Semi-active Control of a Banded Rotary Friction Device

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Structural Damping

Purpose: Reliably absorb and dissipate energy from dynamic loadings, e.g., earthquakes and wind

Passive

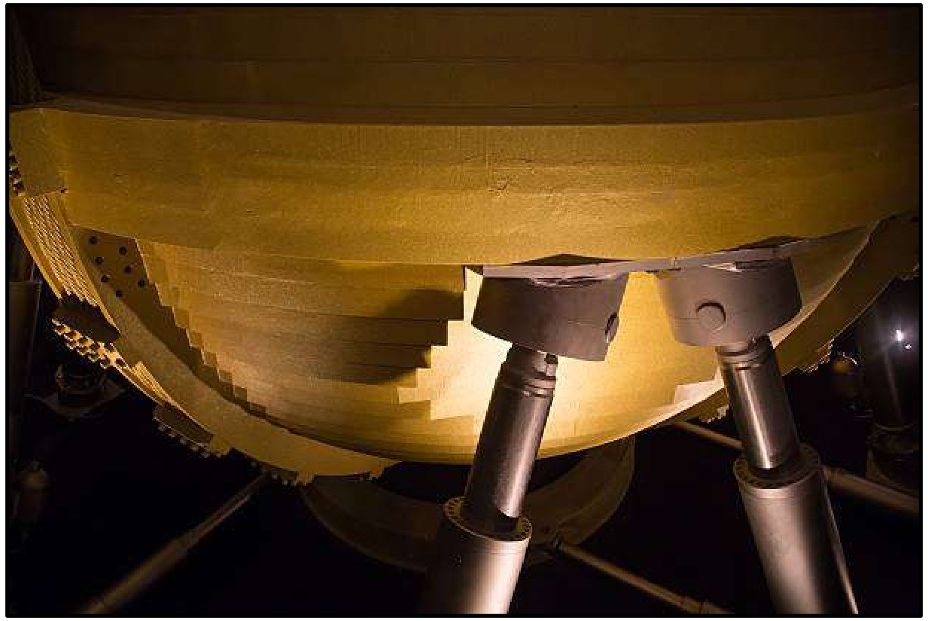
- Require no external power
- Limited functional bandwidth

Active

- Adaptable/quick
- Require much external power

Semi-active

- Purely reactive
- Require little external power



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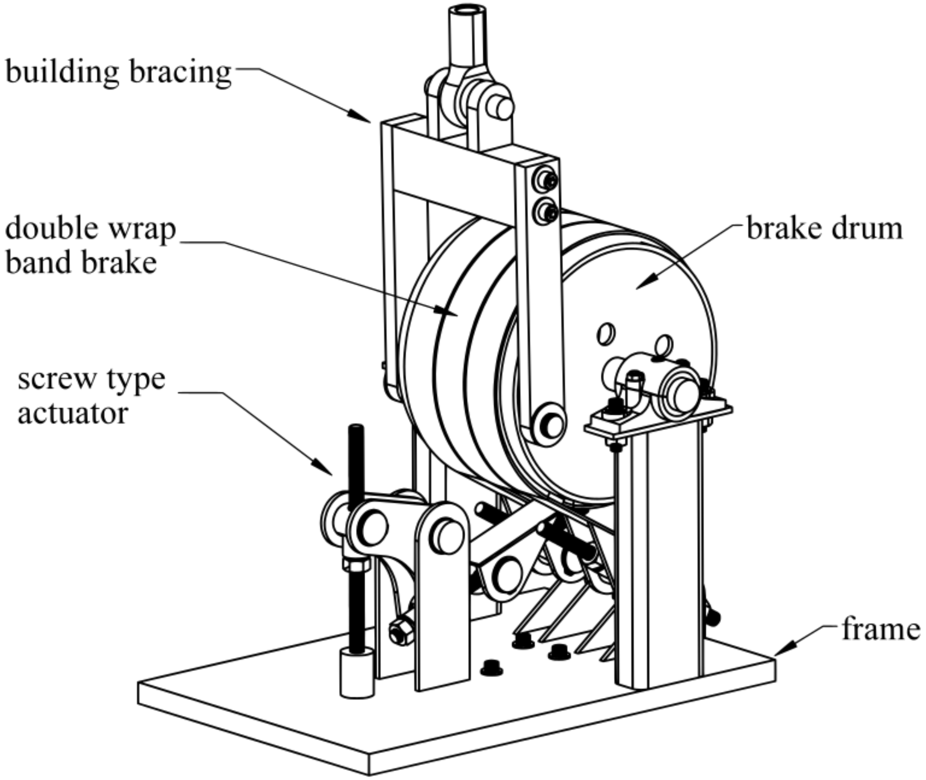
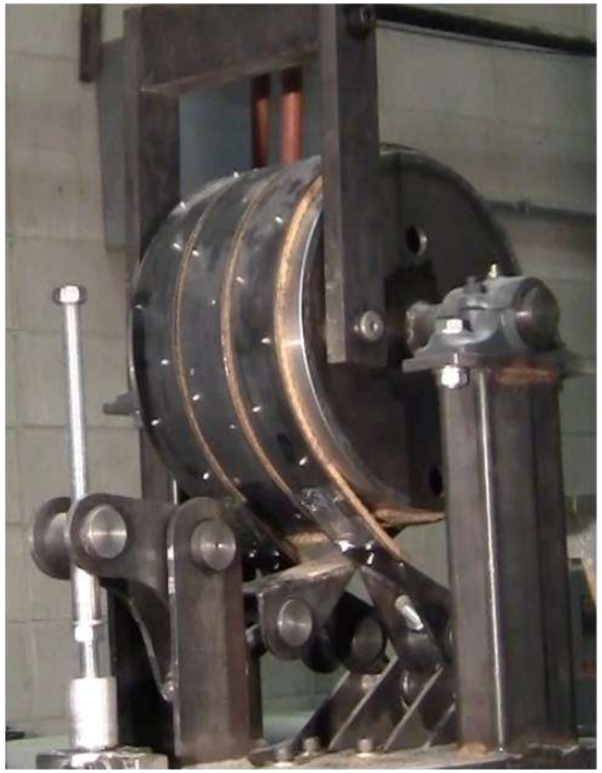
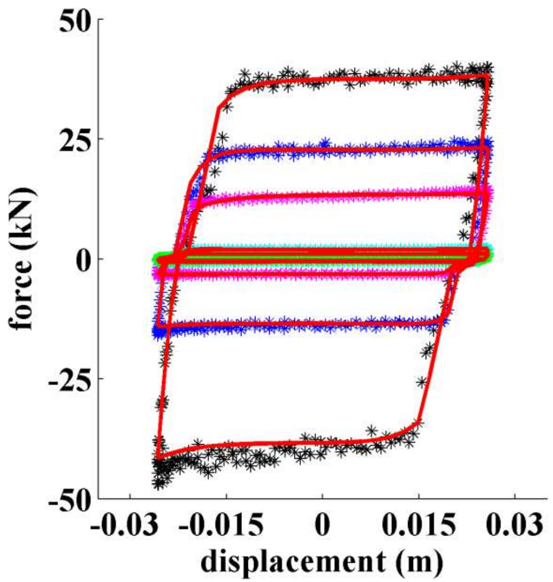
Banded Rotary Friction Device (BRFD)

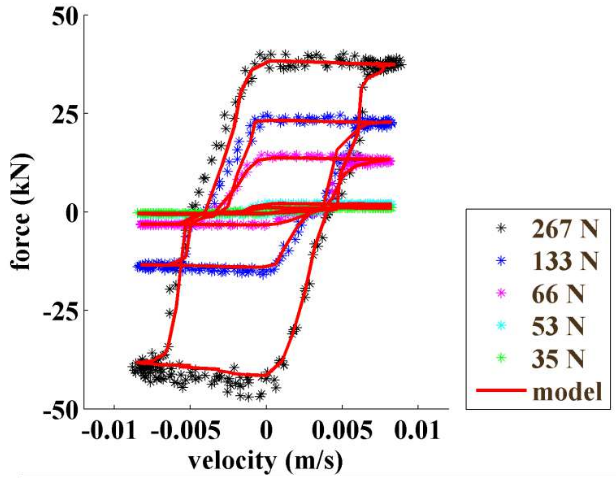
- Variable friction damper inspired by band brake technology





mechanical advantage of 142

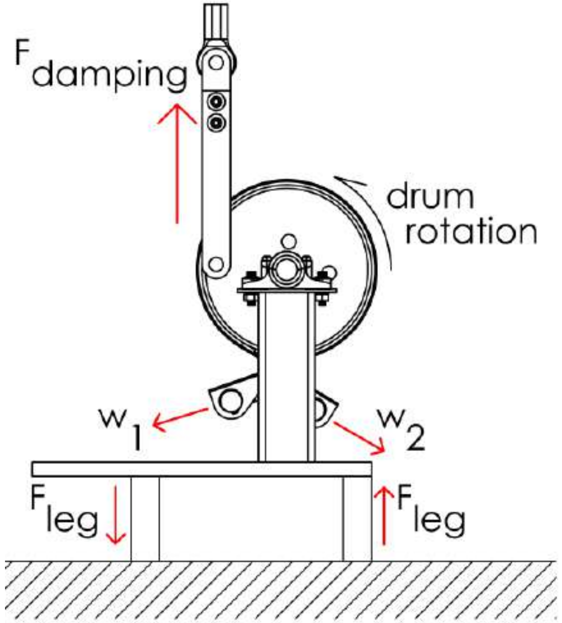


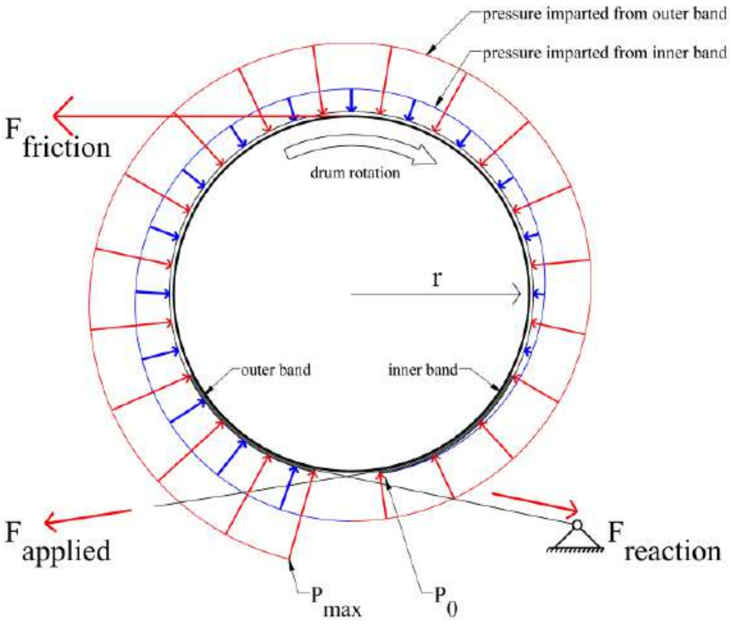


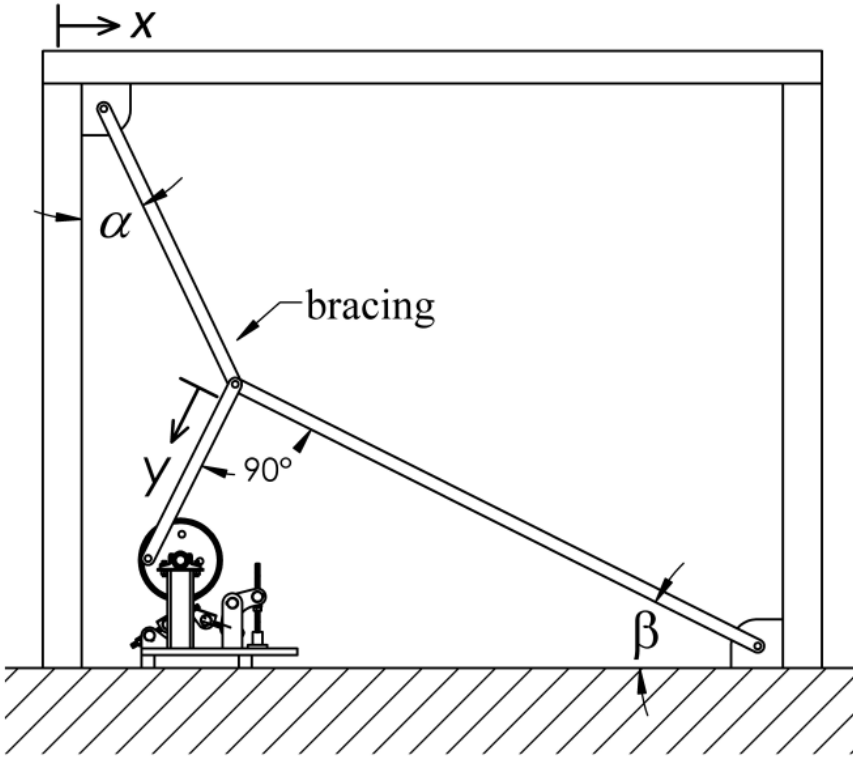
Austin Downey, Liang Cao, Simon Laflamme, Douglas Taylor and James Ricles. High capacity variable friction damper based on band brake technology. *Engineering Structures*, vol. 113, 2016, p. 287-298. doi:10.1016/j.engstruct.2016.01.035

Banded Rotary Friction Device (BRFD)

- Lateral displacement **transduced** into angular motion
- Friction develops as the drum rotates against friction bands
- Electric actuators adjust band tension → control damping







$$F_{\text{reaction}}/F_{\text{applied}} = e^{\mu\phi}$$

$$F_{\text{applied}} = \frac{F_{\text{friction}}}{(e^{\mu\phi} - 1)}$$

$$F_{\text{damping}} = \frac{T}{r_b} = \frac{F_{\text{friction}} \cdot r}{r_b}$$

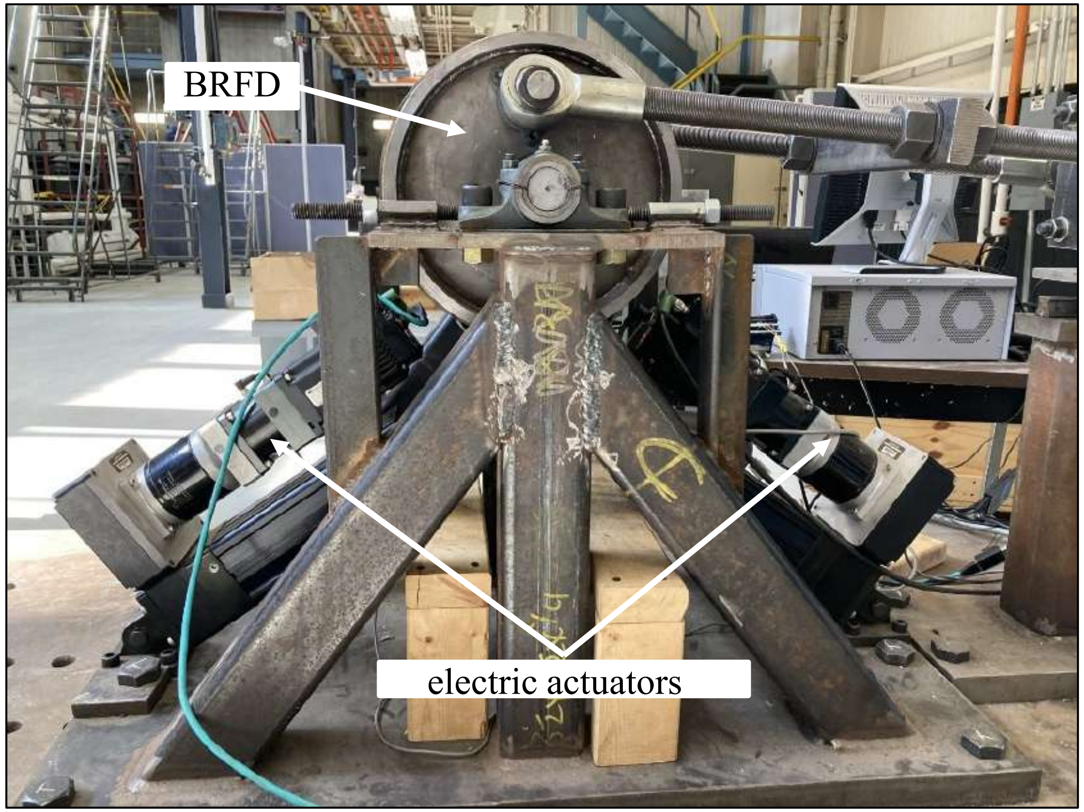
NSF-funded Testbed at Lehigh University

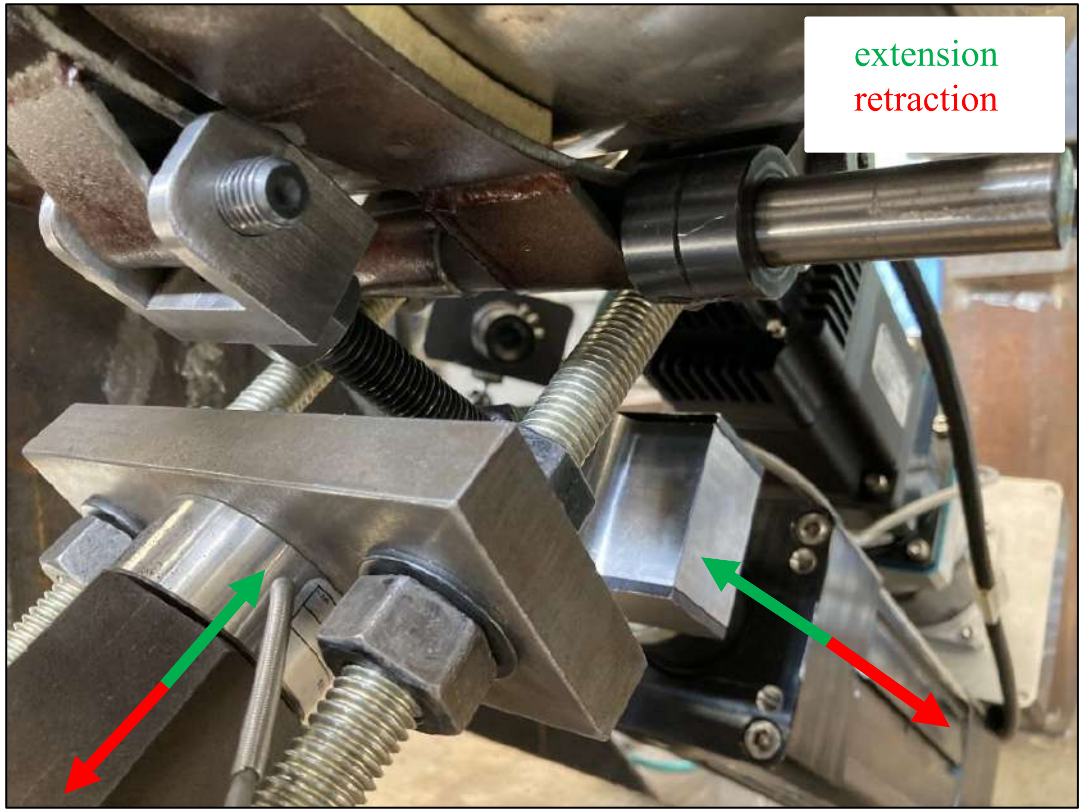
- The Device is at Lehigh University in their NSF-funded NHERI faculty.
- Open-source data will hopefully allow others to use the device for their investigations.
- Hopefully updates in the near future will move it closer to a “final” product.

GitHub

Will have again in the slides
in case you miss it.

Banded Rotary Friction Device





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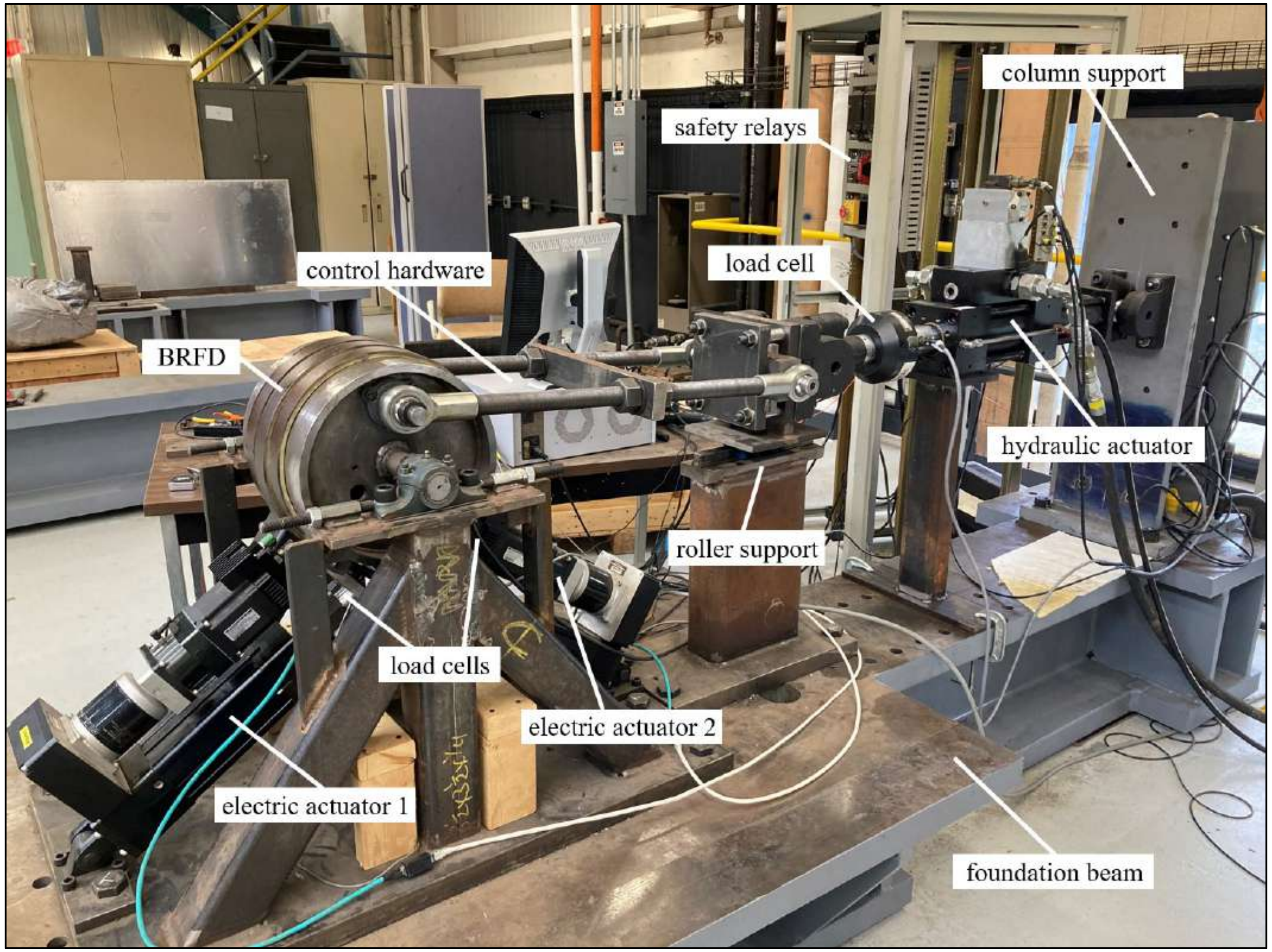
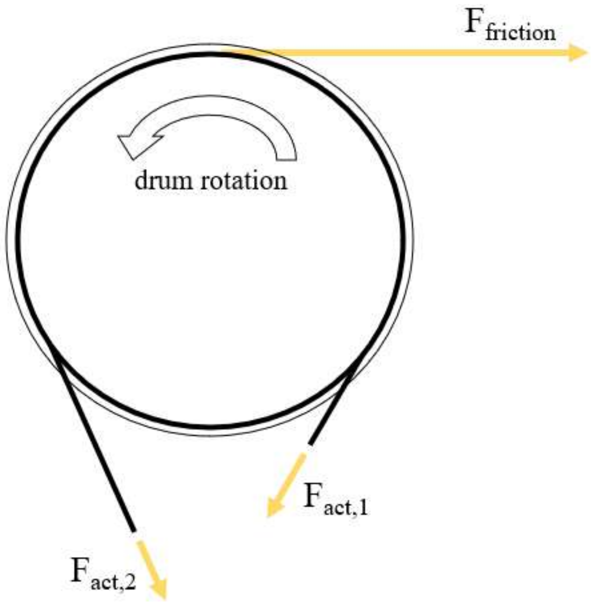
Test Setup

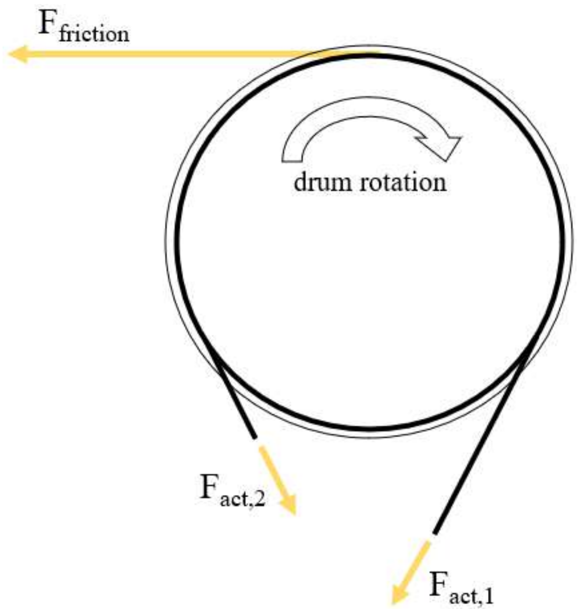

column support
safety relays
control hardware
load cell
BRFD
hydraulic actuator
roller support
load cells
electric actuator 2
electric actuator 1
foundation beam

Passive Operation

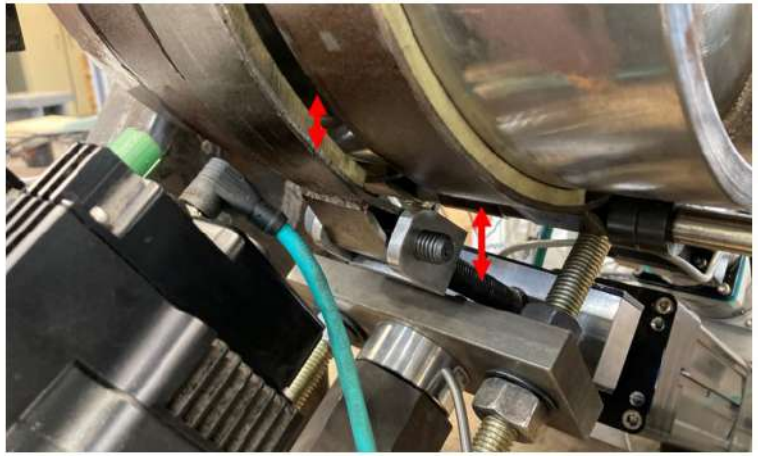
BRFD Modeling Difficulties

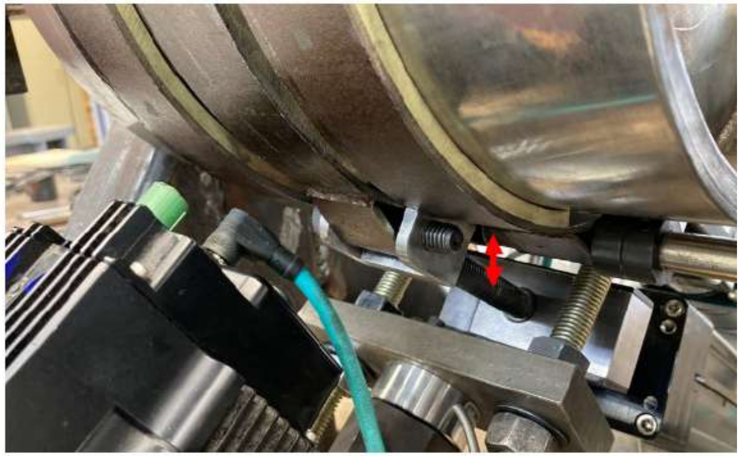


forward rotation



backward rotation





- **Friction:** stiction, hysteresis, etc.
- **Deflections:** electric actuators/ friction bands
- **Sensitivity:** initial conditions

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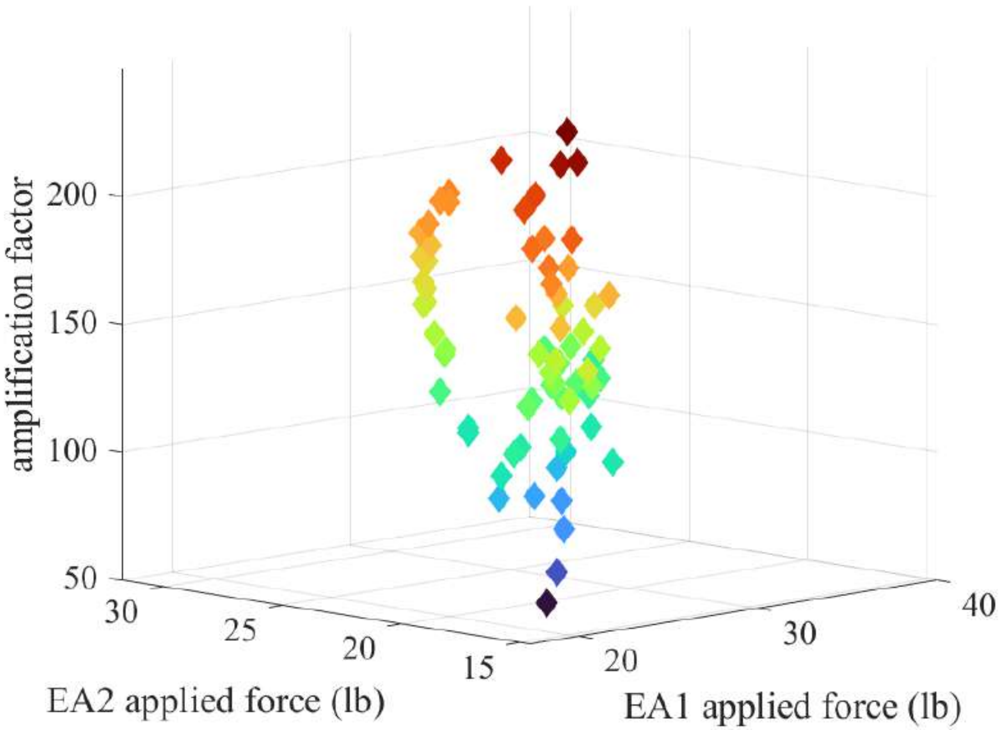
Damper Force Amplification



- Factor by which the BRFD amplifies its input
- Ratio of damping force to slack-actuator force

Forward rotation: $C_{fwd} = \frac{F_{c,fwd}}{F_{act,1}}$

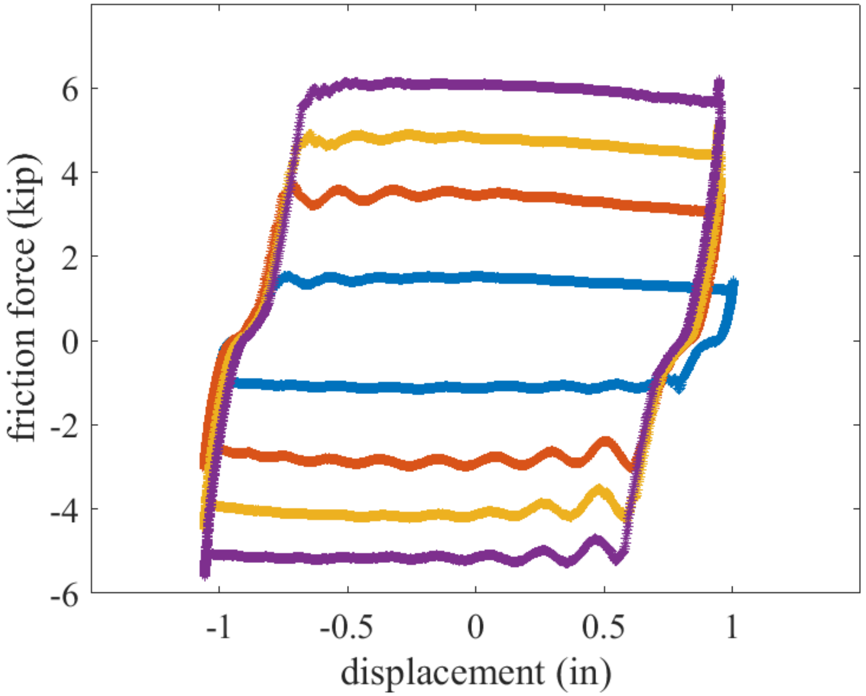
Backward rotation: $C_{bwd} = \frac{F_{c,bwd}}{F_{act,2}}$

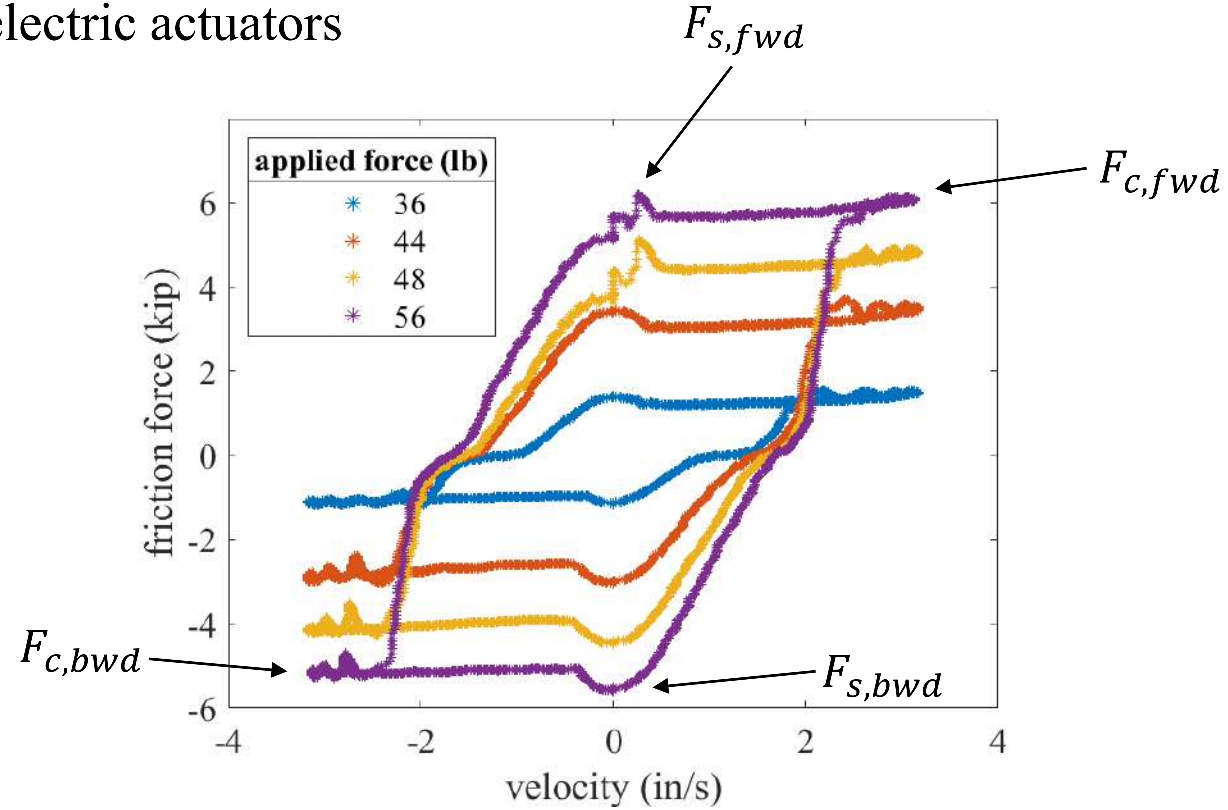
- BRFD capable of achieving amplification factors ≫ 1
- Amplification **increases** with pretension forces

Passive to Semi-active

- Applied forces determine damper output level
- Area of force-displacement curves ≡ energy dissipated by the damper

Goal: Control static/kinetic friction with the electric actuators





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Approach

- Sets of passive characterization tests conducted for analysis
- Used sinusoidal input with amplitude **1 in** and frequency **0.5 Hz**
- Electric actuators incrementally retracted between tests
- Data from **90** tests collected in total

Actuator 1 position (in)

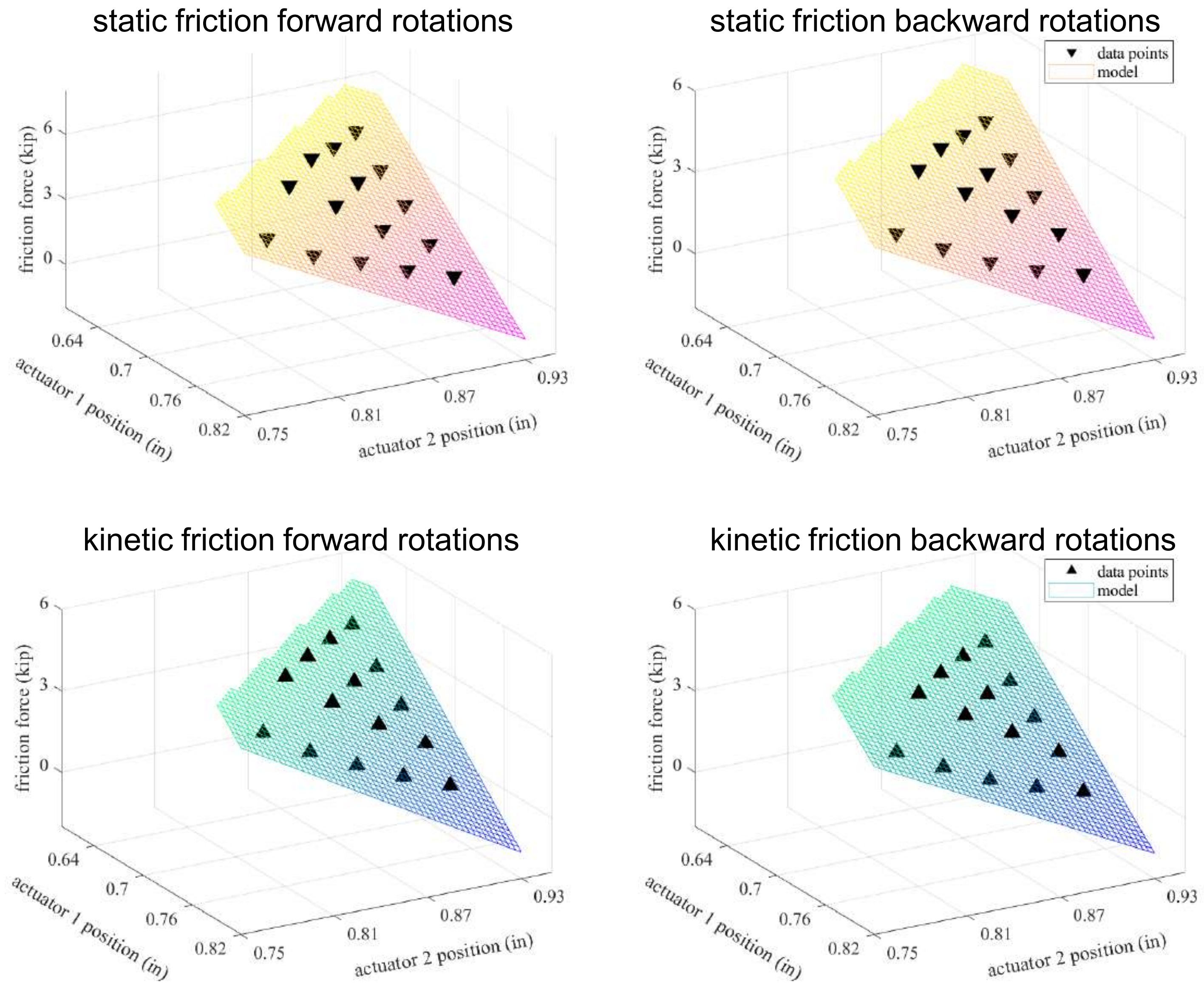
Actuator 2 position (in)	0.715	0.73	0.745	0.76	0.775	0.79	0.805	0.82	0.835
0.81									
0.825						x	x		
0.84					x	x	x	x	
0.855				x	x	x	x	x	
0.87			x	x	x	x	x	x	
0.885		x	x	x	x	x	x	x	
0.9	x	x	x	x	x	x*	x	x	
0.915		x	x	x	x	x	x	x	
0.93		x	x	x	x	x	x	x	
0.945									

Full Test

Safety Limit

*conducted twice

Regression Analysis



- Actuator initial positions **vs.** static/kinetic friction
- Slopes → rates at which damping changes with actuator **displacements**
- Linear models ignore potential for actuator coupling

LuGre Model

- Dynamic friction model with state variable z
- Introduced for the control of dry friction interfaces

$$\dot{z} = v - \sigma_0 \frac{|v|}{g(v)} z \qquad \text{Eq. 1}$$

$$g(v) = F_c + (F_s - F_c) e^{-(\frac{v}{v_s})^2} \qquad \text{Eq. 2}$$

$$F = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 v \qquad \text{Eq. 3}$$

- Model is passive → F_s and F_c are constants

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Semi-active Model

- Standard LuGre model serves as a baseline
- F_s and F_c modified to be functions of electric actuator positions/drum velocity

$$F_s(x_1, x_2, v) = \begin{cases} s + S_1(x_1 - x_1') + S_2(x_2 - x_2'), & v \geq 0 \\ s + S_3(x_1 - x_1') + S_4(x_2 - x_2'), & v < 0 \end{cases} \quad \text{Eq. 4}$$

$$F_c(x_1, x_2, v) = \begin{cases} c + C_1(x_1 - x_1') + C_2(x_2 - x_2'), & v \geq 0 \\ c + C_3(x_1 - x_1') + C_4(x_2 - x_2'), & v < 0 \end{cases} \quad \text{Eq. 5}$$

- Actuator displacements are computed using knowledge of current and initial positions, i.e., $(x_1 - x_1')$ and $(x_2 - x_2')$

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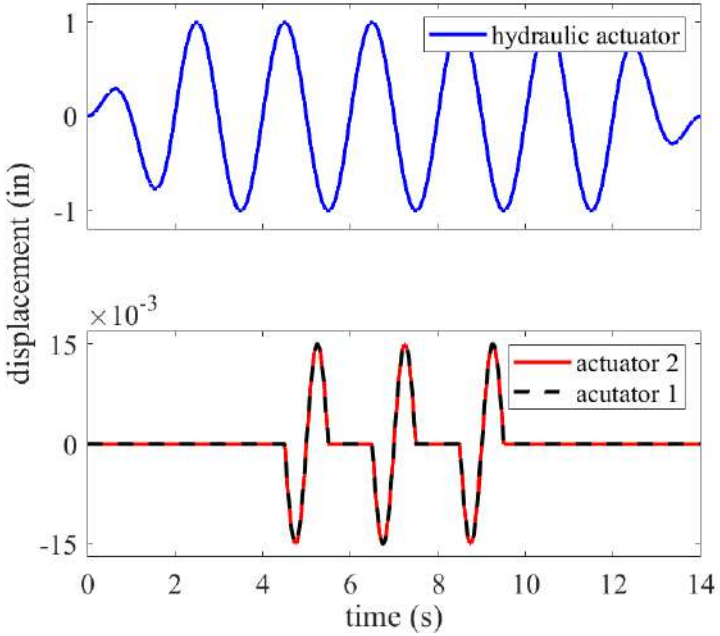
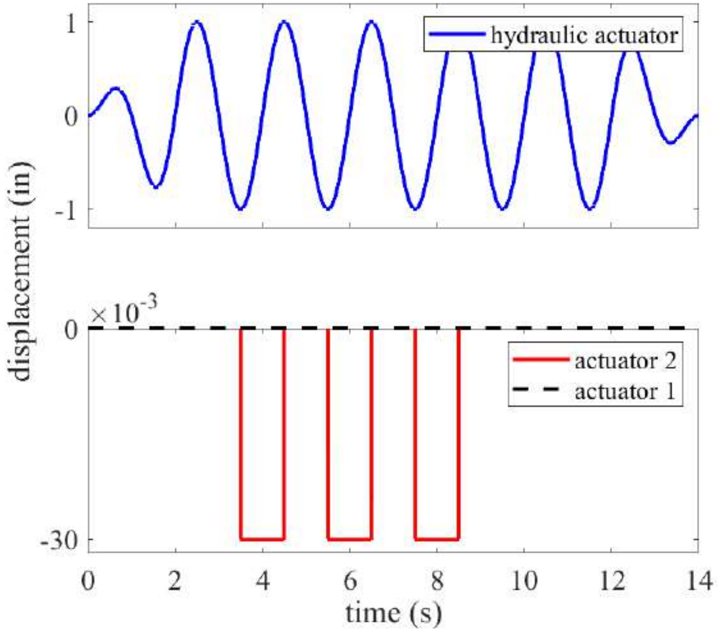
Validation Tests





- Semi-active validation tests devised that run hydraulic/electric actuators simultaneously
- **12** validation tests conducted in total
- **6** used sinusoidal electric actuator displacements
- **6** used step electric actuator displacements

Test #	Controlled Actuator(s)	Displacement Amplitude (in)	Drum Rotation
1	one	0.03	forward
2	one	0.03	backward
3	two	0.03	forward
4	two	0.03	backward
5	one & two	0.015	forward
6	one & two	0.015	backward

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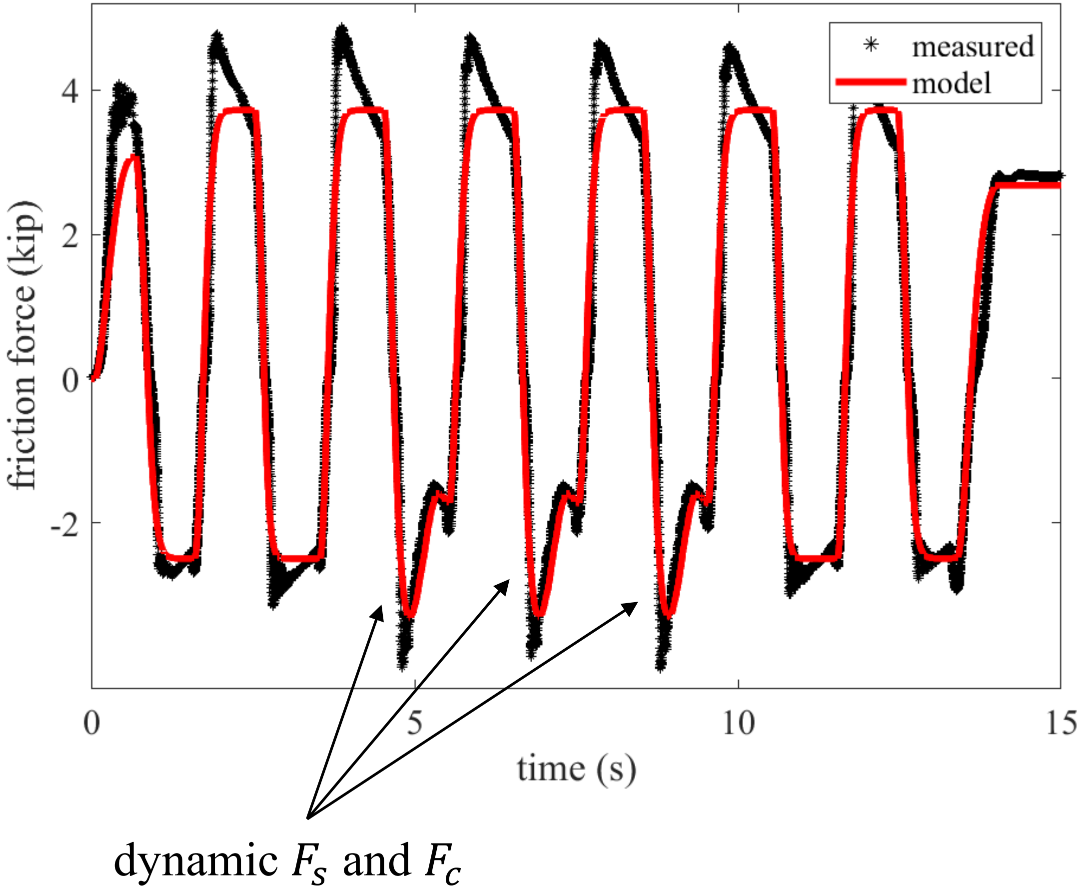
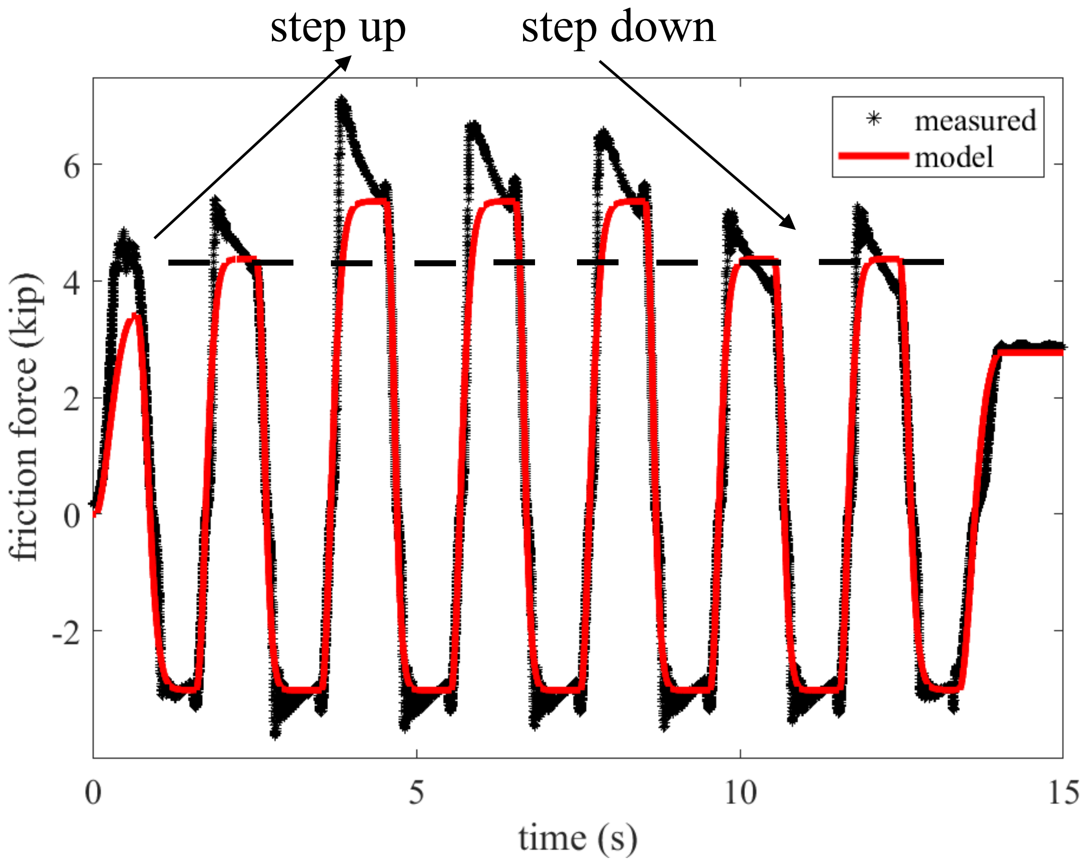
Results

- Model able to predict changes in damping induced by electric actuator displacements





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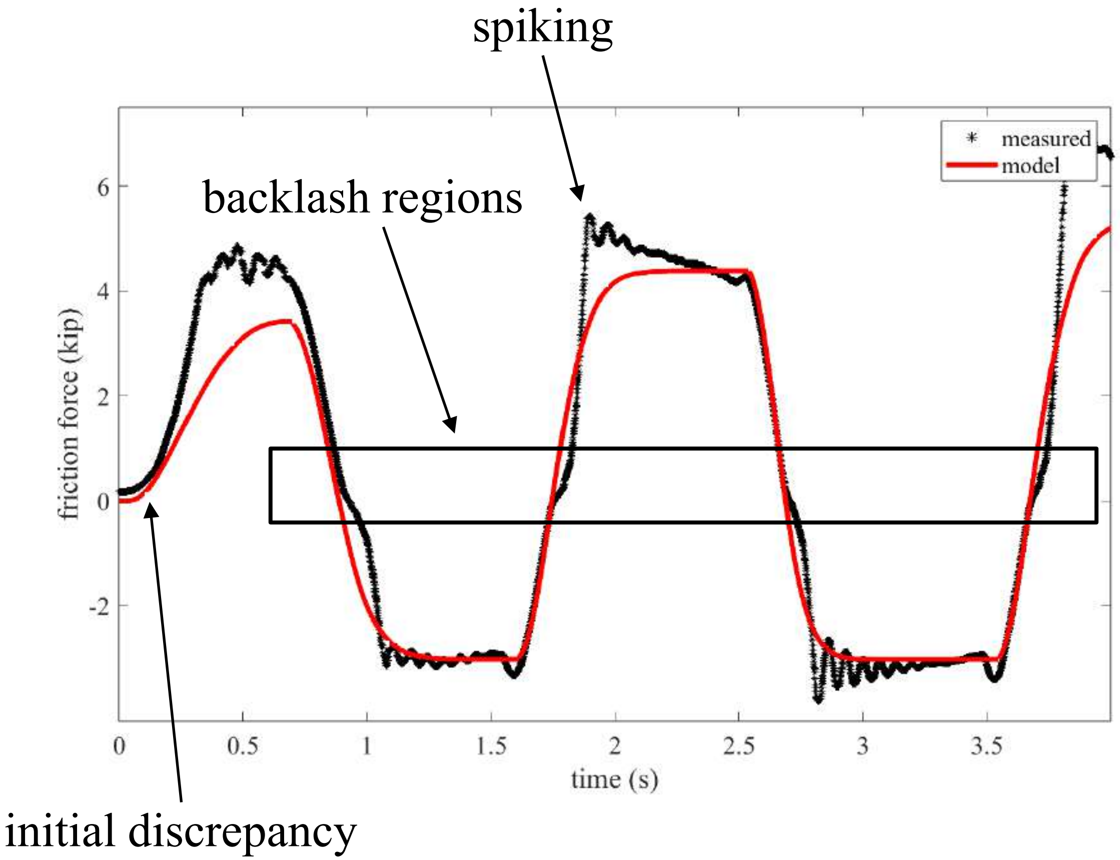
Discussion



- With just **0.03 in** actuator displacements, damping increased as much as **1 kip**
- Much of model error stems from the following:
  1. Residual static force causing initial prediction discrepancies
  2. Fitting LuGre model parameters to semi-active data
  3. Spikes in damping observed upon reversal of drum rotation
  4. Backlash effect

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Conclusion

- Using passive characterization data, a semi-active model for a rotary friction damper was developed
- A modified LuGre model consisting of dynamic static/kinetic friction parameters was proposed
- The model was validated using designed semi-active displacement profiles
- Future work may now focus on the development of internal control algorithms

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THANKS!

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Your Turn!

GitHub

https://github.com/ARTS-Laboratory/Dataset-Friction-Damper-with-Backlash

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