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Smart-Material Based Hydraulic Pump System for Actuation of a Morphing Wing

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A magnetostrictive material is used as a high frequency driving element in a hydraulic pump that provides fluid power for actuation of a planned morphing wing. In the particular morphing concept, the pump serves as a centralized hydraulic power unit with distributed hydraulic lines to eight separate end-effectors in the wing, but the technology can also be used to create lightweight, compact electrohydrostatic actuators, which allow for distributed power-by-wire operation. The pump exceeds all flow rate and pressure requirements for actuation of the morphing wing. Magnetostrictive pump design and test results are described. Hydraulic and control systems are laid out in detail for a morphing wing demonstration on a small unmanned air vehicle. Looking towards future, non-experimental flights, information and test results are also provided on pump reliability and dual pump arrangements.

I. Introduction

Over the past decade, smart materials have been incorporated into lightweight, compact pumps and actuation systems.[1-9] The high energy densities of smart materials make possible a power dense class of pumps and actuators suitable for driving flight control surfaces and other unmanned air vehicle (UAV) subsystems.[10] Piezoelectric and magnetostrictive materials, in particular, have been successfully implemented as high speed drivers of the pressurization systems. Due to the limited strokes of these driving elements, they must be operated at high frequencies in order to generate reasonable flow rates. A reciprocating action has typically been used to produce oscillating fluid pressure that must be rectified to yield controllable fluid power. Mechanical output power can then be delivered at a desired (and usually much lower) frequency using directional control valves.

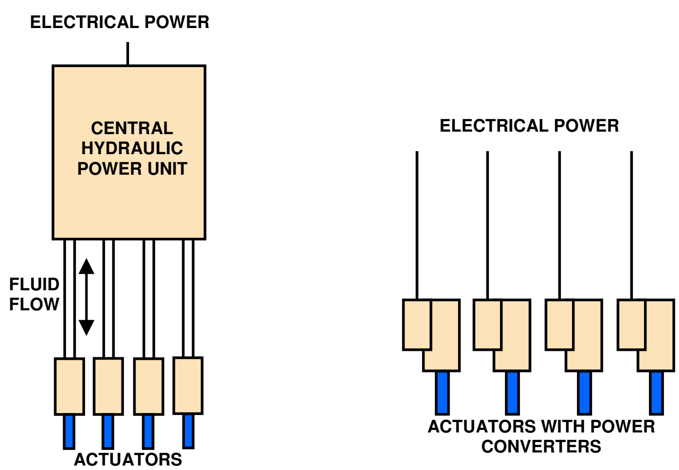

Figure 1. Traditional hydraulic actuation architecture requiring distributed high pressure fluid lines (left) vs. electrohydrostatic (EHA) architecture relying on distributed electrical power and localized pressurization (right)

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This technology is generally intended for the development of smart-material based electrohydrostatic actuators (EHAs). EHAs eliminate centralized hydraulic systems and require only distributed electrical power (Fig. 1). This power-by-wire operation has become more popular in aircraft and other applications because it eliminates distributed hydraulic lines, which are massive, maintenance intensive, cumbersome, and vulnerable to military fire.[9-10] Reduced risks allow higher pressures (up to 5000 psi) to be considered, and overall system reliability is improved by using dissimilar power sources. Conventional EHAs driven by rotary pumps do not scale down effectively to lower power applications, leaving a niche that is well suited for reciprocating smart-material based EHAs. This actuation approach was targeted initially towards conventional flight control surfaces but it applies as well to newer air vehicle concepts.

II. Morphing Wing Actuation for a UAV

DARPA funded research and development under its Compact Hybrid Actautor Program (CHAP) including some of the work described here. Separately, DARPA, the Air Force, and others have been developing morphing aircraft structures as part of a larger effort.[11-13]

Under a smaller program bridging these research thrusts, two concepts for flight testing of actuation were identified. One concentrated on exploration of turbulence and energy harvesting, and the other, referenced here, focused on a morphing wing. The morphing wing test program evolved over time, and several test aircraft were considered, before a final aircraft was identified.

The unmanned air vehicle (UAV), shown in Fig. 2, was custom built by AeroTelemetry for NextGen Aeronautics to allow for thirty minute flight tests. It has a gross take-off weight of 273 lbs. and is 14 ft. long with ample space available within a 14 in. × 12 in. rectangular cross-section fuselage. The UAV was designed to be flown with a morphing wing capable of span changes from 9 ft. to 16 ft. and aspect ratio changes from 3.5 to 7. The morphing wing is comprised of a scissors-like Bennett linkage structure covered with an elastomeric skin. The leading and trailing edges consist of telescoping sections to accommodate the span changes.

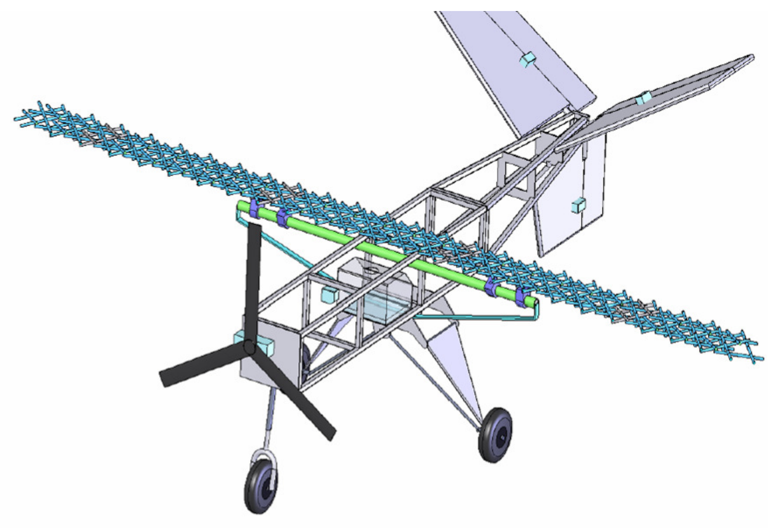


Figure 2. Concept for UAV with morphing wing structure

A. Morphing Wing Actuation

Despite the advantages of EHAs and power-by-wire operation described above, distributed actuation is not utilized for this morphing wing demonstration. With a priority towards gaining flight test heritage, a smart-material based pump serves as a centralized hydraulic power source that distributes power hydraulically to multiple end effectors in the wing. A particular challenge in this architecture was a lack of available volume within the morphing wing structure, a structure that was itself new and untested. The successful design of a morphing wing already posed a serious challenge and making spatial allowances within the wing for EHAs was impractical. While the layout differs from the proposed implementation of this smart material technology as an EHA, the critical stages of a smart-material based EHA are the utilization of the smart material as the pressurization system driver and the effective rectification of the resulting oscillating fluid power. These elements can readily be adapted into a distributed EHA implementation using basic mechanical hardware and well-established servo valve technology.

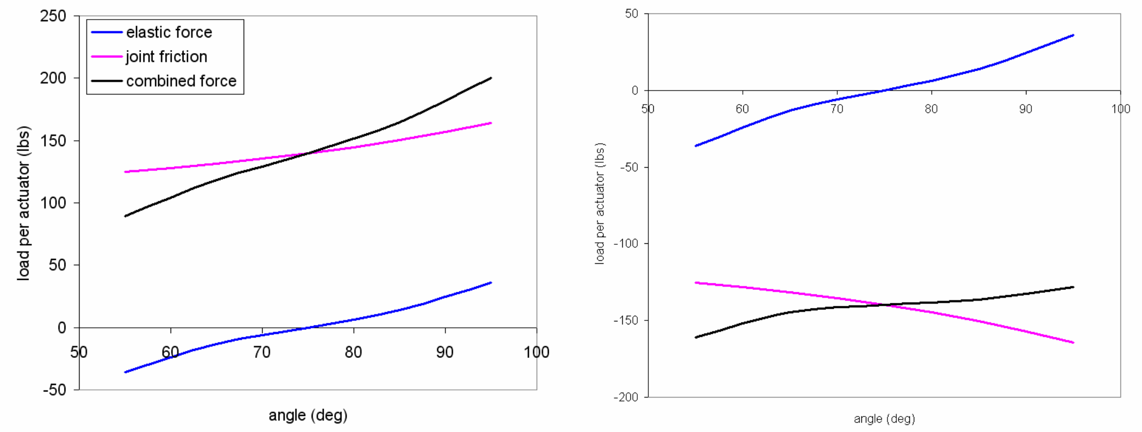


Figure 3. Actuation load profile for morphing wing angle during extension (left) and retraction (right)

Actuation requirements, shown in Fig. 3, were estimated based on testing of a prototype wing segment under simulated aerodynamic loads. The morphing angle refers to the angle formed by the links of the Bennett structure with the smallest angle (55^o) corresponding to the fully retracted condition and the largest angle (95^o) corresponding to the fully extended wing. The skin is applied such that the elastic forces are zero at the mid-extension point of the wing. Friction in the joints of the Bennett linkage accounts for the majority of the total loading.

The output cylinders were sized and selected based on the load testing. Originally, the cylinders were expected to be embedded chord-wise in the wing. However, the joint friction was much higher than anticipated and the size of the cylinders had to be increased to avoid an excessive number of end effectors and hydraulic lines. The larger cylinders are arranged span-wise in the leading and trailing edge volumes of the wing where they have an improved mechanical advantage (Fig. 4).

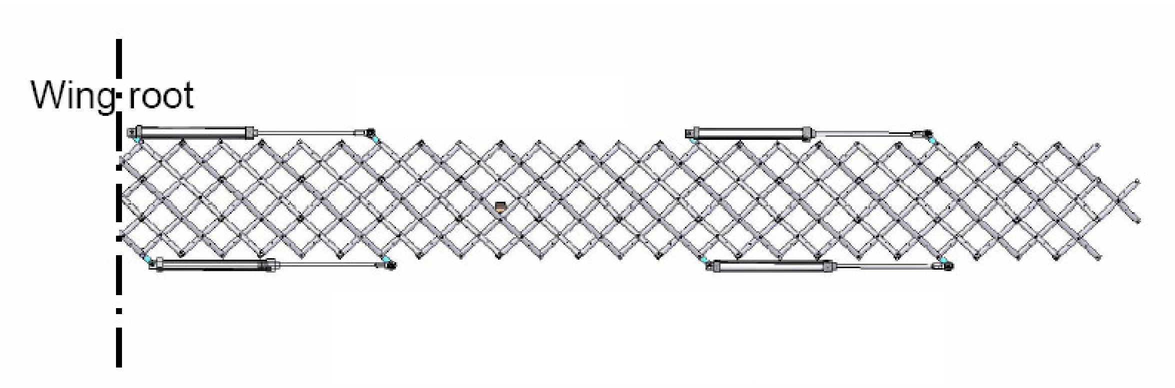


Figure 4. Span-wise actuator placement in the leading and trailing edges of the morphing wing

The final actuation layout employs eight (four on each side of the wing) single-ended, double-acting hydraulic cylinders. Each actuator has an 8.5 in. stroke, 0.75 in. bore, and 0.3125 in. rod. The program set a goal to achieve a complete morph (from full extension to full retraction) in 30 s or less. The total fluid volume needed for a full morph was 30 cubic inches, leading to a flow rate requirement for the pump of 0.26 gpm at pressures up to 1000 psi. The pressure includes a safety factor of two to allow for inaccuracies in the load testing of the wing demo article.

B. Smart-Material Pump Design and Testing

A major decision for the smart-material pump design was whether to use a piezoelectric or magnetostrictive driving element. Successful designs and comparable power outputs have been achieved with both smart materials.[14] Piezoelectric-based pumps have typically produced higher power-to-mass ratios because magnetostrictive materials require a substantial coil to generate the necessary magnetic flux. However, the associated drive electronics for each smart material also had to be taken into consideration. Piezoelectric materials require a high voltage power supply that was deemed problematic for the proposed UAV experiment. As a result of its simpler drive electronics and because a parallel program was testing piezoelectric EHAs, a magnetostrictive driving element (Terfenol-D) was selected.

The design pressure of 1000 psi was considered the primary goal while developing the magnetostrictive pump. If the pump could not achieve the necessary pressure, the wing could not morph completely without modifying the number or size of the output cylinders. Reduced flow rates would only slow the morphing speed. In order to meet or exceed the pressure specification, a large amount of design effort was focused on reducing unnecessary pump compression chamber volume. A larger diameter magnetostrictive rod was used to increase the blocked force capability of the driving element, and the pump infrastructure was stiffened to reduce any parallel compliance. A smaller piston-to-driver element diameter ratio was also used to increase the pressure capability.

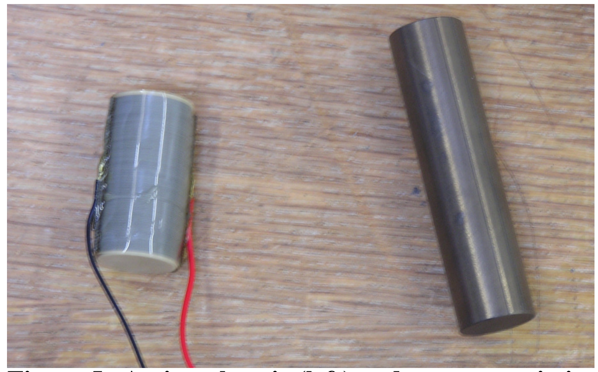


Figure 5. A piezoelectric (left) and magnetostrictive (right) driver element

The coil that drives flux through the magnetostrictive was designed in conjunction with the drive amplifier and DC power supply. Magnetic circuit analysis of the pump revealed the magnetomotive force (amp-turns) necessary to generate the required magnetic field. A coil with a larger number of turns reduces the current that must be supplied by the batteries (a requirement for test flights) and drive amplifier, but it is more massive and has higher inductance. The larger inductance necessitates a higher battery bus voltage to generate a given waveform at a specified frequency. Smaller coils can dissipate less heat, which reduces the allowable duty cycle of the pump. Each of these factors must be considered to select an appropriate balance of components. The final design included a coil with 400 turns, a switching amplifier with a maximum current output of 45 amps, and a battery bus voltage of 165 Volts.

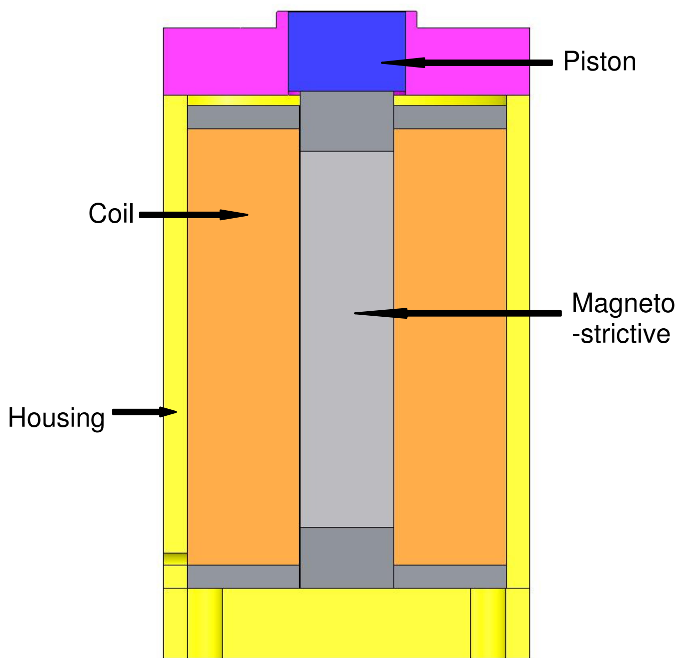


Figure 6. Magnetostrictive pump cross-section

The magnitude of strain in a magnetostrictive material such as Terfenol-D is not affected by the direction of the magnetic field passing through it, as shown in Fig. 7. A magnetic field bias is required to obtain maximum stroke. This can be achieved with permanent magnets or with a DC current. Magnets do not consume power or generate heat, but a DC current allows for more control over the bias field. Magnets also contribute significant mass which more than offsets their savings in battery weight for the relatively short test flights. The DC current was selected primarily for the mass reduction.

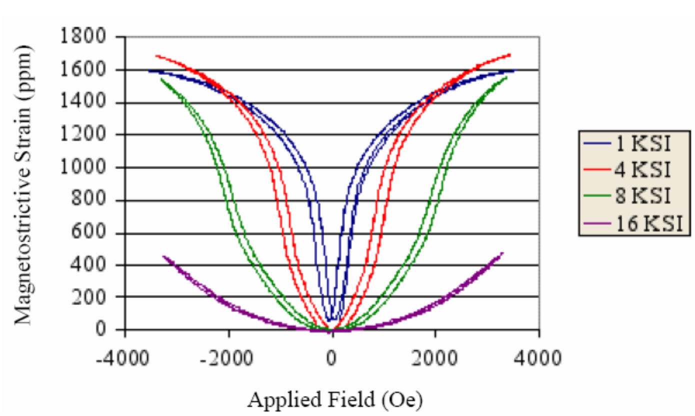


Figure 7. Magnetostrictive strain vs. magnetic field (Data provided by Etrema Products)

Following the mechanical and electrical design, the magnetostrictive pump was fabricated and tested. Many variables could be adjusted to achieve optimal pump performance including preload (bias pressure), DC bias current, drive waveform, drive frequency, compression chamber height, and reed valve stiffness. These variables were studied in laboratory tests.

In addition to the bias magnetic field, magnetostrictive materials require a mechanical preload to operate properly. The preload maintains constant contact between the piston, magnetostrictive material, and the pump base and prevents the materials from undergoing tension where they are prone to damage or failure. As seen in Fig. 7, the preload also impacts the strain of the magnetostrictive materials. A preload is typically applied by incorporating a bias pressure into the hydraulic system. The bias pressure provides two other advantages: it prevents cavitation within the pump and increases the bulk modulus of the hydraulic fluid by reducing the effects of entrained air. The optimal bias pressure can be estimated by weighing its various effects, but is most readily determined through testing. A relatively high bias pressure of 1000 psi was preferred in this case.

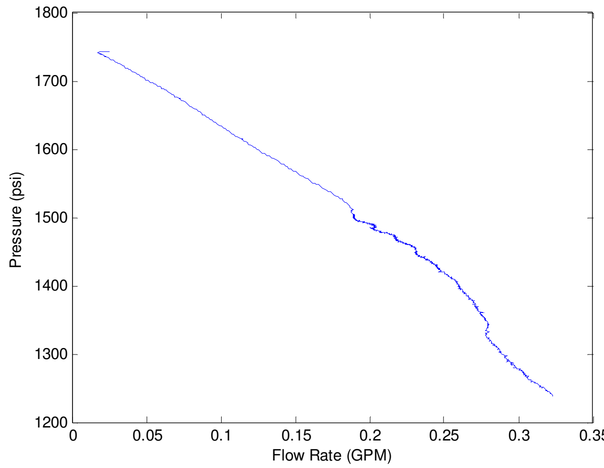


Figure 8. Measured differential pressure vs. flow rate for magnetostrictive pump. Maximum power is approximately 180 W.

Different drive waveforms were tested to determine their effect on performance. Not surprisingly, square waves showed the highest power outputs, but not necessarily the highest efficiencies. Sine waves produced power outputs that were approximately 10% lower than square waves. Triangle waves performed roughly 10-20% worse in terms of power output compared with sine waves.

Drive frequency is an important parameter with smart-material based pressurization systems. Theoretically, higher drive frequencies will increase flow rates and, in turn, power outputs. The optimal drive frequency for this relatively large magnetostrictive pump was 200 Hz. This frequency is lower than desired for maximizing fluid power output per unit mass and is constrained by a combination of check valve bandwidth and drive electronics limitations.

The size of the compression chamber is typically reduced as much as possible to increase the maximum pressure that the pump can generate. However, reed-type check valves cover the intake ports and open into the compression chamber. An exceedingly small compression chamber height restricts the opening of the reed valves and reduces flow rates. In this case a 0.009 in. compression chamber height allowed for maximum performance.

Reed valve stiffness is another important performance parameter for the pump. If the reeds are too stiff, they restrict flow by failing to open sufficiently. Valves with low stiffness are prone to "valve float" or fatigue failure. A thickness of 0.007 in. provided the optimal valve stiffness.

Pump performance testing was carried out on the test bench shown in Fig. 9. The pump drives a hydraulic cylinder against a varying load. High and low side pressure transducers and a LVDT were used to assess the differential pressure, flow rate, and power output of the magnetostrictive pump. Differential pressures up to 1800 psi were measured, and the pressure vs. flow rate curve, shown in Fig. 8, demonstrates that sufficient flow rates (> 0.26 gpm) can be produced at the maximum differential pressure of 1000 psi to complete a morph under the 30 s time limit. The pump can produce peak power outputs around 180W and exceeds all design goals for the morphing wing application.

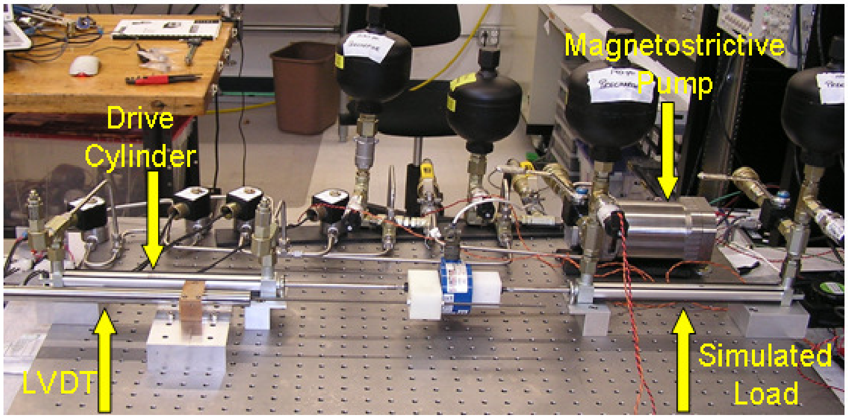
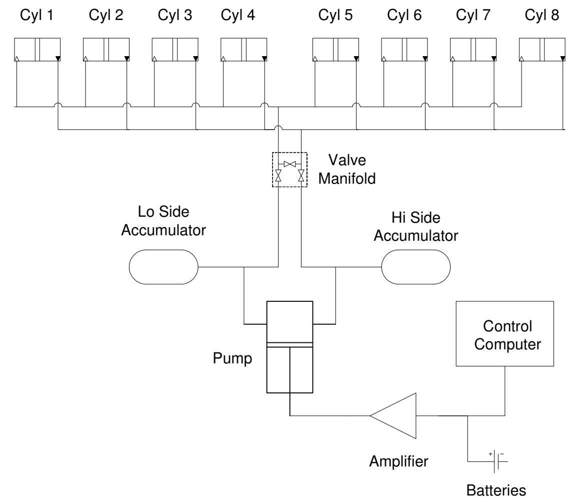


Figure 9. Pump performance test bench with an adjustable varying load

C. Hydraulic System Architecture

In addition to the smart-material based pump, a complete hydraulic distribution circuit is required for the flight test. The hydraulic circuit must include a small low-pressure side accumulator to maintain the system bias pressure. The bias pressure is applied with an external pump prior to operation of the magnetostrictive pump. The accumulator has the added benefit of damping out pressure pulsations. A high-pressure side accumulator can also be used in the circuit to store pressurized fluid between wing morphing events. This would allow for a very rapid morph, but it would require relatively large and massive high and low-side accumulators to accommodate the necessary fluid volume. Because the pump can keep up with the flow requirements without the assistance of a high-side accumulator, it is not necessary to meet the program goals. However, both configurations have been included in the testing plans to show versatility of the technology. High speed actuation capability will be demonstrated with a more massive system, and successful morphing is expected with a 20% lighter system. The two configurations can be interchanged in a matter of minutes.



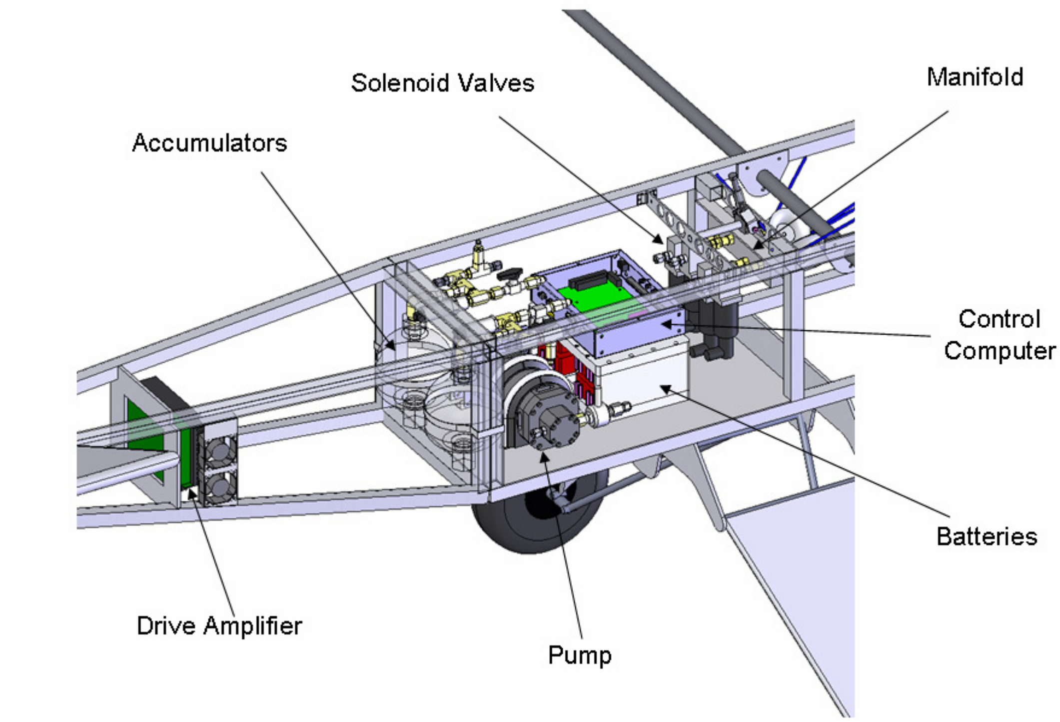


Figure 10. UAV morphing wing hydraulic and control system layout (bottom) and block diagram (top right)

Directional control valves are needed to route the pressurized fluid to and from either the extension or retraction side of the double-acting cylinders. Because the morphing wing structure is designed to act as a one degree-of-freedom system, individual directional control valves are not required for each cylinder. A single set of directional control valves is placed on one side of a manifold which distributes fluid to the eight end-effectors. Precision positioning of the morphing wing is not required for this application, permitting leak-free solenoid valves to be used in lieu of servo valves.

D. Control System Architecture

The control system needed to coordinate the directional control valve operation and supply the appropriate commands to the magnetostrictive pump is relatively simple. Fail safety items add other requirements. The system has multiple elements but response times are moderate. A small control chassis (9 × 7 × 2 in.) is located within the fuselage to house a control computer and route electrical power to the pump, solenoid valves, sensors, and cooling fans for the pump and drive amplifier. The control computer also performs data acquisition of wing position, high and low-side pressure, flow rate, temperatures (pump, battery, and ambient), battery voltages, and drive current and voltage. System shutdown faults are included in the control code for over-temperature of the pump or batteries, under-voltage of the high or low voltage bus, and under-pressurization caused by a fluid leak. System shutdown includes cutting power to the pump and closing all directional control valves to lock the wing into its current position.

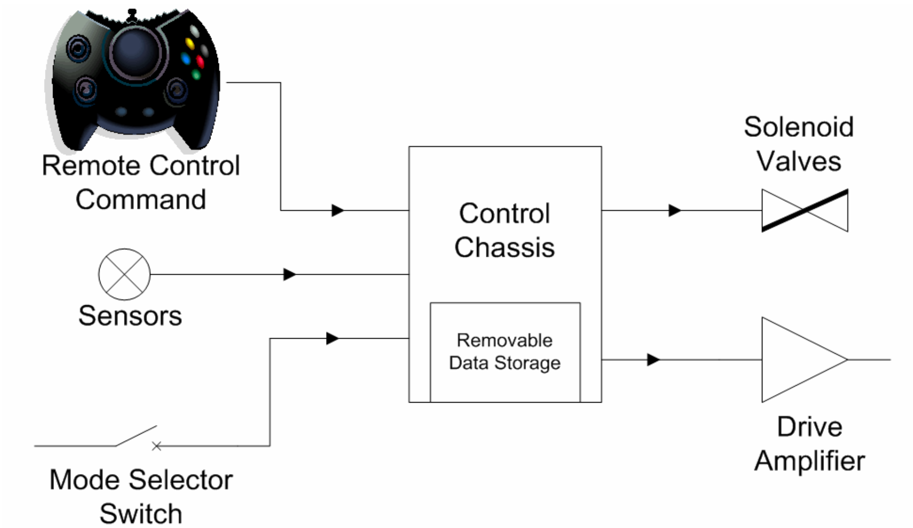


Figure 11. Block diagram of control chassis functionality

The morphing wing actuation is commanded from a remote control transmitter using a single servo control knob. The remainder of the UAV operation is also controlled from the same remote transmitter. The morphing wing control system is currently run open loop, but closed loop control over wing position could be readily added if it is desired.

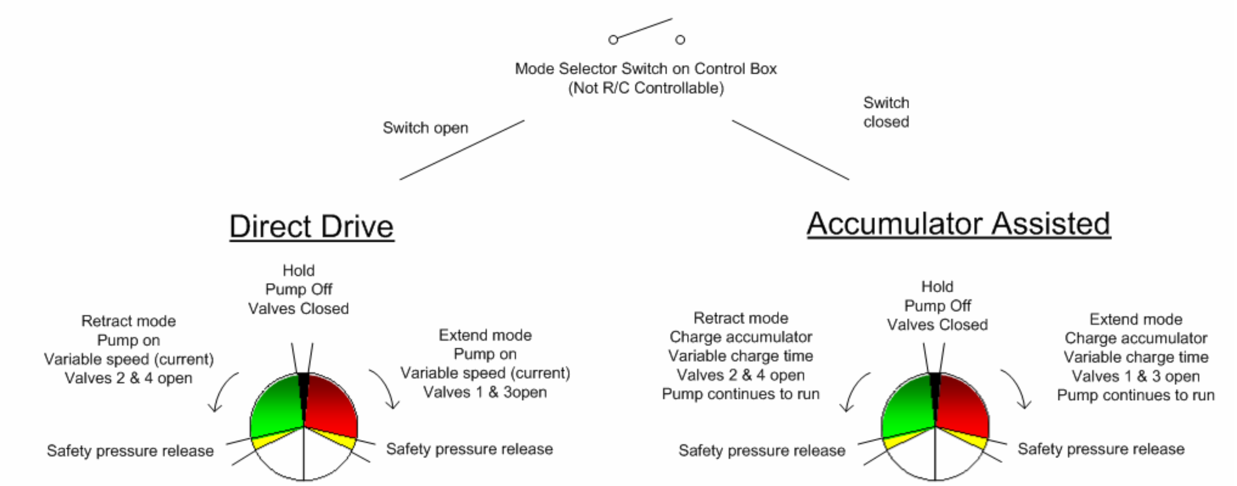


Figure 12. Servo control knob schematic for the direct pump drive configuration (left) and the accumulator assisted configuration (right)

The single servo control knob allows the pilot to control the morphing wing actuation in either the direct drive or accumulator assisted configuration. A mode selector switch located on the control unit toggles between the two configuration modes. In either mode the neutral knob position corresponds to a hold command with the pump turned off and all solenoid valves closed, and the extreme clockwise and counterclockwise positions cause a safety pressure release that shuts down the pump and opens all valves. While in direct drive mode, a clockwise rotation turns on the pump and opens the appropriate valves to allow a wing extension. Larger knob rotations increase the current input to the pump and result in faster morphing speeds. A counterclockwise rotation works similarly, but produces a wing retraction. In the accumulator assist mode, clockwise and counterclockwise rotations again correspond to wing extension and retraction, respectively, but the pump and valve operation differs. A larger knob rotation creates a longer time period for the pump to charge the high-pressure side accumulator. When the charging period expires, the appropriate valves are opened to allow the desired wing movement. The valves remain open and the pump continues to run until the knob is returned to the hold position. A two second delay is included in the control system to allow the knob to be positioned as desired before the command is registered, but a safety release can be initiated immediately if the morphing structure appears to bind or other problems are witnessed.

E. Laboratory Testing

Prior to integration into the morphing wing UAV, the hydraulic and control system needed to be assembled, combined, and tested to confirm performance. Six small hydraulic cylinders were set up to drive separate spring loads in both extension and retraction to roughly mimic the loading of the morphing wing (Fig. 13).

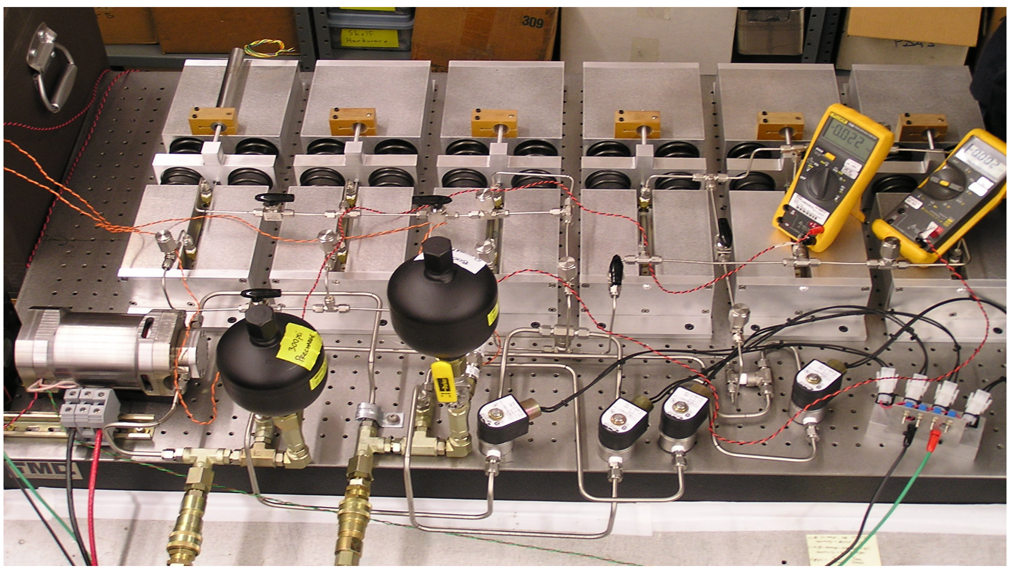


Figure 13. Laboratory test set-up that mimics the morphing wing actuation with multiple end-effectors driving spring loads

Both the direct pump drive and accumulator assisted configuration modes were verified with the test set-up, and a few improvements were identified for the final UAV integration. The actuation speed was slower than expected in the accumulator assisted configuration. This was traced to large flow restrictions through the solenoid valves, and as a result, less restrictive valves were obtained for the final assembly. The switching drive amplifier emitted a large amount of electromagnetic interference that created large noise levels on several sensor signals. Several strategies were implemented to address this problem in the UAV assembly including increasing the switching frequency, using shielded cables, reducing sensor lead wire lengths, and locating the amplifier in the tail section of the fuselage as shown in Fig. 10.

F. Reliability Considerations

Reliability is a major concern with all flight systems. There are three components within the magnetostrictive pump that have a reasonable likelihood of experiencing failures: the reed valves, the coil, and the magnetostrictive core. Because the reed valves experience minimal displacements (0.005 in. to 0.015 in.), fatigue failure is a reduced concern. In fact for the many tens of millions of cycles that various pumps have been tested, no reed valve failures have occurred and wear or damage has only been observable in extreme situations. With the coil, potential shorts or open circuits are possible, particularly when subjected to vibrations created by an aircraft or the pump itself. The coil is bound in place with epoxy which helps to alleviate these concerns. Overheating of the coil is a serious risk when operating at high frequencies or high duty cycles. An over-temperature shutdown is planned for the flight system. The magnetostrictive material appears to be the component most prone to failure. It is a brittle material that may crack if the pump is run with a low or nonexistent system preload. Misalignment of the magnetostrictive element can lead to chipping or flaking near the edges of the material. Close machining tolerances and proper assembly procedures help alleviate this problem. Hysteresis losses can also lead to overheating of the magnetostrictive material. In typical pump designs, the coil reaches its temperature limit before the magnetostrictive core, but additional temperature monitoring of the Terfenol-D element may be needed.

Although smart material pumps are conceptually reliable due to a small number of moving parts, redundancy can improve flight system designs. The current morphing wing system uses only a single pump to reduce weight, but a dual pump may be required for future flight qualified systems. The pumps can be placed in series or parallel to theoretically double the maximum output pressure and flow rate, respectively. Both architectures were tested using two identical magnetostrictive pumps in preparation for future flight opportunities.

When connected in series, the pumps produced a maximum total pressure of 3150 psi and flow rates equivalent to a single pump. The first pump in the series created a maximum differential pressure of 1800 psi as expected from individual pump test results. However, the differential pressure output of the second pump was reduced to approximately 1350 psi. The diminished performance can be explained by the relatively larger effect of stray compliance and the excessive preload applied to the magnetostrictive driver of the second pump. This pump experiences an effective bias pressure of 2800 psi compared to the ideal bias pressure of 1000 psi applied to the first pump. The performance curves of the magnetostrictive material (Fig. 7) show that the strain is reduced by excessive preloads. This could be rectified by modifying the piston to smart material diameter ratio of the second pump. The relative phasing between the two pumps' operation also had a small impact (up to 5%) on performance with 180 degrees being preferred.

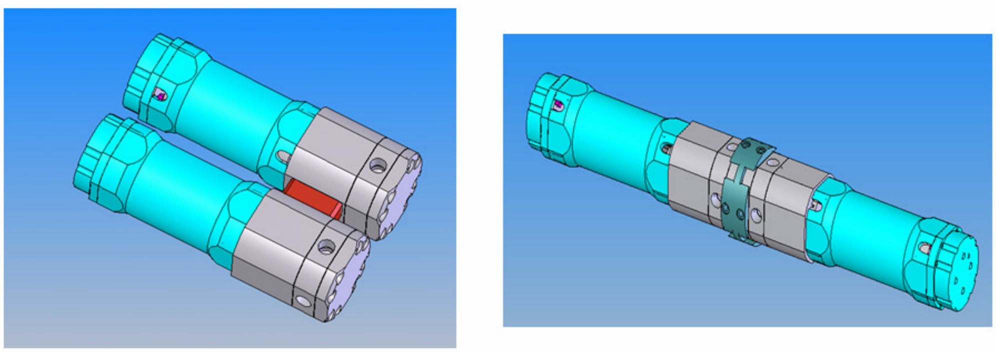


Figure 14. Possible dual pump configurations can be operated in series or parallel

With the pumps operating in parallel, the total flow rate increased by approximately 100% at a given pressure, and the maximum differential pressure was comparable to a single unit. In this case the pumps were not subjected to different preloads, and the expected performance was achieved. The relative phasing between the pumps again had a small impact with 120 degrees being preferred.

Dual pumps could be positioned in either a side-by-side or inline arrangement to elicit vibration cancellation. Available space permitting, the inline arrangement would be preferred as it would not induce a moment. Testing has been performed with the two pumps in the inline arrangement, but the open loop vibration cancellation has been minimal. The ineffectiveness has been attributed to the nonlinear behavior of the magnetostrictive materials, but further investigation is necessary.

III. Morphing Wing Demonstration Program Status

Wind tunnel testing on the morphing wing UAV was planned for November 2006 with flight testing expected to follow early in 2007. Unfortunately, additional funding is needed for the completion of the morphing wing, and the program has been put on hold until supplemental funds can be secured. The wing actuation and control systems are complete and prepared for installation in the UAV. Tests of slower (~30 s) morphing and faster (~10 s) morphing using stored hydraulic power are planned.

A separate program is now underway that will culminate in a smart-material pressurization system flying on a smaller UAV platform. The existing servos which provide actuation for the UAV control surfaces will be replaced by a smart-material based actuation system. Flight testing is scheduled for late 2008.

IV. Conclusion

A magnetostrictive-based pump was designed and developed to provide hydraulic power for morphing wing actuation on a custom-built UAV. The pump performance was optimized by adjusting parameters such as preload on the magnetostrictive, bias magnetic field, drive waveform, drive frequency, compression chamber height, and valve stiffness. Test results showed that the pump can provide more than adequate flow rates to achieve a complete wing morph from a 9 ft. retracted wing span to a 16 ft. extended wing span within 30 s with the expected loading during flight.

Complete hydraulic and control systems were also designed and tested. While the actuation layout, due to volume constraints, uses a centralized hydraulic power source with distributed hydraulic lines providing fluid power to eight separate end-effectors, the smart-material based pressurization system could readily be adapted to allow power-by-wire operation. The hydraulic system includes two configurations that provide for both high speed actuation with a heavier system and moderate speed actuation with a lighter system. In either configuration, the control system allows for data recording and simple remote control operation of the wing from a single remote unit.

Future work must focus on demonstrating the lightweight and reliable actuation capabilities of smart-material based pressurization systems. Distributed actuation experiments with EHAs should be performed and the benefits and potential of dual pump arrangements need continued study. Results to date show peak power output increased from 180 W to 300W. Other applications outside of flight control surface and UAV subsystem actuation should be explored as well.

Acknowledgments

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