modulus and low viscosity are preferred. In practice, the effective fluid bulk modulus is compromised by the presence of entrained air. Finally, as indicated above, operation of the device at a pressure bias or pre-charge is preferred.

The valves are in many ways the key elements of the overall actuator.⁸ Pressure drop across valves limits bandwidth and overall output power, with the intake valves being most critical. In the development, several passive and active valves have been tested. High speed passive valves offer lower performance but far greater simplicity. There are several options for passive valve architecture. Active valves are required at minimum to provide directional control, reversing flow to and from the output device to change direction of the output action. Timing of active valve opening and closing is critical to high efficiency operation, and valve geometries that automate the timing to some extent without inertia reversal on each cycle are preferred.

Piezoelectric Materials and Actuators

During the device development and evolution, the nature of the use of the piezoelectric actuators has been recognized as being different from that in many of the “smart structures” applications over the last two decades. The fundamental needs are for high energy density and high energy transfer rather than precision positioning or vibration control.

The hybrid actuators require smart materials for the primary pressurization and in certain architectures, as a means to drive active valves. Piezoelectric materials were chosen over other options for a variety of reasons. Compared to shape memory materials of the size required, the piezoelectric bandwidth, and therefore ability to deliver pressure at high frequency, is considerably greater. Compared to magnetostrictives, piezoelectrics provide lower energy density in the material, but greater density when auxiliary field-generating coils are included. Compared to electrostrictives, there are simply more options for piezoelectric materials and actuators. Availability is far greater. However, nothing about the analysis, modeling or design would preclude the future substitution of an alternate smart material.

Among piezoelectric materials, the primary quantity of interest is power density, i.e. the amount of mechanical power output that can be generated per unit volume or per unit mass. The electromechanical coupling coefficient should be high to convert electrical to mechanical energy. Since the interest is in more than simply one-time operation of the device, and since the nature of the actuation approach requires a large number of cycles, other factors are also important. The dielectric loss tangent is important for three reasons. First, it indicates wasted energy in the conversion from electrical input to mechanical output. Second, the heat generated at persistent high drive levels can cause material degradation. Finally, the heat must be dissipated somehow within the actuator body. A high Curie temperature is also desirable, to allow operation in elevated temperature environments in which actuator self-heating further raises temperatures. In contrast to the common focus on the piezoelectric coefficients d_{33} and d_{31} , it is these other properties that control high power applications such as the one of interest here.

The piezoelectric materials are to be used in a stack actuator configuration within the device. This stack should be mechanically stiff, introducing negligible compliance in interlayers or end caps. However, the stack geometry can be optimized to yield a stiffness that is well matched to the fluid medium. It should be mechanically rugged, and free from internal manufacturing stresses. It must be able to withstand a high thermal, electrical and mechanical stress environment over billions of cycles of operation. This application is at least as demanding as others in terms of number of cycles.¹⁰ Consider that an actuator operated at 2000 Hz for 140 hours experiences over 1 billion cycles.

Pressurization Chamber Design

Within the piezohydraulic actuator, the goal of the piezoelectric pump is to convert electrical power into fluid power. The energy conversion is achieved with two main steps. First, the piezoelectric material pressurizes

hydraulic fluid in a small chamber. Then, valves rectify the oscillating pressure to provide pressurized fluid flow. However, to convert the most energy per cycle from the piezoelectric requires an impedance match between the piezoelectric and the fluid (Figure 6). The total amount of energy available in the specific example shown in the figure is about 0.5 J/cycle. Such an actuator would make available 1000 W if operated at 2000 Hz.

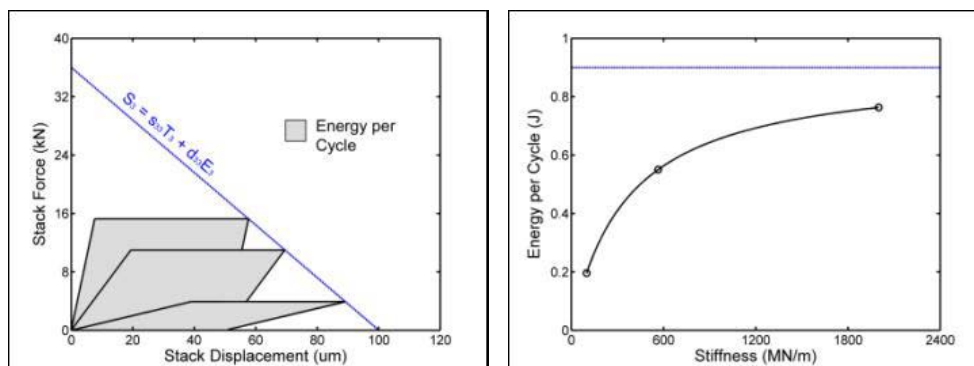


Figure 6: Energy per cycle for a given load stiffness on the piezoelectric

While the available power is large, the piezoelectric's high stiffness and the fluid's compressibility makes an impedance match difficult to achieve in practice. As an example, the calculated stiffness of a cylinder of hydraulic fluid demonstrates the difficulty in creating a load that converts the maximum energy per cycle from the piezoelectric (Figure 7). The result shows that even for a small fluid chamber, the finite stiffness reduces the achievable energy per cycle from the piezoelectric.

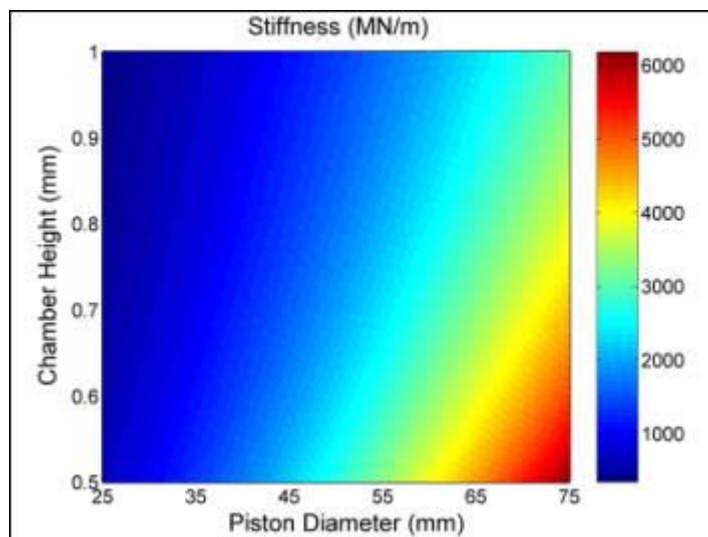


Figure 7: Typical stiffness of cylinder of hydraulic fluid

In addition to the fluid stiffness, the housing stiffness from the metal assembly also reduces the performance of the device. To study the effect of housing designs for stiffness, a piezoelectric pump was manufactured to determine the maximum achievable pressure drop with the piezoelectric (Figure 8). In this design, the smart material pumps fluid from one side of the device to a port on the far side of the device. The piezoelectric pumps fluid into a completely closed chamber and creates a pressure rise in the far chamber of the block pressure (Figure 9). The values of the block pressure quantify the effective stiffness of the metal housing and fluid chamber (Figure 10).

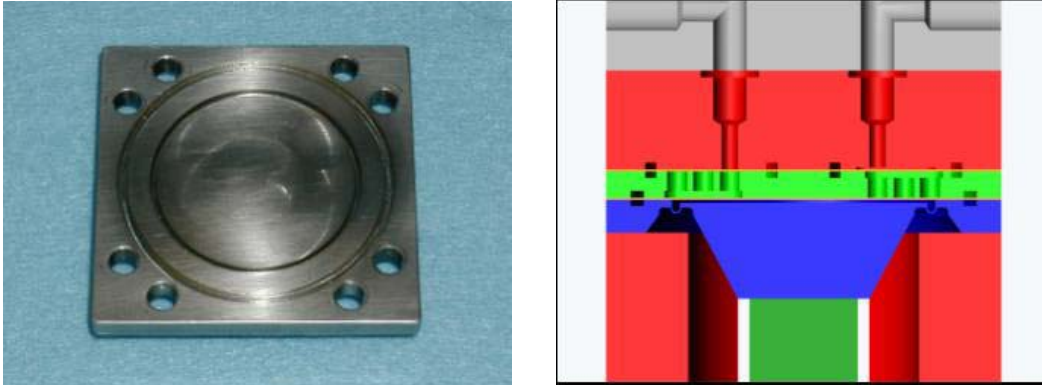


Figure 8: Design of test assembly for pressurization of hydraulic fluid

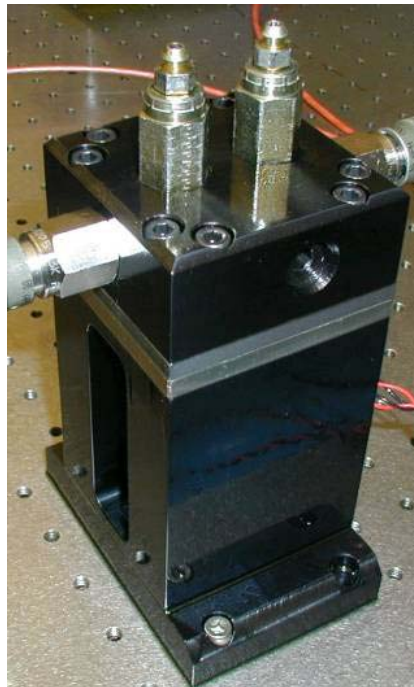


Figure 9: Experimental test setup for pressurization of hydraulic fluid

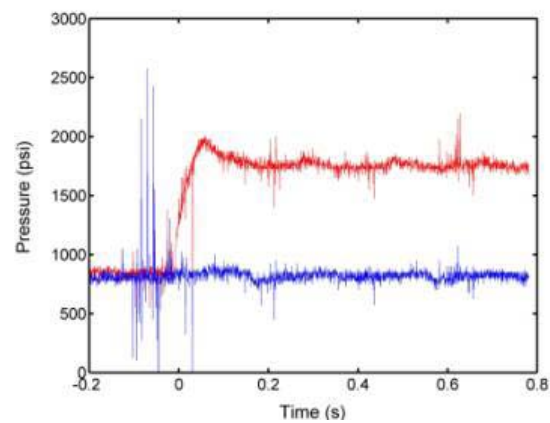


Figure 10: Results of fluid pressurization with a piezoelectric material

Typically, the bulk modulus of a pure hydraulic fluid is independent of pressure. However, most hydraulic oil has some entrained air, which causes the fluid mixture's effective bulk modulus to vary at low pressure. To minimize the effects of entrained air, a high precharge pressure reduces the volume fraction of air in the fluid. Typically before a block pressure test, an external hydraulic pump pressurizes the intake port to a pressure usually between 250 and 1000 psi. However, typically any precharge above 700 psi as minimal improvement in device performance.

Device Level Tests and Results

Several prototype actuation devices have been developed and tested. Each device generation increased important quantities such as level of integration, bandwidth or power output. Devices are characterized at different levels of integration, from the piezoelectric stacks alone, to measurement of the complete mechanical power output. A primary distinction is made between the fluid power producing core of the unit, i.e. the pump, and the complete actuator that outputs mechanical power.

Usually, the first test of the piezoelectric pump is to measure the block pressure of the device (Figure 11). In this case all external valves are closed and the piezoelectric is actuated at low frequency. The small flow from the pump increases the pressure in the exhaust port until the block pressure is reached. This block pressure test measures the overall device stiffness, which is important to quantifying the load impedance seen by the piezoelectric. Then, fully opening the valve from the exhaust port to the intake port determines the no-load flow rate of the device. In this case the flow rate is recorded for multiple piezoelectric drive frequencies. The point at which increasing the frequency does not increase the flow provides an estimation of the device's maximum operating frequency. Then, partially closing the throttling valve allows measurement of the pressure versus flowrate for multiple drive frequencies. This is a measurement of the power from the piezohydraulic pump for a purely resistive load.

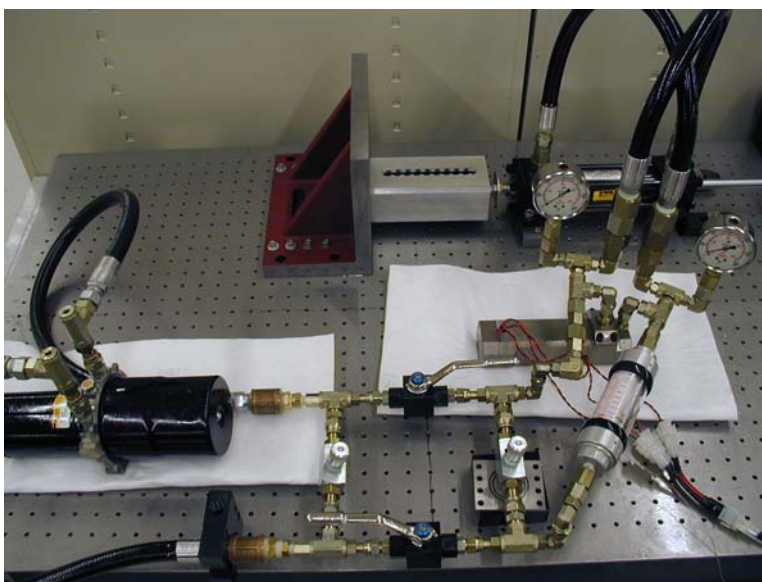


Figure 11: Experimental test setup to characterize the force versus velocity performance

The next test is that of a spring load using a hydraulic actuator driven from the piezoelectric pump (Figure 12). As the hydraulic actuator compresses the spring, the velocity is recorded during the rod stroke. This one test gives the entire force velocity behavior (Figure 13) of the device because as the spring compresses, the load increases and the velocity decreases. This test is then recorded for multiple operating frequencies to give the frequency that maximum power occurs in the force versus velocity performance.

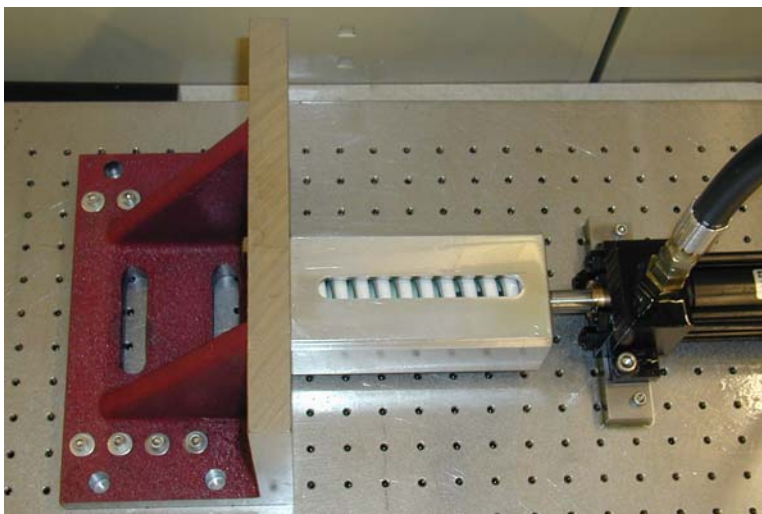


Figure 12: Spring load used to determine the force velocity performance of the device

In the figure, the actuator is driven from one extreme (high velocity, low force) to the other (low velocity, high force). Note that the product of force and velocity is power and the maximum power output is reached at approximately 50% of the maximum velocity. The particular data is shown for 400 Hz internal drive frequency. The particular device has been driven to 600 Hz, while others have operated above 1 kHz.

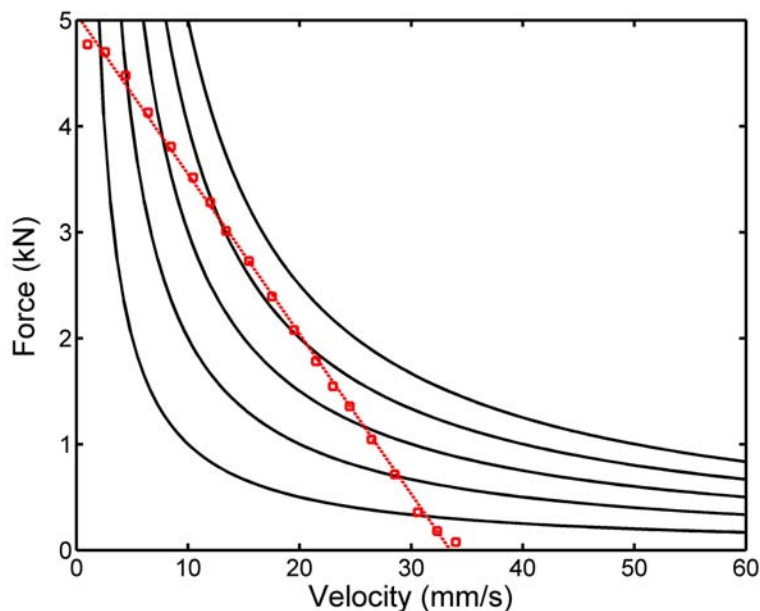


Figure 13: Results from the spring load testing of the piezohydraulic actuator

The 42 W output power is encouraging, and the device output power has continued to increase with each prototype. Nonetheless, the measured power is approximately 40-50% of the predicted performance using the idealized models that incorporate only basic fluid losses. More recent models capture additional fluid losses and predict performance more accurately.¹¹ Future versions of the device will attempt to double both the velocity output and the force output, more than quadrupling total output power.

Conclusions

This paper has presented a concept for actuation that uses smart materials such as piezoelectrics in combination with a hydraulic transmission to produce compact hybrid devices. Smart materials have often been used for low force

positioning or vibration control, but one of their inherent strengths is their high inherent energy or power density. This can be exploited in several ways, one of which is described in this paper.

Fundamental modeling considerations for this piezohydraulic actuator type were presented. Basic operation was explained, and limitations due to viscosity, compressibility and inadequate internal valve openings were summarized. The particular architecture appropriate for practical devices was presented. Key subsystems and components were discussed, and important considerations in the design of each subsystem and the interaction of subsystems were highlighted. Issues related to piezoelectric materials and actuators were addressed.

Design considerations for achieving high internal pressure were discussed. In this type of device an impedance match between the stiff piezoelectric actuator and a short column of fluid is critical. Several types of tests were noted and a comprehensive device test setup was described. Typical results from a device were presented, and other high speed devices are currently in development.

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