Project 16MA1: Efficient, Integrated, Freeform Flexible Hydraulic Actuators

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Outline of Project

• Research Motivation
• Research Targets
• Improved modeling for hydraulic artificial muscles.
• Model Validation of hydraulic artificial muscles.
• Control design and experiments.
• Current work: Application of hydraulic artificial muscles in additively manufactured systems.
Research Motivation

• Decrease the overall energy consumption in fluid power industry.
  – 2-3 Quads consumed by fluid power in U.S.
    • 1 Quad = 1 Quadrillion BTUs.
  – Total energy consumption in U.S. is 100 Quads per year.
  – 310-380 MMT CO$_2$ produced by fluid power in U.S.
  – Fluid power is 2-3% of U.S. energy demands.
  – System efficiencies ranging from 9% to 60%.

• Reducing energy consumption in fluid power is critical to CCEFP’s strategic plan.
Research Targets

• Increase specific power of hydraulic actuators.
• Utilize AM technologies to reduce energy consumption in hydraulic machinery.
• Reduce energy consumption by optimal control.

Applications:

(Hydraulic Hand Tool)

(Robot Arm/Leg)

Increasing the Specific Power of Hydraulic Actuators

• HAM = Hydraulic artificial muscle
  – Powered by hydraulics.
  – Contracts when pressurized; acts like a human muscle.
  – Highest power-to-weight ratio in class of flexible actuators.
Background

• HAMs are a type of flexible fluidic actuator
Flexible Fluidic Actuators

Flexible fluidic actuators transmit mechanical power through large deformations of elastic or hyperelastic membranes by an energized fluid.

- **Prolate (contract/pull)**
- **Oblate (expand/push)**
- **Helical (Twist)**
Artificial muscle components

- End Caps
- Helical Fiber Braid
- Hyperelastic Tube
How it works
Background: Modeling

• First modeled by Gaylord using principle of virtual work

\[ F = \frac{P(3L^2 - b^2)}{4\pi n^2} \]

Modeling: Actuator Dynamics

• Nonlinear lumped parameter spring-mass-damper model; Based on Gaylord model

- Hyperelasticity of rubber tube.
- Internal damping.
- Nonlinear kinetic friction.
- Inertia.
- Braid stiffness.
Experimental Setup: HAM

- Inlet End Cap
- Moving End Cap (Free end)
- Braid and Tube
Failures Modes

End Cap Failure

Blow By

Braid Failure
Experimental Setup: Test Stand

- Real-time PC
- Accumulator
- Relief Valve
- 4-3 Proportional Valve
- Tank
- Gear Pump
- Motor
- String Pot
- Pressure Sensor
- HAM
Experimental Setup: Test Stand

1. Motor
2. Pump
3. Accumulator
4. Relief Valve
5. Check Valve
6. Proportional Flow CV
7. Hydraulic artificial muscle
8. Tank

Not shown: Pressure transducers
Experimental Results

• Quasi-static tests:
  – Free contraction - Pressure = 7 MPa ~ 1000 psi
  – Isometric – Pressure 3.5 MPa ~ 500 psi

• Dynamic tests: 3.25 MPa ~ 475 psi
  – Square wave input response @ 0.25

• Control Experiments
  • Sine wave tracking
  • Square-like wave trajectory tracking
Static test – Free Contraction

![Graph showing static test results]

- **Pressure** vs. **Time**
- **Stroke** vs. **Time**
- **Force Generation** vs. **Stroke**

Graphs illustrate the pressure and stroke profiles over time, along with the comparison of experimental and simulated force generation. The graphs highlight the transition zone and the kinematic limit. 

ΔF represents the difference between the experimental and simulated force generation, indicating areas of interest for further investigation.
Static test – Isometric Results

![Static test setup](image)

![Graph showing force vs. pressure](image)

- **Y-axis:** Force [N]
- **X-axis:** Pressure [MPa]

- **Legend:**
  - **Experiment** (diamonds)
  - **Model** (solid line)

The graph illustrates the relationship between force and pressure, with both experiment and model results depicted. The experiment data points align closely with the model line, indicating a strong correlation between the two.
Dynamic Results (0.25 Hz)
Model Based Control

Used model to develop Sliding mode control law

\[ u = u_{eq} + u_{rb} \]

Sine wave tracking (0.25 Hz)
Sine wave tracking (0.25 Hz)

- Outperforms PID control
Trajectory Tracking

Maximum Error < 0.3 mm
Current work: Applications

- Topology optimization using Solidthinking Inspire and ParetoWorks
Current work: Applications

• System integration in hydraulic hand tool
Current work: Applications

- Goal: Reduce weight
  - Integrate hydraulic artificial muscle
  - 3D print components

Redesign, Optimized, and 3D printed
Current work: Applications

• Multiple degree of freedom robot
Current work: Applications

• Multiple degree of freedom robot
  – How much energy can be saved using HAMs and Additive Manufacturing?

Conclusions

• Demonstrated lightweight, flexible hydraulic actuation.
• Developed and validated model.
• Improved control performance using model-based methods, e.g., SMC.
• Working on applications of HAMs and 3D printing technology to quantify benefits.
  – Call for participation.
Acknowledgements

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