Control Schemes for Shock Mitigation Using Adaptive Shock Absorbers

Harinder J. Singh
PhD Candidate

Dr. Wei Hu
Associate Research Scientist

Dr. Norman M. Wereley
Minta Martin Professor and Chair

Department of Aerospace Engineering, University of Maryland, College Park, MD

Seventh Triennial International Fire and Cabin Safety Research Conference, Philadelphia, PA Dec 2-5, 2013

Objective

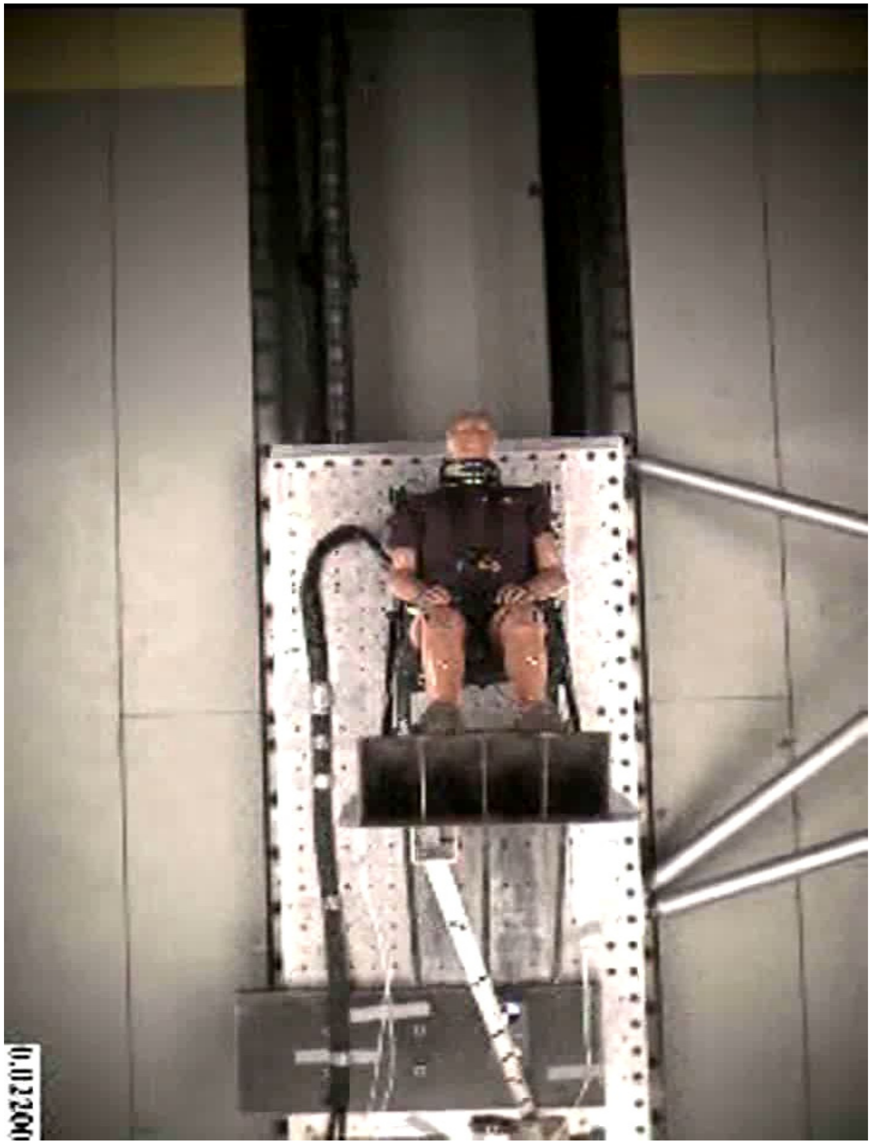
Helicopter hard landing

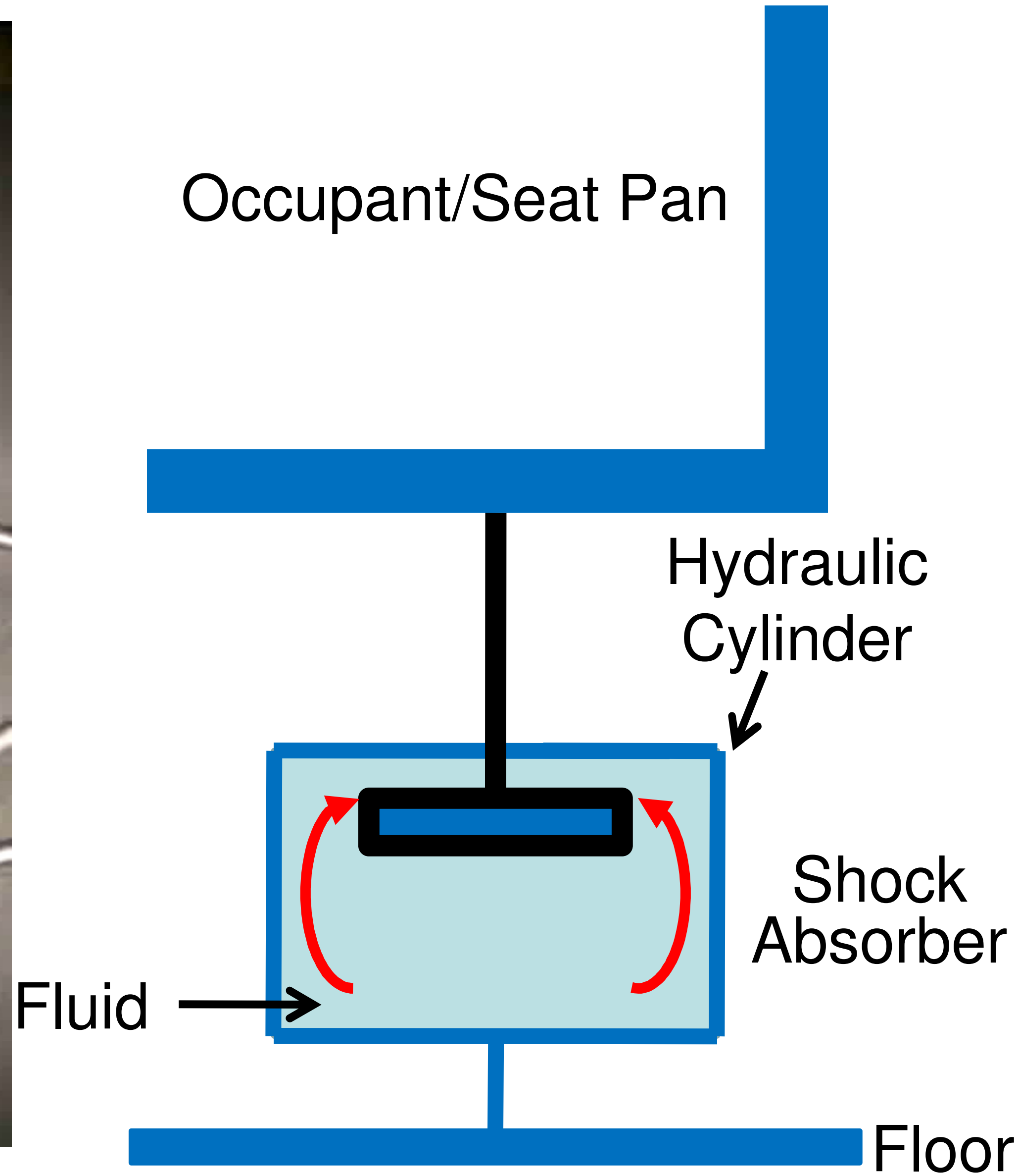
Landmine blast of armored vehicles

Large lumbar load transmissions to the seated occupants exposed to crash/impact events

To develop an adaptive occupant protection seat suspension for minimizing transmitted lumbar loads during shock events

Operation


0.012500


Occupant/Seat Pan
Hydraulic Cylinder
Shock Absorber
Fluid
Floor

Outline

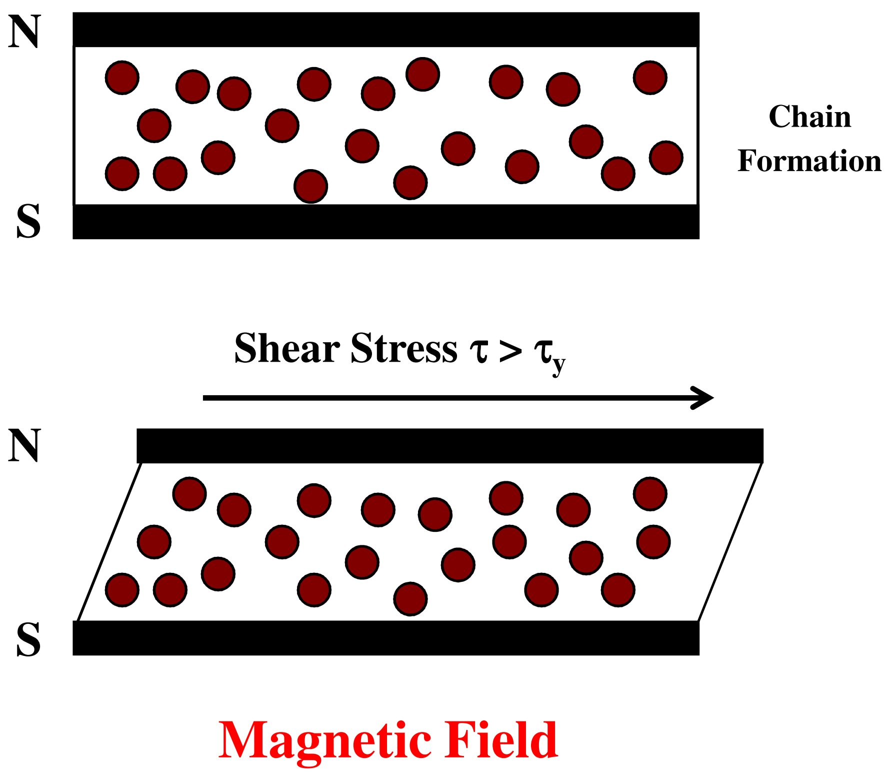
Design and Testing of Magnetorheological Energy Absorber

Control Algorithms

- Constant Stroking Load Control
- Terminal Trajectory Control

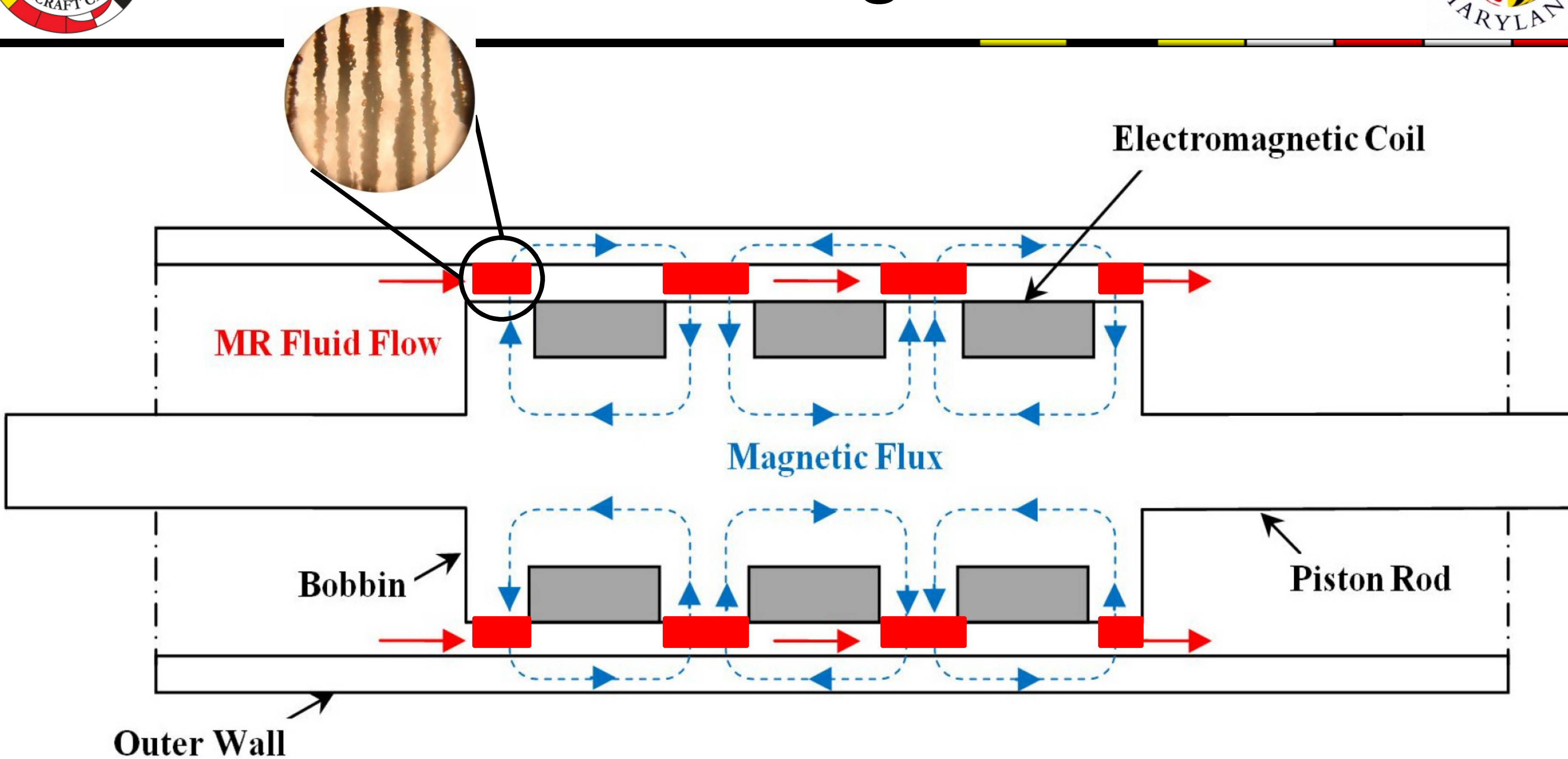
Conclusions

Magnetorheological Fluid



- Magnetic field induces change in viscosity of MR fluid
- Formation of chains of magnetic particles due to magnetic induction
- Yield behavior results at a shear stress leading to breaking of chains

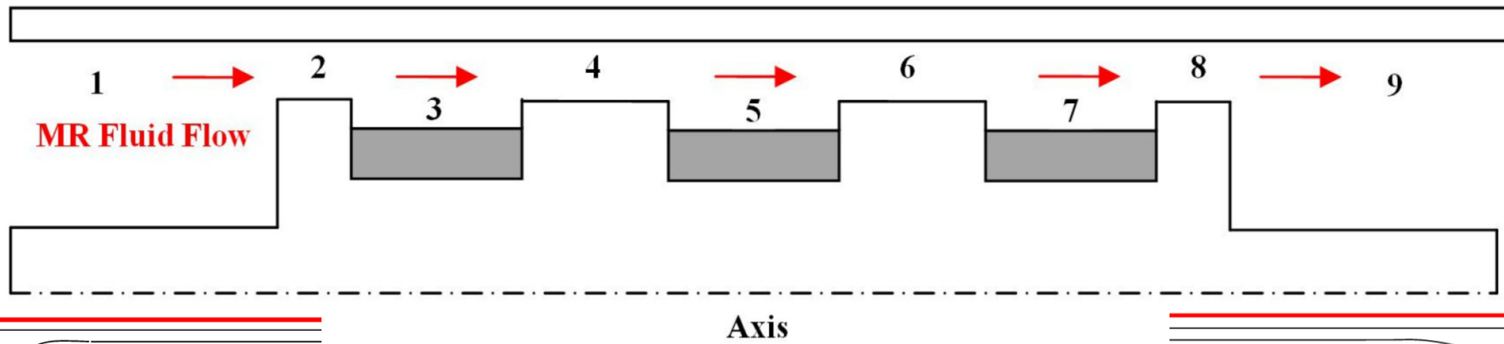
MREA Configuration

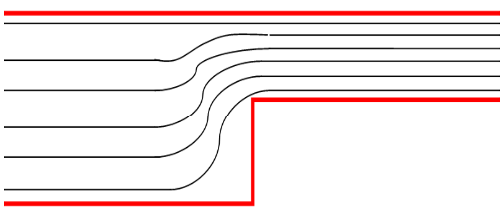


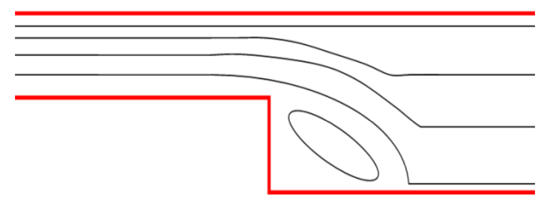
Double-ended MREA with multi-stage electromagnetic coils.

MREA Stroking Load: **Yield force (controllable) & Viscous force (passive)**

MREA Analysis



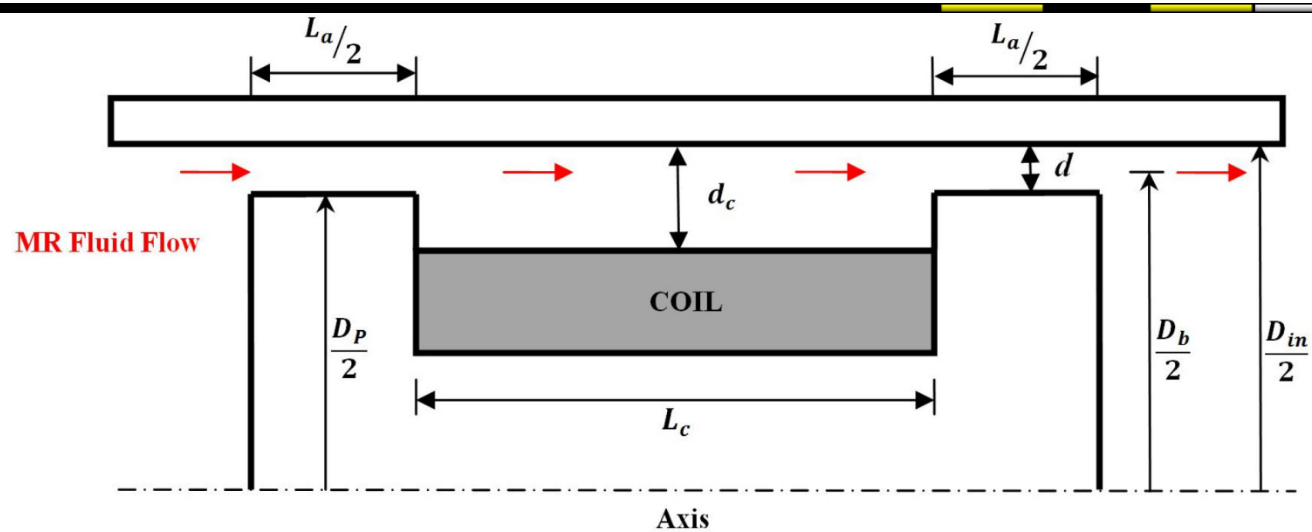




Pressure Drop Regions

- **Entrance effect** from region 1-2.
- **Sudden expansion** from region 2-3, 4-5 and 6-7.
- **Sudden contraction** from region 3-4, 5-6, 7-8.
- **Exit effect** from region 8-9.
- **Viscous Darcy friction losses** in coil gap 3, 5 and 7.
- **Viscous Darcy friction losses** in MR valve 2, 4, 6 and 8.
- **MR effect pressure losses** in MR valve 2, 4, 6 and 8.

Bingham Plastic Model



Geometric fluid circuit for a single-stage electromagnetic coil

MREA Yield force

The pressure drop due to yield stress and the corresponding force is

$$\Delta P_{MR} = \frac{2L_a \tau_{MR}}{d}$$

$$\boxed{F_{MR} = \frac{2nL_a \boxed{\tau_{MR}} A_p}{d}}$$

Bingham Plastic Model

Total Passive (Off-state) Force

$$\boxed{F_V = A_p\left[n\left(\Delta P_\eta + \Delta P_{ml} + \Delta P_{coil}\right) + \Delta P_E\right]}$$

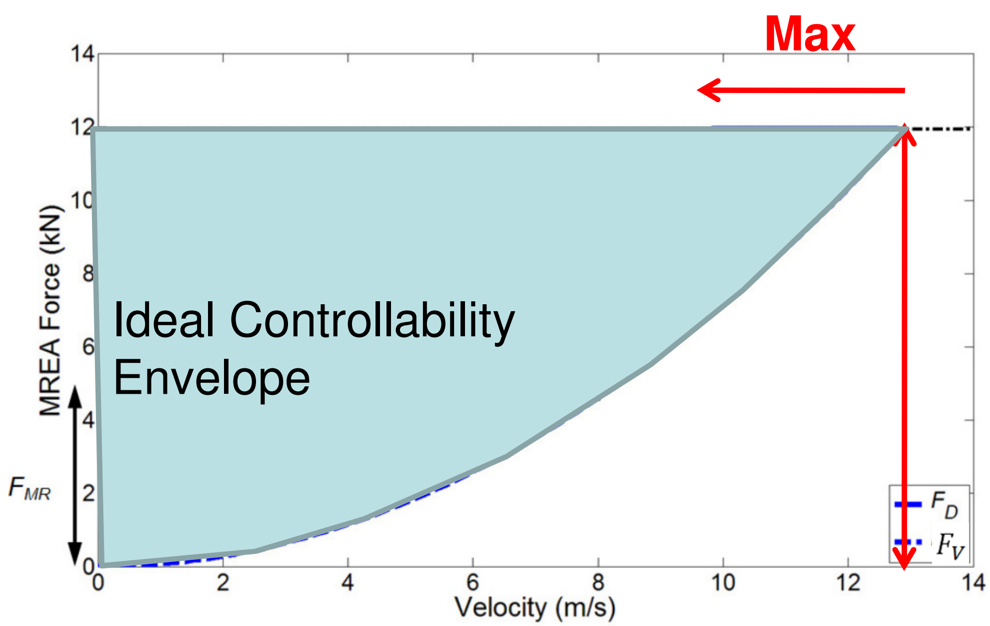
MREA Stroking Load: **Yield force (controllable) + viscous force (passive)**

$$F_D = \left(F_V + F_{MR}\right).sign\left(\dot{z}_0(t) - \dot{z}_{Floor}(t)\right)$$

$$\boxed{F_D = \left(F_{MR} + F_V \right).sign(V_p)}$$

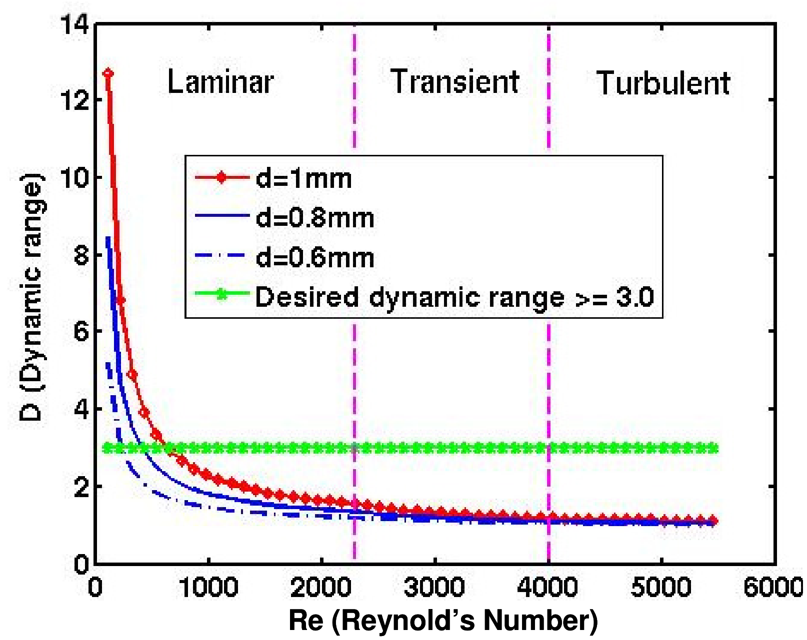
BUT HOW TO SELECT MREA DIMENSIONS ???

Controllability Envelope Optimization



Quadratic variation α V_p^2

Schematic of controllability envelope of MREA

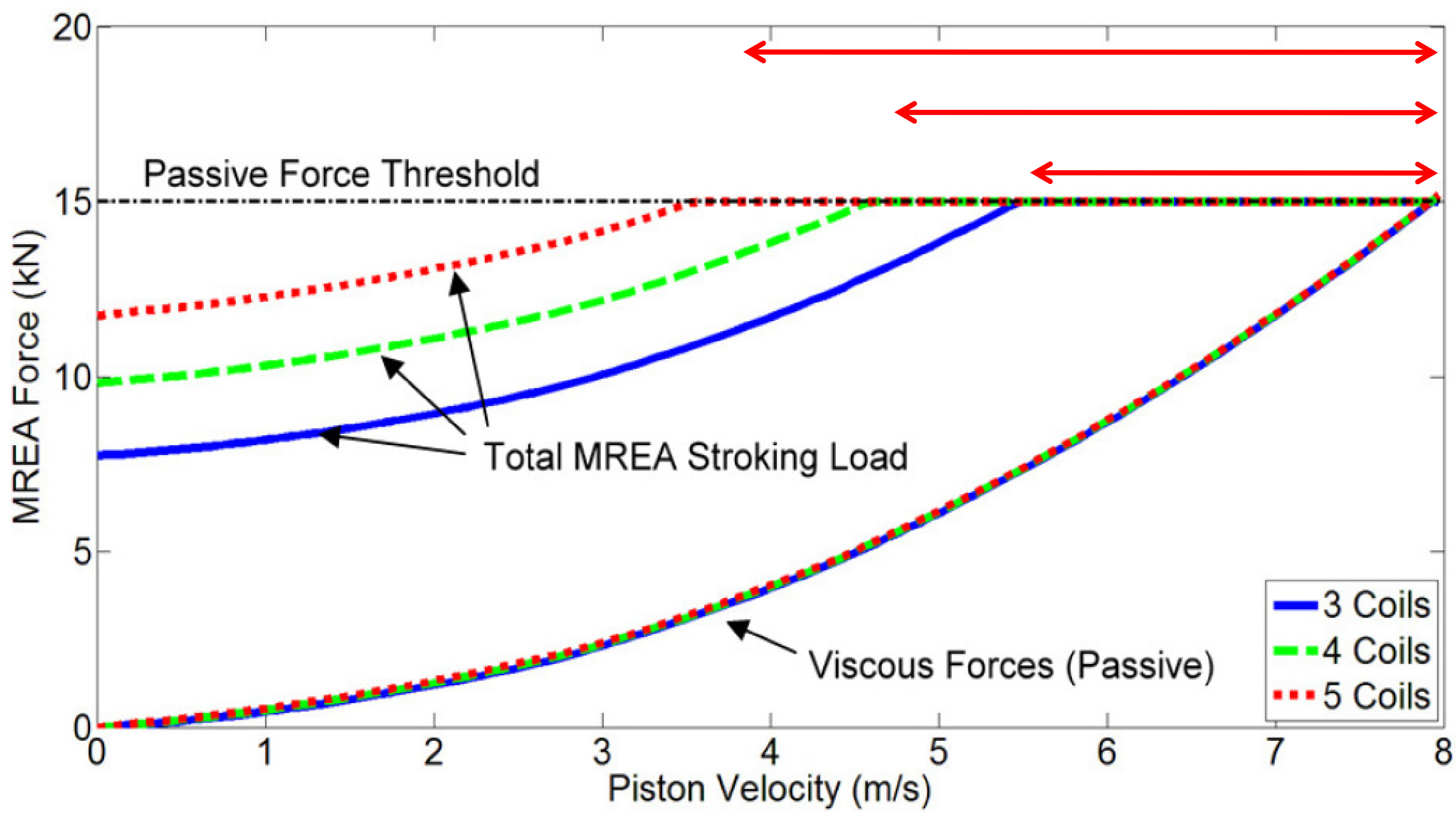


(Mao, Choi, & Wereley, 2005)

$$DR = \frac{F_D}{F_V} = \frac{F_{MR} + F_V}{F_V} = 1 + \frac{F_{MR}}{F_V}$$

DR approaches 1 at higher velocities because of increased off-state forces

Optimized MREA



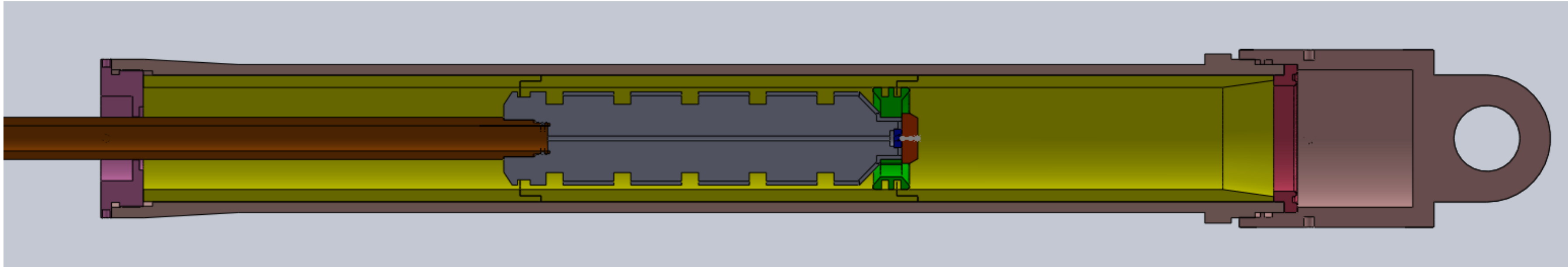
- Increased electromagnetic coils increased MR yield force
- Passive viscous forces remained the same

MREA Design: Practical Issues

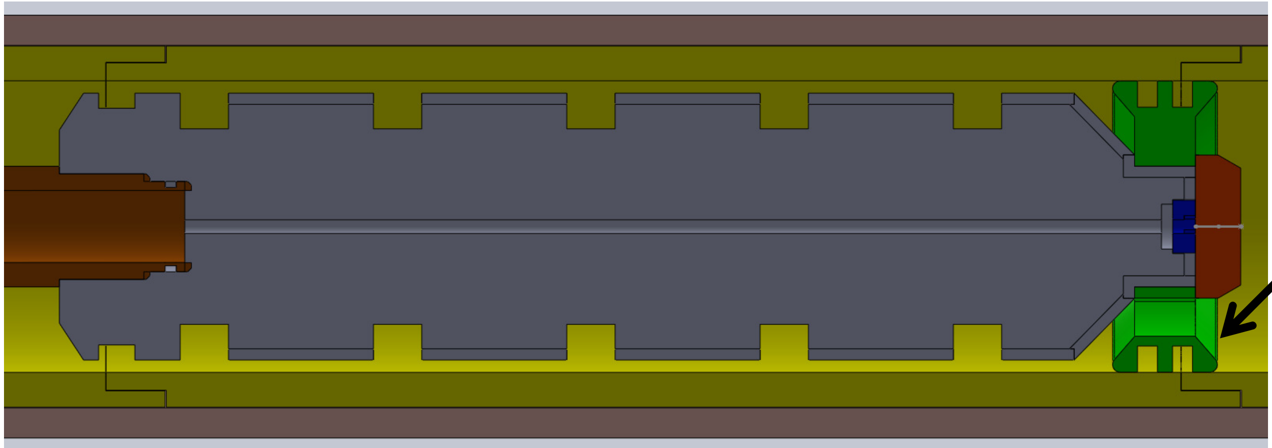
– A piston with 5 coils has a length of 8 inches

– MREA stroke is 16 inches

– The hydraulic cylinder of MREA has approximately 24 inches length



– Imperfect longitudinal loads might cause impact of piston with cylinder

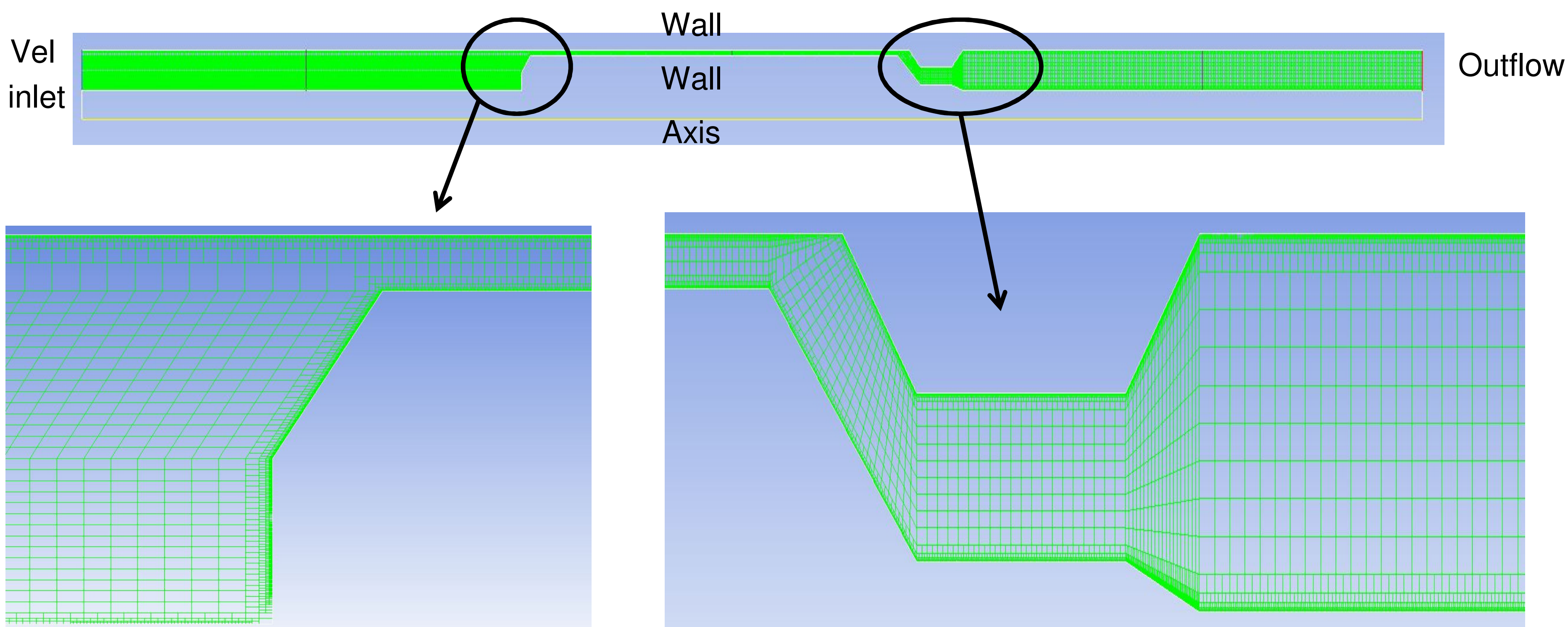


A piston guide was proposed to allow pure longitudinal motion

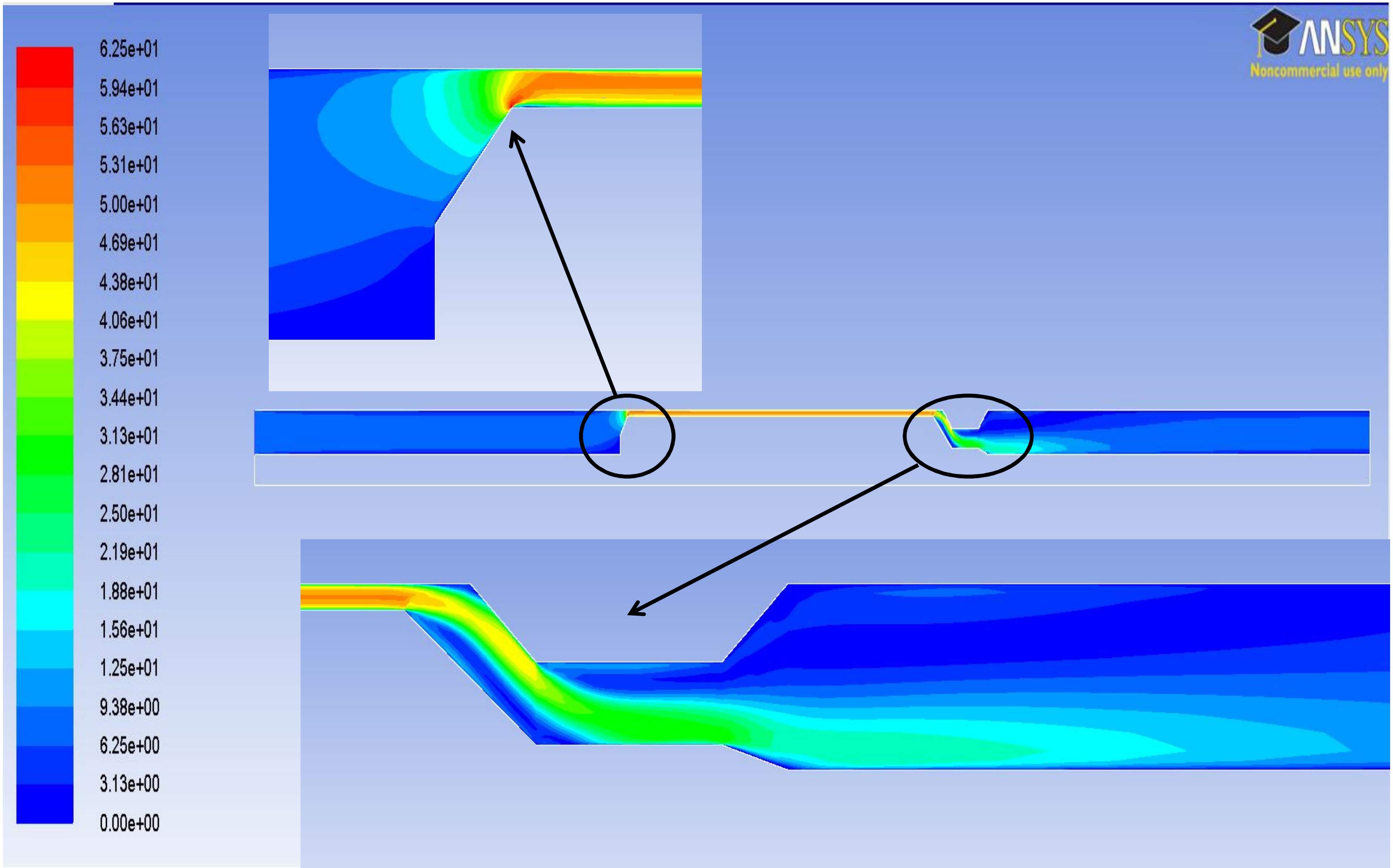
How does that affect the MREA forces??

CFD Analysis

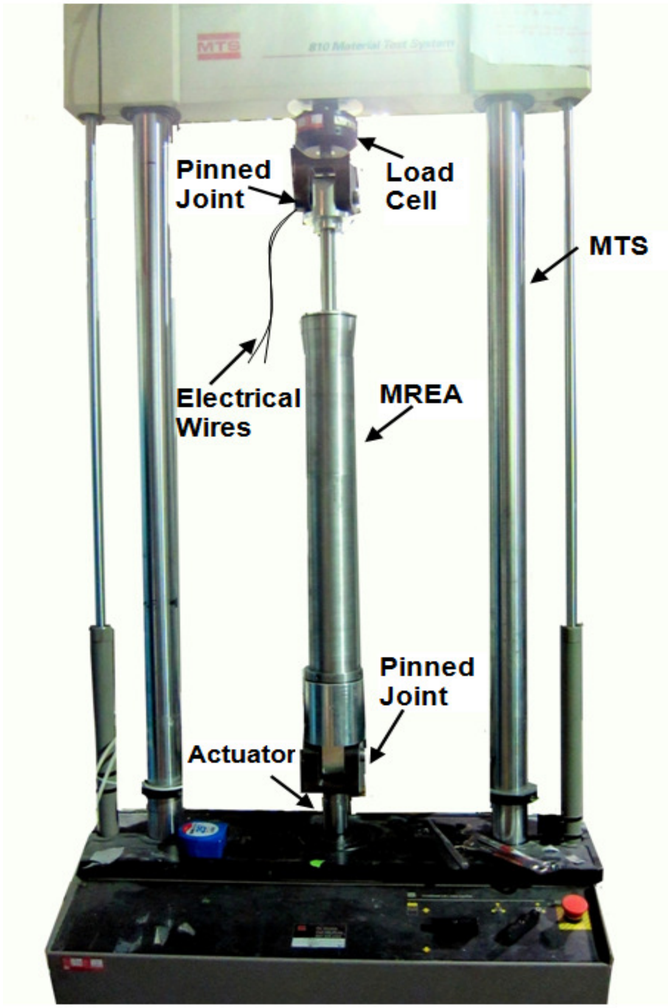
- A 2d CFD analysis was carried out using FLUENT software
- Refined grid near the walls for boundary layer effects
- BC were defined
- The pressure drops were estimated due to fluid motion



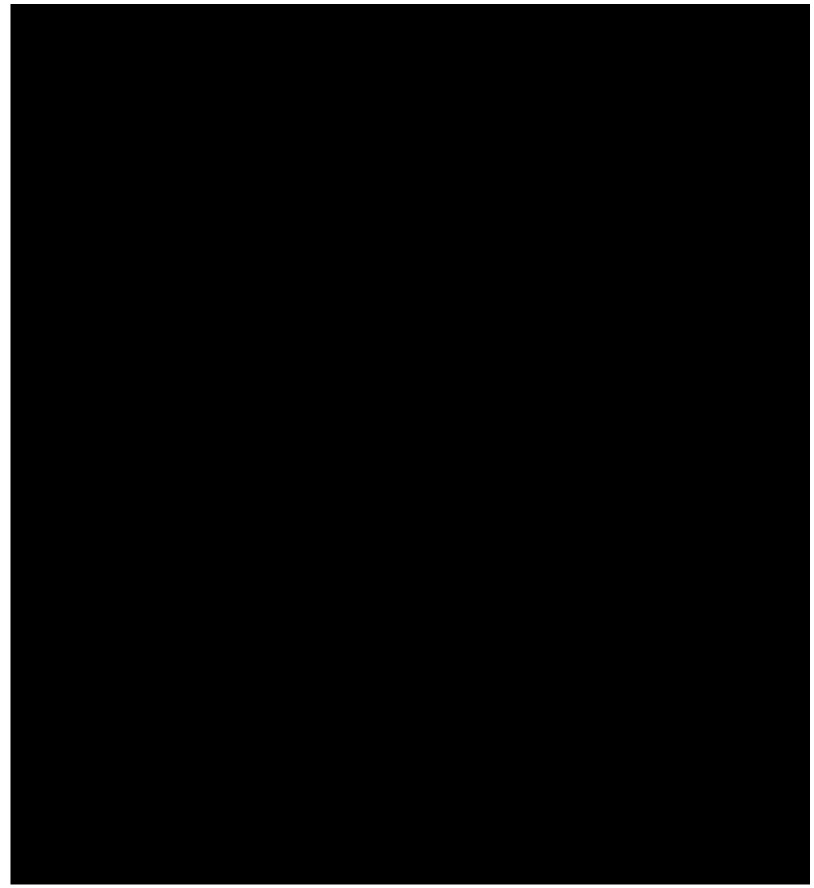
CFD Analysis



MREA Characterization

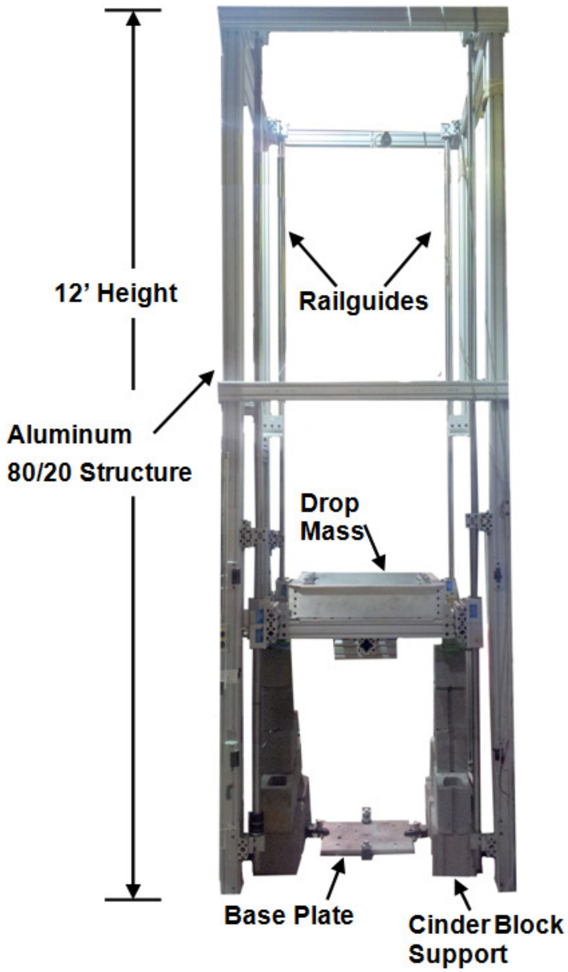


MTS cyclic testing setup

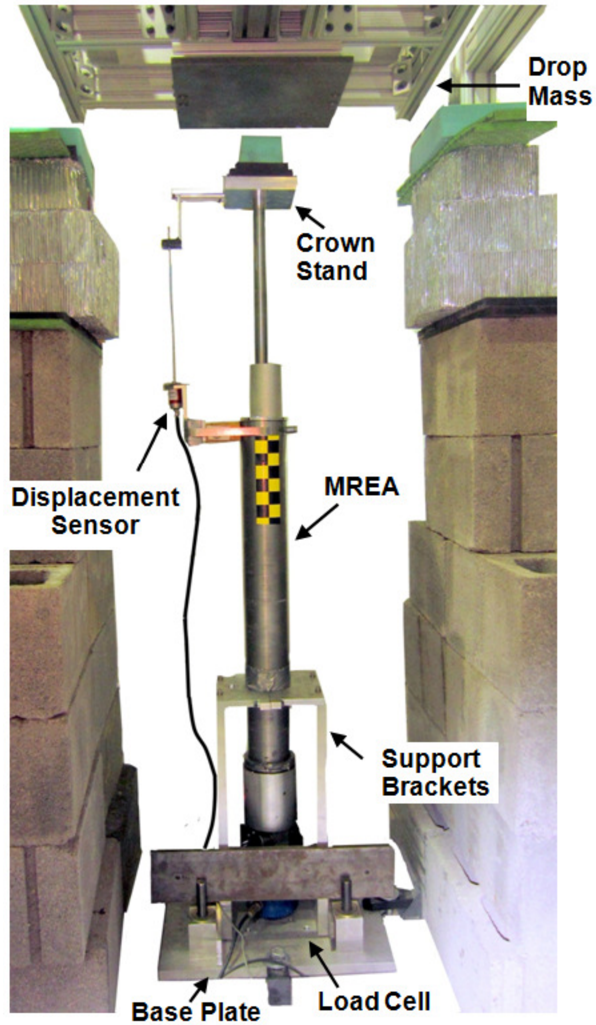


MTS cyclic testing up to 5 ft/s
(0.5-6 Hz; 0-5.5 A)

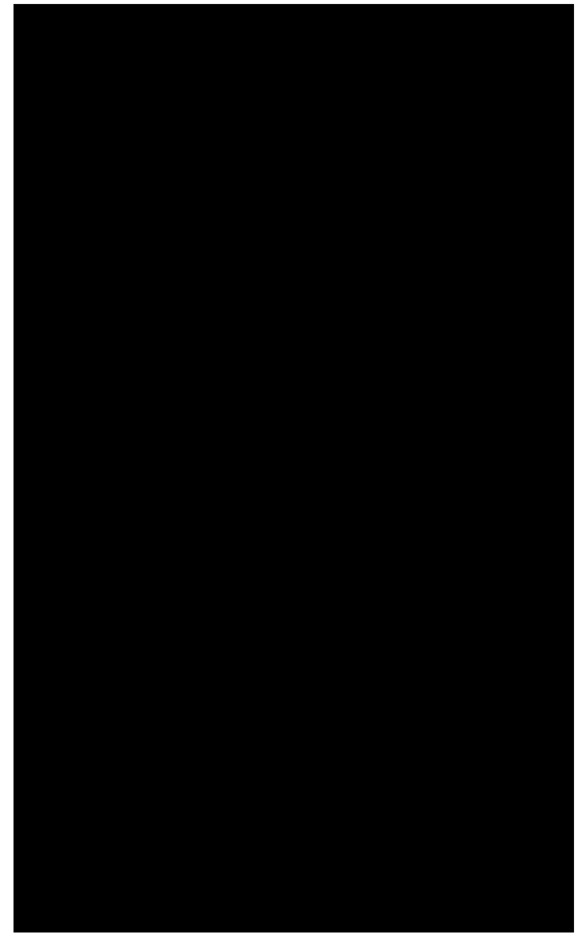
Drop Tests



Drop stand

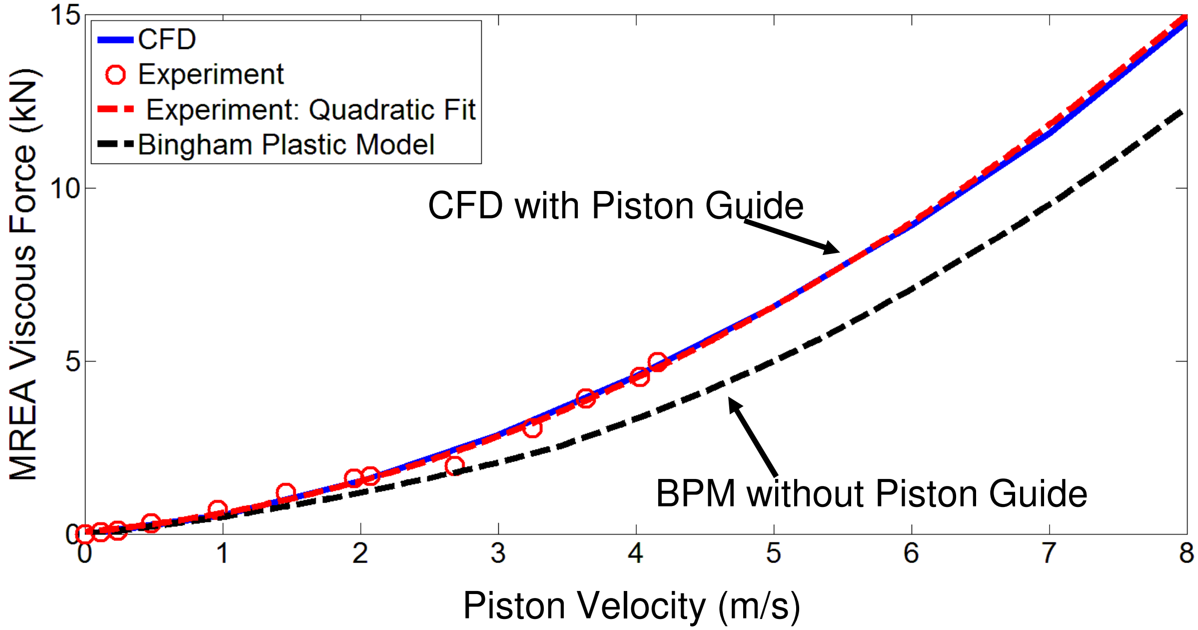


Drop test setup



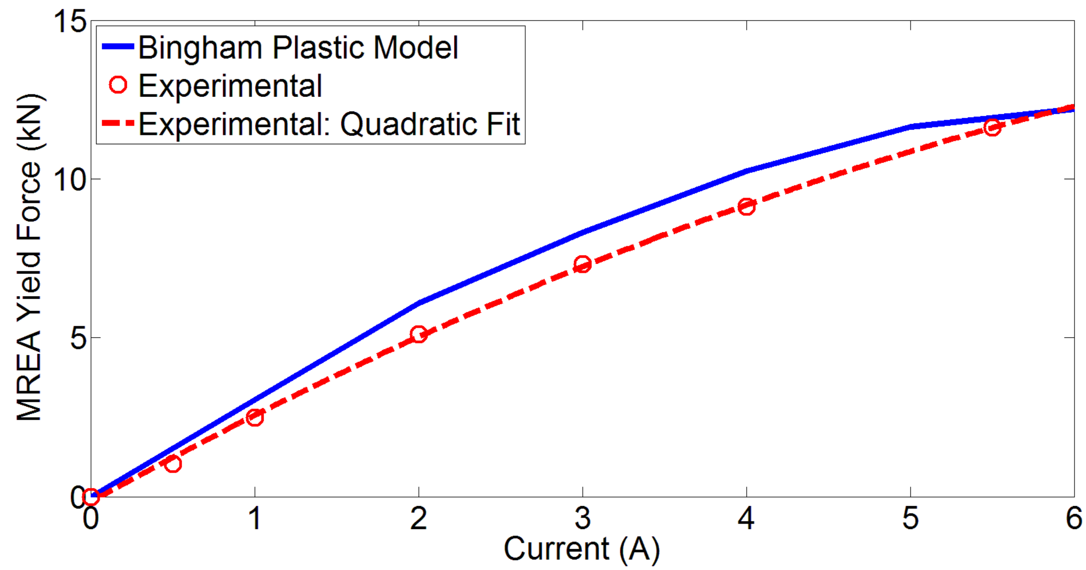
Drop tests
up to 15 ft/s
(Field off only, 0A)

Results



- Tests conducted up to 15ft/s
- Experiments and CFD predictions match well
- Bingham Plastic Model under predicted the viscous forces

- Experimental yield force was higher than BPM
- BPM does not capture the dynamic yield stress of MR fluid precisely



Outline

Design and Testing of Magnetorheological Energy Absorber

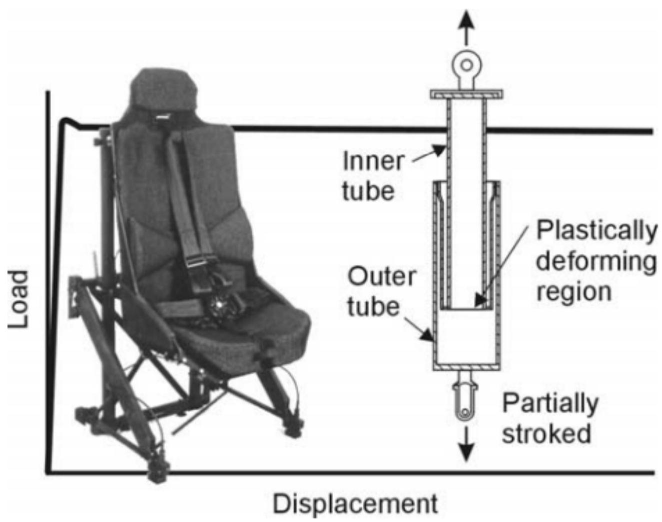
Control Algorithms

- Constant Stroking Load Control
- Terminal Trajectory Control

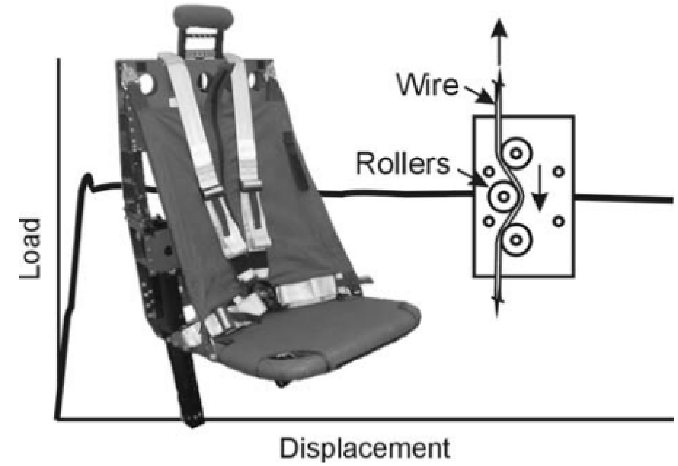
Conclusions

Existing Constant Stroking Load Concepts

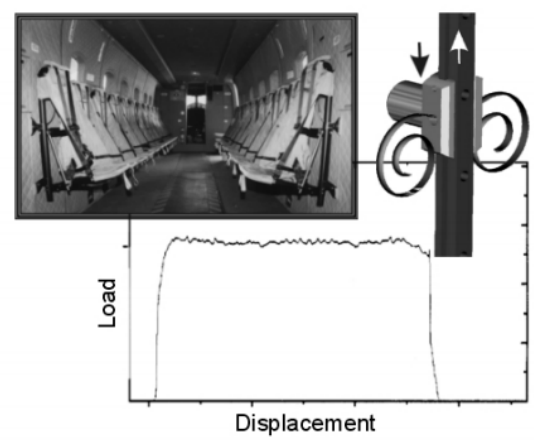
- Inversion tubes
- Wire bending
- Cutting and Slitting



UH-60 Black Hawk Armored Crewseat, Inversion Tube Energy Absorbers



EH101 Foldable Troop Seat, Wire Bender Energy Absorbers

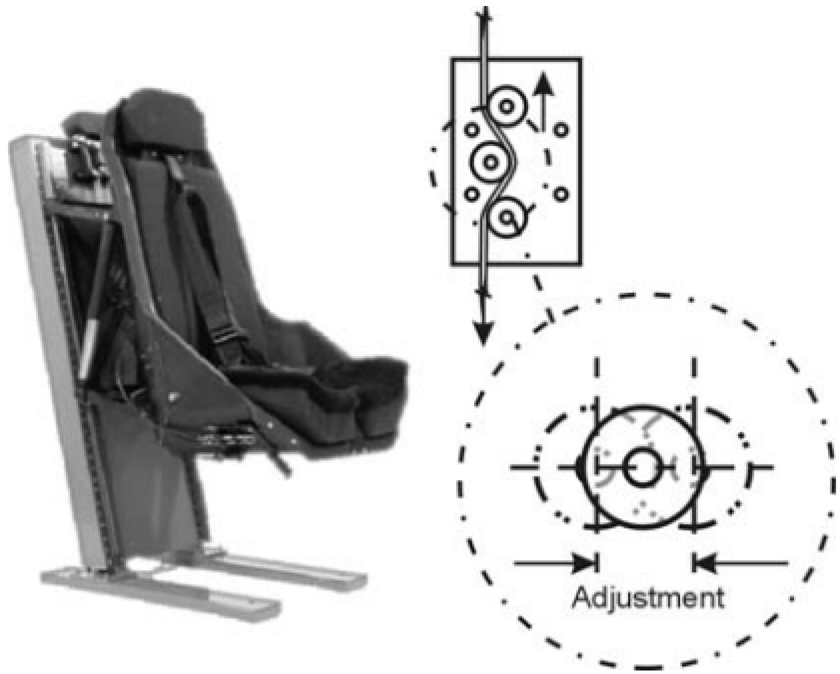


Utility Seat (CH-53Troop Seat), Metal Cutter Energy Absorbers

Desjardins, S.P., "The Evolution of Energy Absorption Systems for Crashworthy Helicopter Seats," *59th AHS Annual Forum*, Phoenix, AZ, 6-8 May, 2003

Variability in CSL Approach

- Adjusting roller location in wire bender



V-22 Osprey Armored Crewseat, Variable Load Energy Absorbers (VLEA), Wire Bender

Desjardins, S.P., "The Evolution of Energy Absorption Systems for Crashworthy Helicopter Seats," *59th AHS Annual Forum*, Phoenix, AZ, 6-8 May, 2003

Constant Stroking Load Control

- Stroking the seat based on dynamic limit load of energy absorber.
- Dynamic limit load is the maximum permissible stroking load to which an occupant can be subjected

$$\boxed{F_{D_L} = 14.5\ Mg}$$

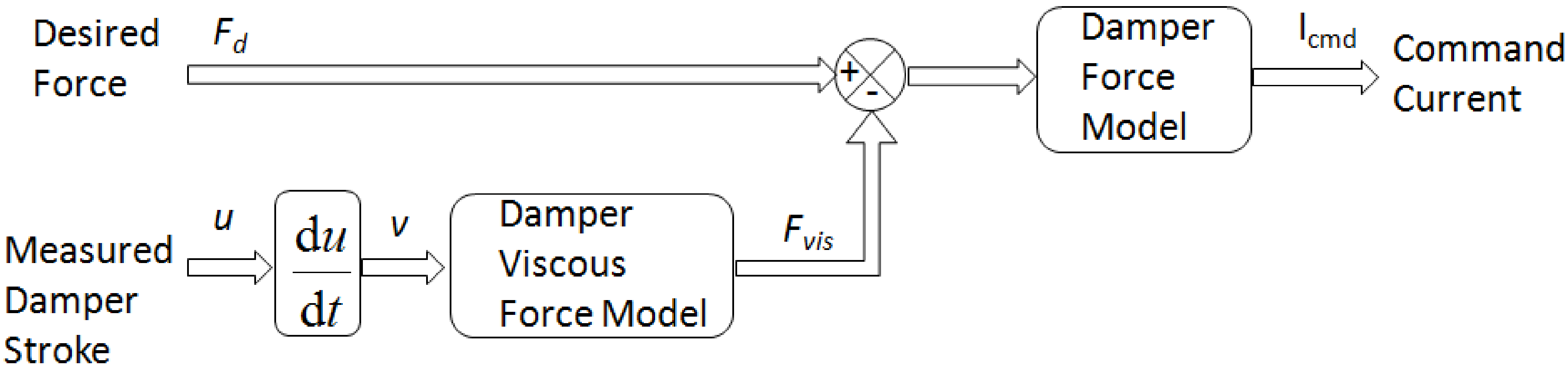
$$F_{D_L} = 14.5\ (0.8M_{5^{th}} + M_{seat})g$$

- The limit load was found to be: 11.70 kN (14.5Mg); 8.07 kN (10Mg)
- No control authority over passive viscous force

$$\boxed{F_{MR} = F_{D_L} - F_V}$$

Desjardins, S.P., Zimmerman, R.E., Bolukbasi, A.O., and Merritt, N.A., "Aircraft Crash Survival Design Guide," ***Aviation Applied Technology Directorate*****, USAAVSCOM TR 89-D-22D, Fort Eustis, VA, 1989.**

Velocity Feedback



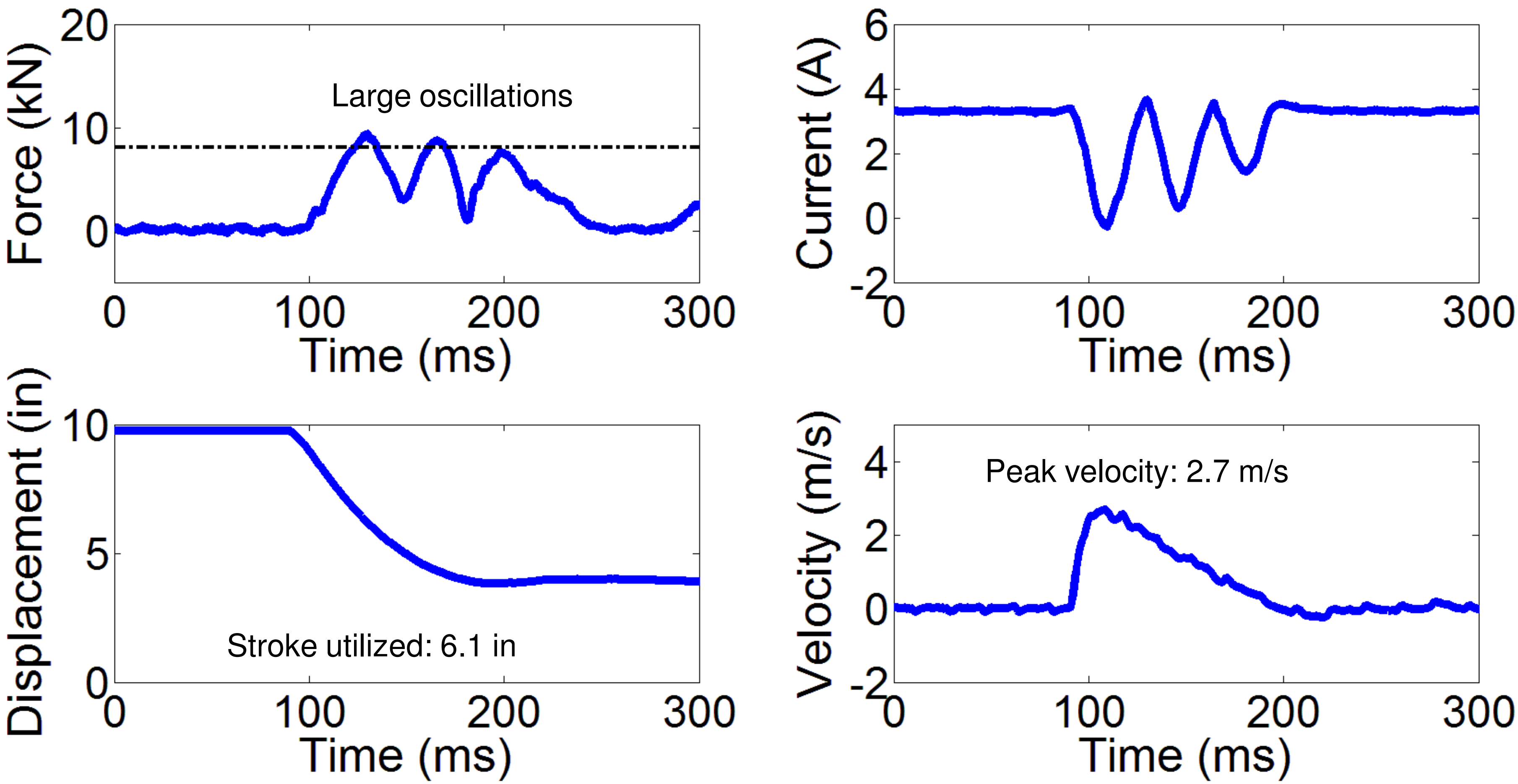
Velocity Feedback

Test condition

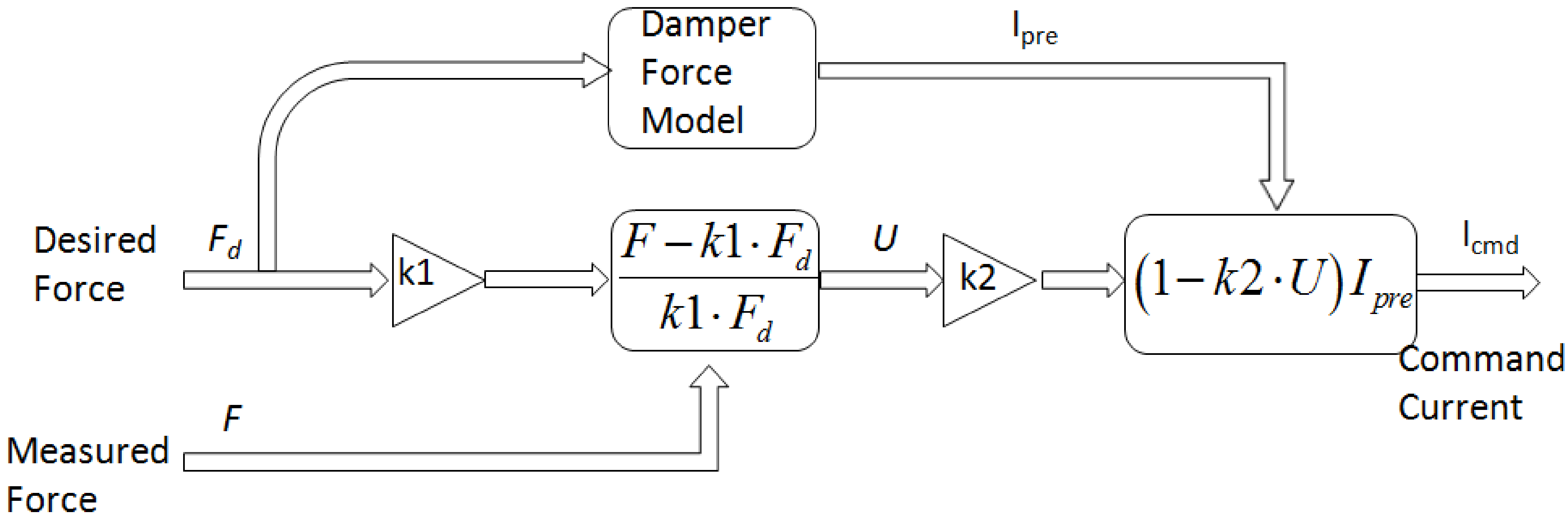
Mass: 380 lb (172 kg)

Height: 35 in (88.9 cm)

Stroke limit: 7 in



Force Feedback



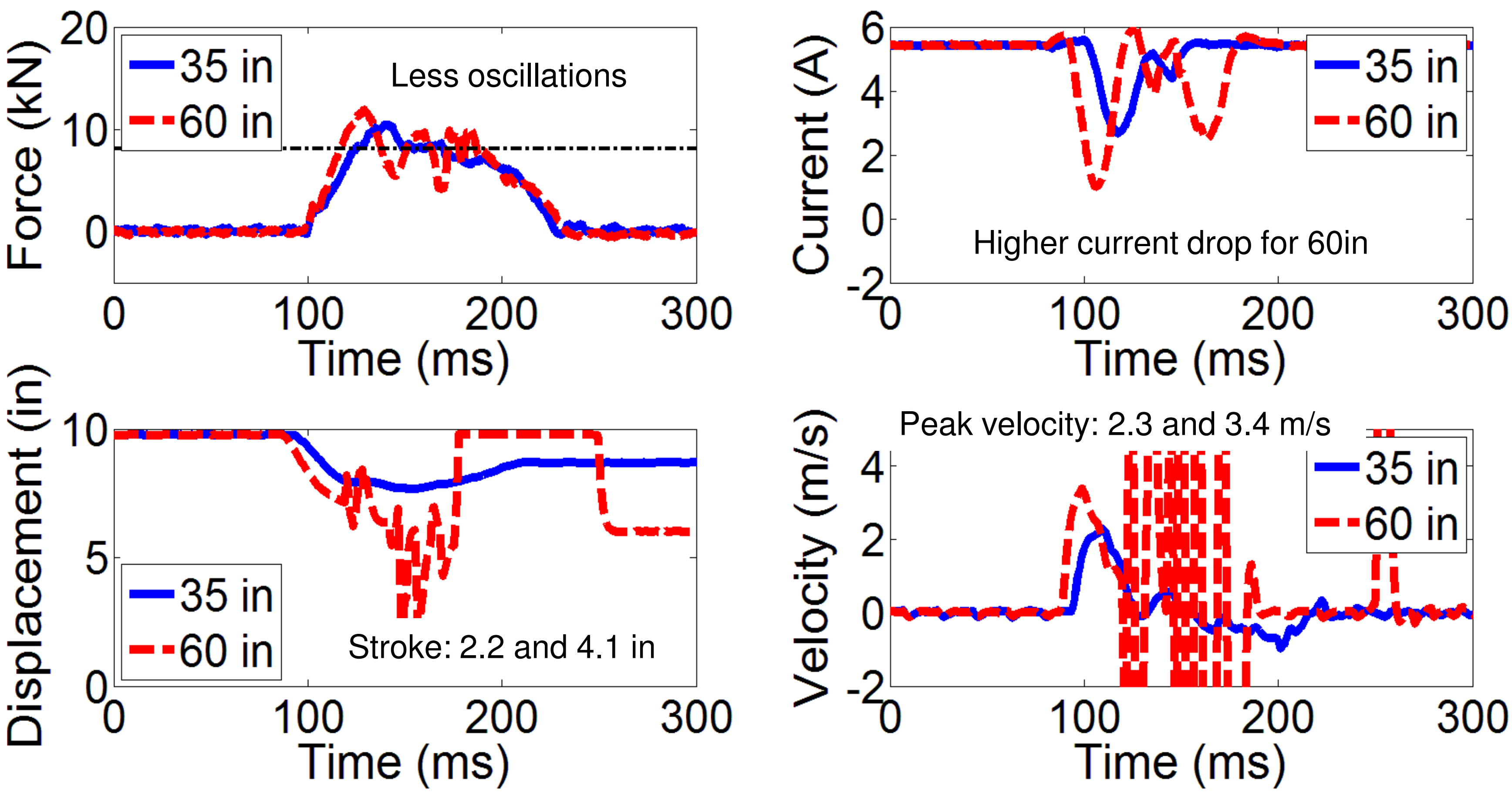
Force Feedback

Test condition

Mass: 380 lb (172 kg)

Height: 35 in (88.9 cm) ; 60 in (152.4 cm)

Stroke Limit: 7 in



Terminal Trajectory Control

- Maximize shock attenuation by utilizing the entire EA stroke

Key goals:

- **Dissipate kinetic energy over the entire stroke**
- **Avoid potentially injurious end-stop impact i.e. soft landing**

Terminal Conditions:

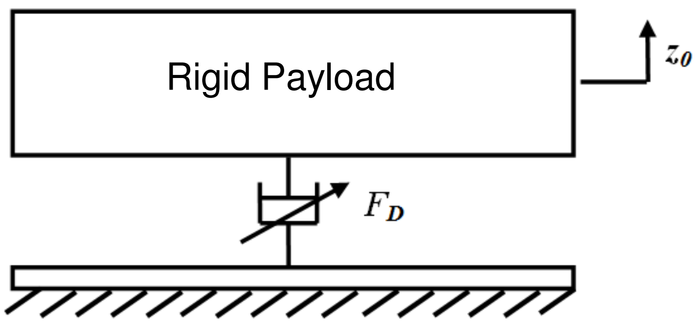
$$z_0(t_s) = -S$$

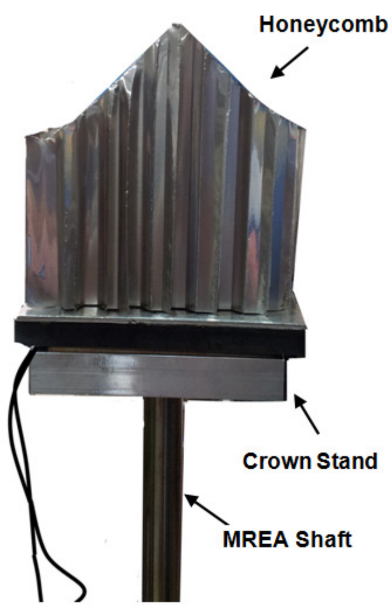
$$\dot{z}_0(t_s) = 0$$

- Simple approach: a **constant MREA yield force** could satisfy the terminal conditions

Current Estimation

- Modeling the shock as an initial velocity impact





$$v_i = f_s\sqrt{2gH}$$

H is the drop height; ***f***

$$KE = \frac{1}{2}mv_i^2$$

Energy dissipated by honeycomb

$$ED_{HC} = PAh$$

P is crushable stress of honeycomb, ***h*** is crushed height.

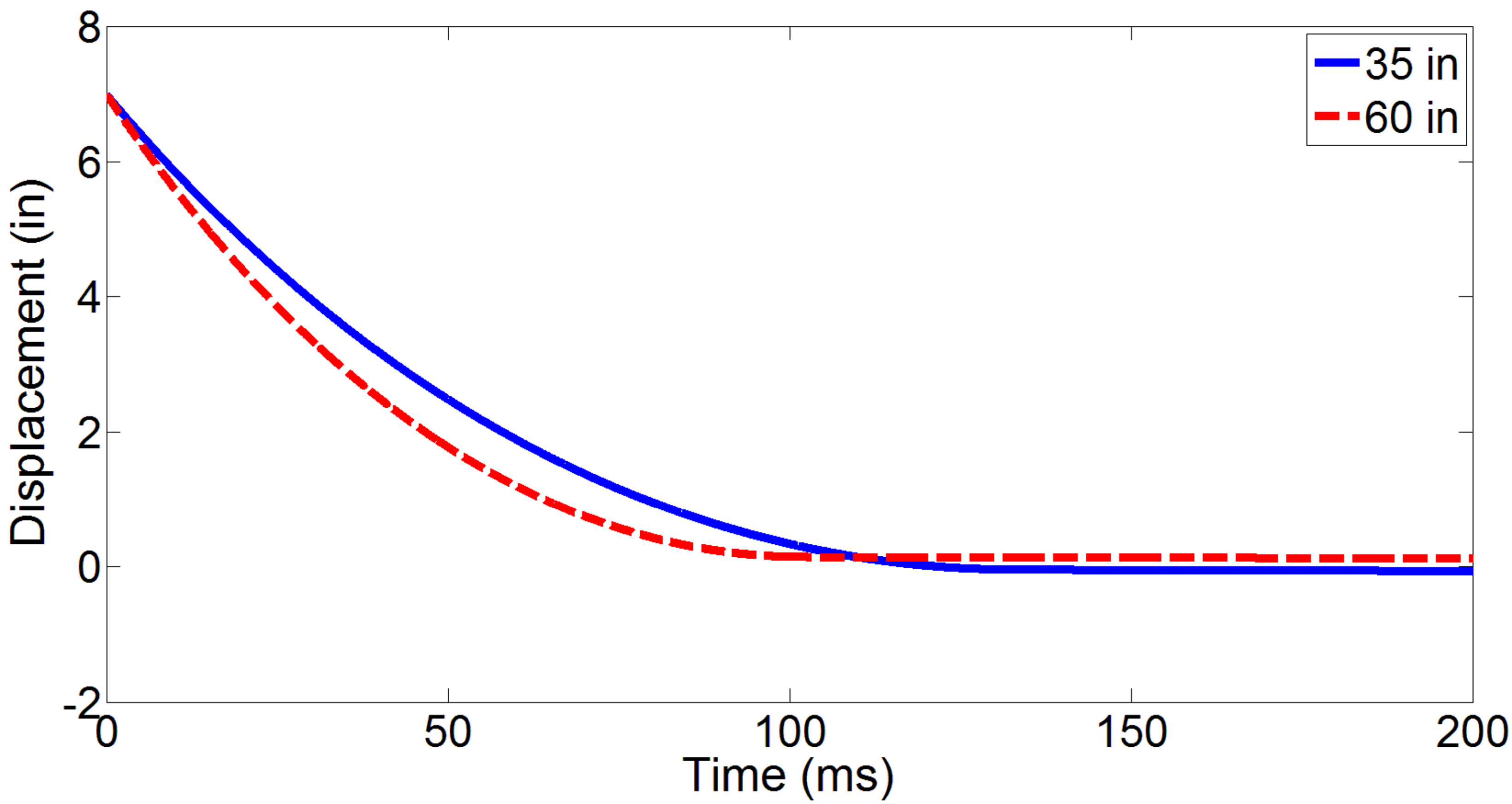
Energy dissipated by MREA

$$ED_{MREA} = KE - ED_{HC}$$

$$\boxed{v_o = \sqrt{\frac{2\,ED_{MREA}}{m}}}$$

Current Estimation

- Current estimated using Fixed Point Iteration scheme
- Current estimations: 1.75 A for 35 in; 2.65 A for 60 in



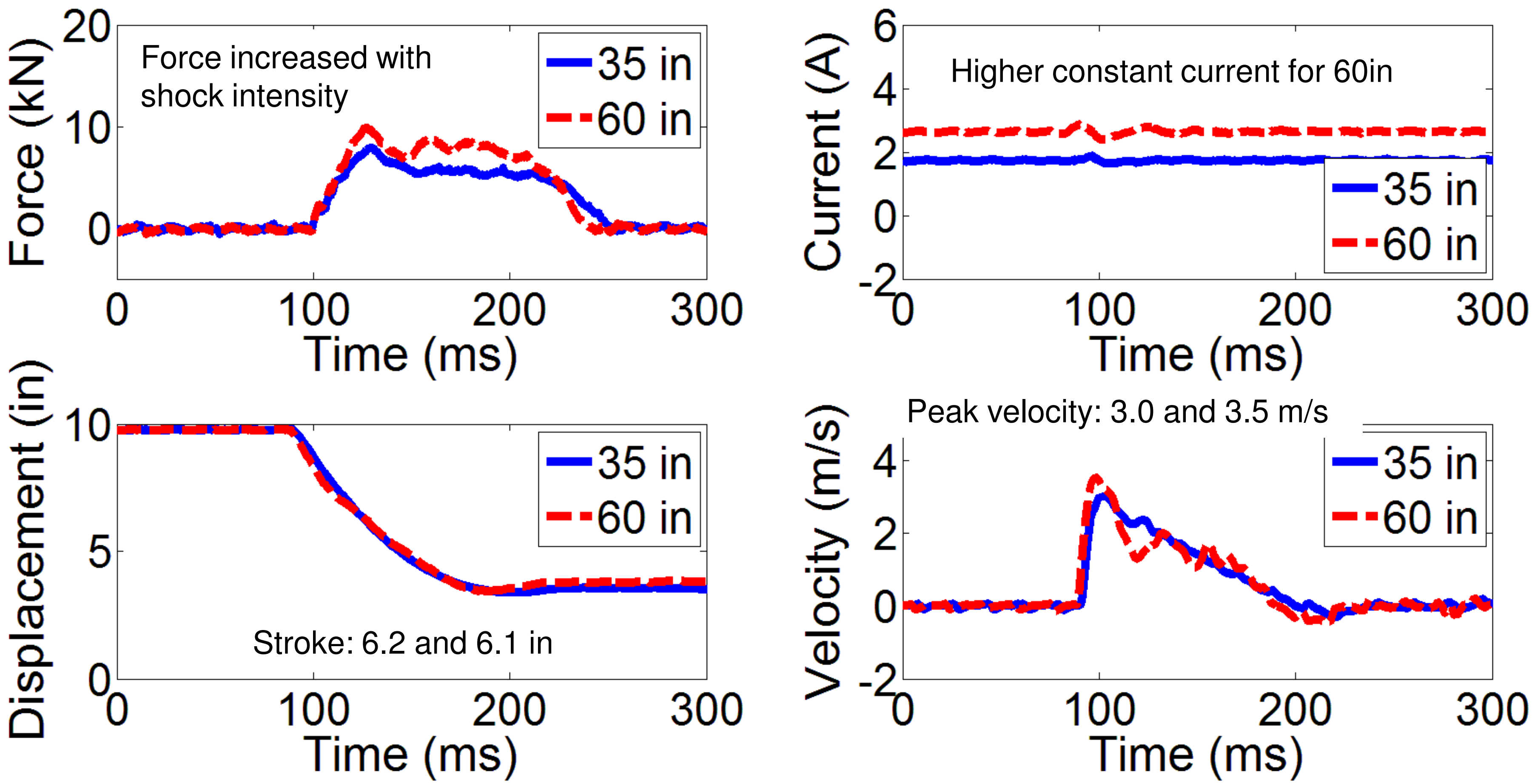
Terminal Trajectory Control

Test condition

Mass: 380 lb (172 kg)

Stroke Limit: 7 in

Height: 35 in (88.9 cm) ; 60 in (152.4 cm)



Outline

Design and Testing of Magnetorheological Energy Absorber

Control Algorithms

- Constant Stroking Load Control
- Terminal Trajectory Control

Conclusions

Conclusions

- MREA was designed for a large dynamic range or control authority
- MREA performance was evaluated using MTS cycling and drop tests for current inputs of 0-5.5A and speeds up to 15ft/s or 4.5m/s
- Constant stroking load and terminal trajectory control were analyzed
- Velocity feedback based CSLC could not maintain constant load due to strong dependence on velocity
- Force feedback based CLSC was relatively better
- TTC had no issue of time delay between current and magnetic field buildup
- CLSC – (Existing wire benders, crushable tubes)

  Same stroking load   Different stroke utilization   Poor Adaptation

- TTC performs superior

  Adaptive Stroking load   Same stroke utilization   Good Adaptation

Acknowledgement

The authors acknowledge support for this research under a contract from The U.S. Naval Air Warfare Center at Patuxent River, MD (Mr. William Glass as Technical Monitor)

The authors are thankful to Dr. Joseph Pellettiere for invitation to 7th Fire and Cabin Safety Conference.

Thank You

&

Questions?