Collaborations through REUs – A Lehigh Facility User Experience

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Research Group, Spring 2023

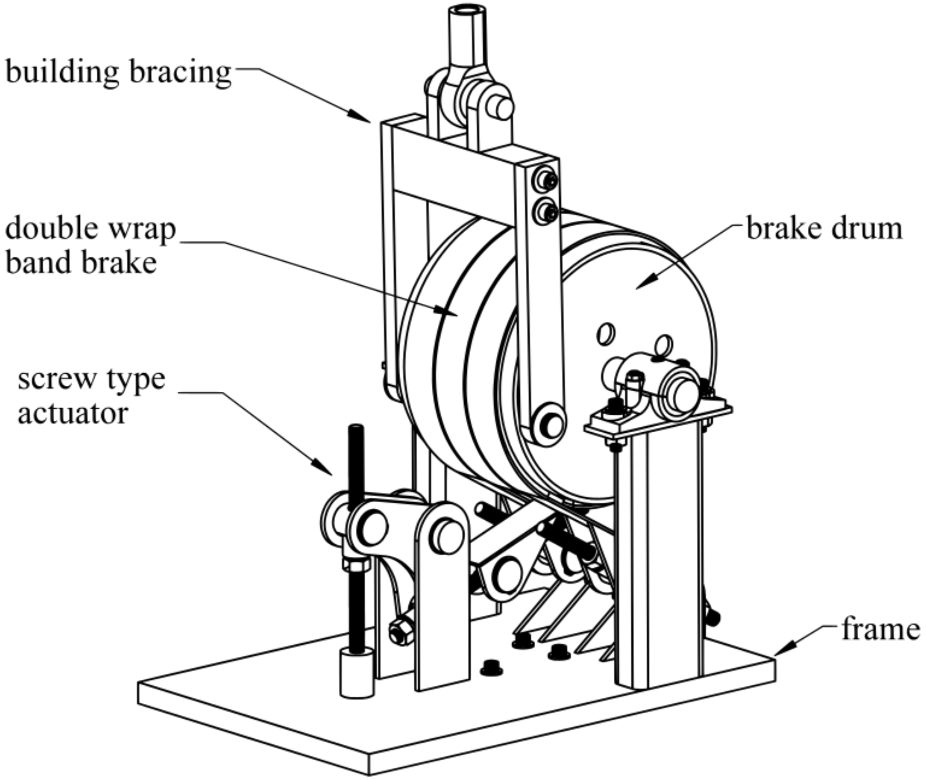
UNIVERSITY OF SOUTH CAROLINA

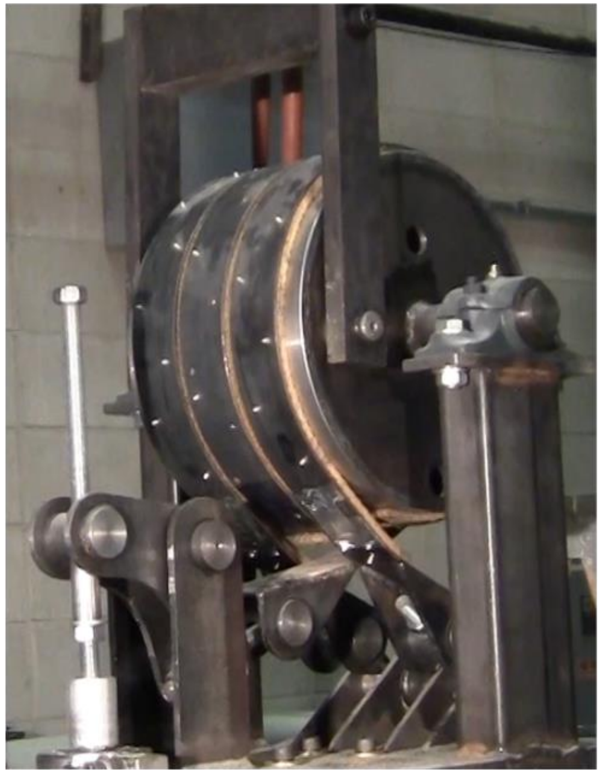
Undergraduate Research

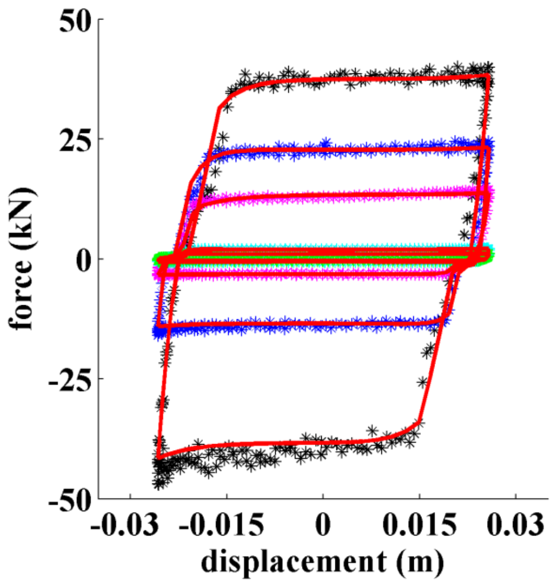
The lab has a large group of undergraduates doing active research. Currently about 25 undergraduate students.

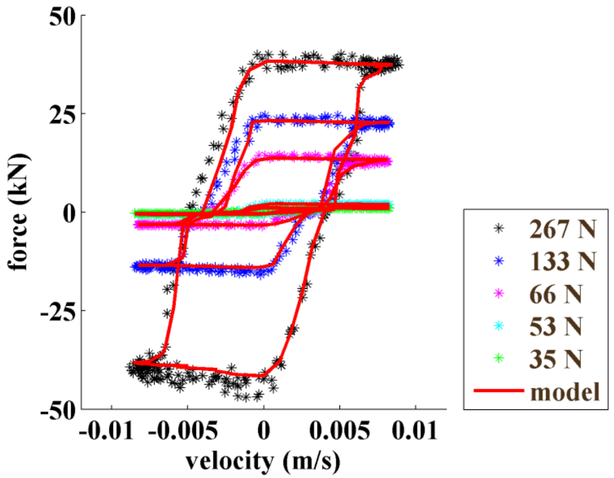
Undergraduate

Banded Rotary Friction Device (BRFD)



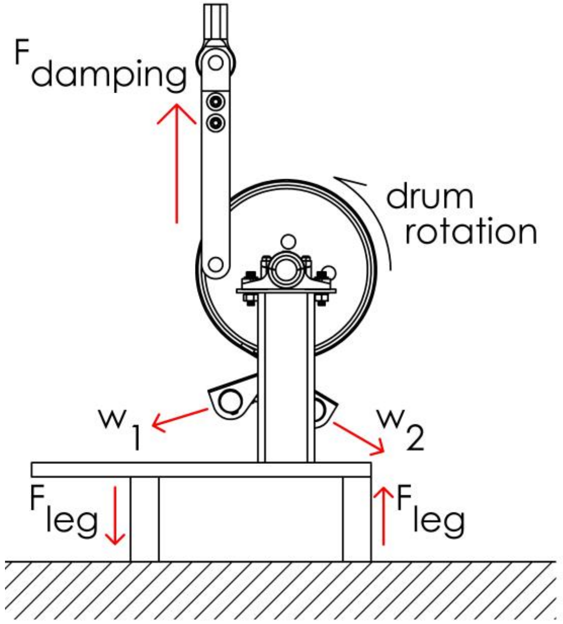


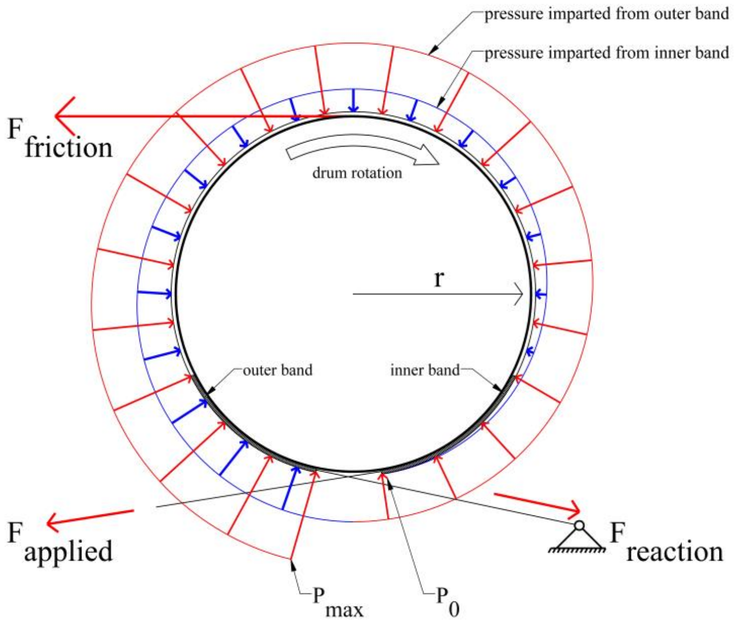


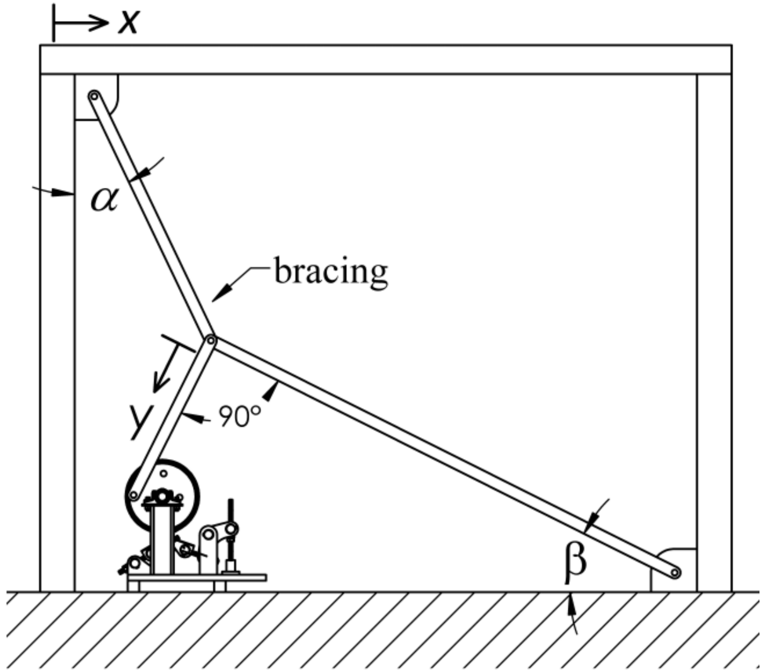


mechanical advantage of 142

Banded Rotary Friction Device (BRFD)







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

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

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

BRFD Timeline

The BRFD was:

- Built in my home shop in 2014
- Journal paper published in 2015
- Iowa State Shop Manager pressed us to trash it in Fall 2017; Jim Ricles asked us to ship it Lehigh.

Iowa State lab manager happy to see it go!

brake

Wood, Douglas L [CCE E] <dwoody@iastate.edu> Thu, Feb 8, 2018, 9:20 AM
to Austin

Austin
I am putting the friction brake on a pallet today in order to have it shipped out. Would like to know what all needs to go with this thing. See me when you have a chance.
Thanks

Douglas Wood, Assoc. Scientist II/Manager
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Ames, IA 50011

dwoody@iastate.edu
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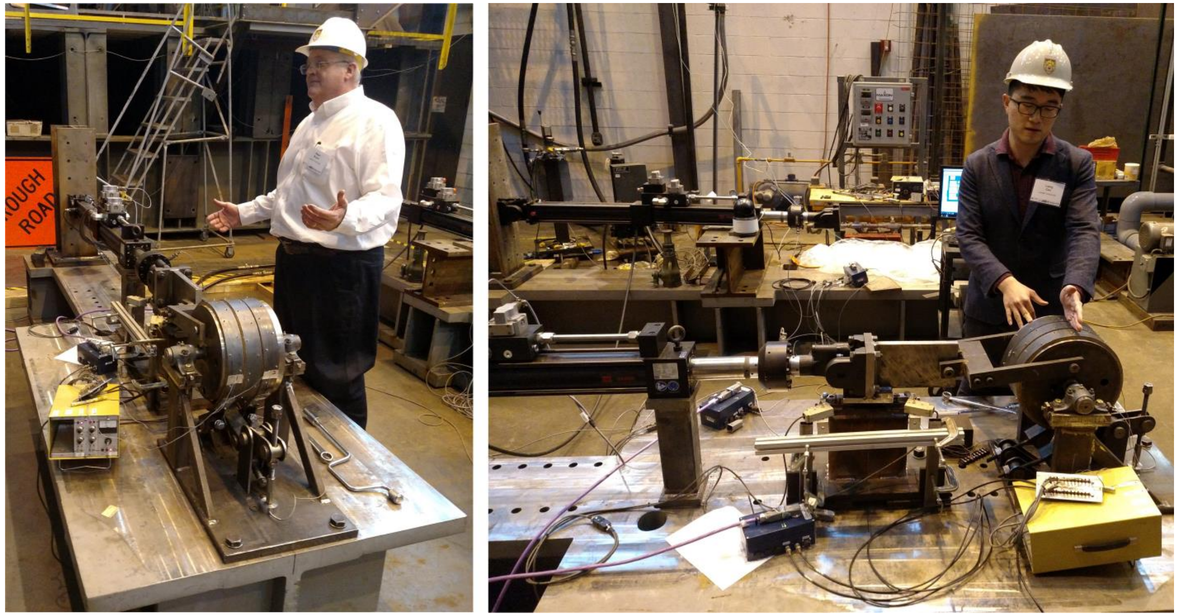
IOWA STATE UNIVERSITY

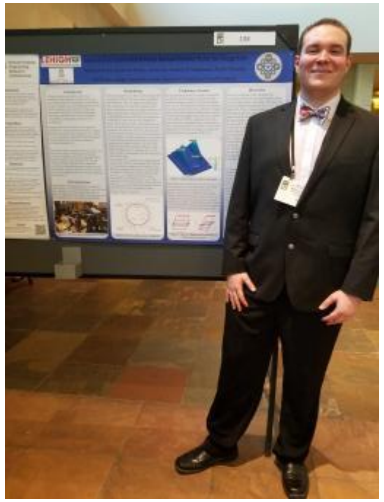
BRFD in 2019 with new bands



BRFD Further Developed over three summers

REU students participating in summer REUs have continued the project since 2019

Mitchell Stiles 2019 → COVID-19 2020 → Daniel Coble 2021 → Parker Huggins 2022



Mitchell Stiles – System Hardware Improvement

Mitchell Stiles
2019

COVID-19
2020

Daniel Coble
2021

Parker Huggins
2022

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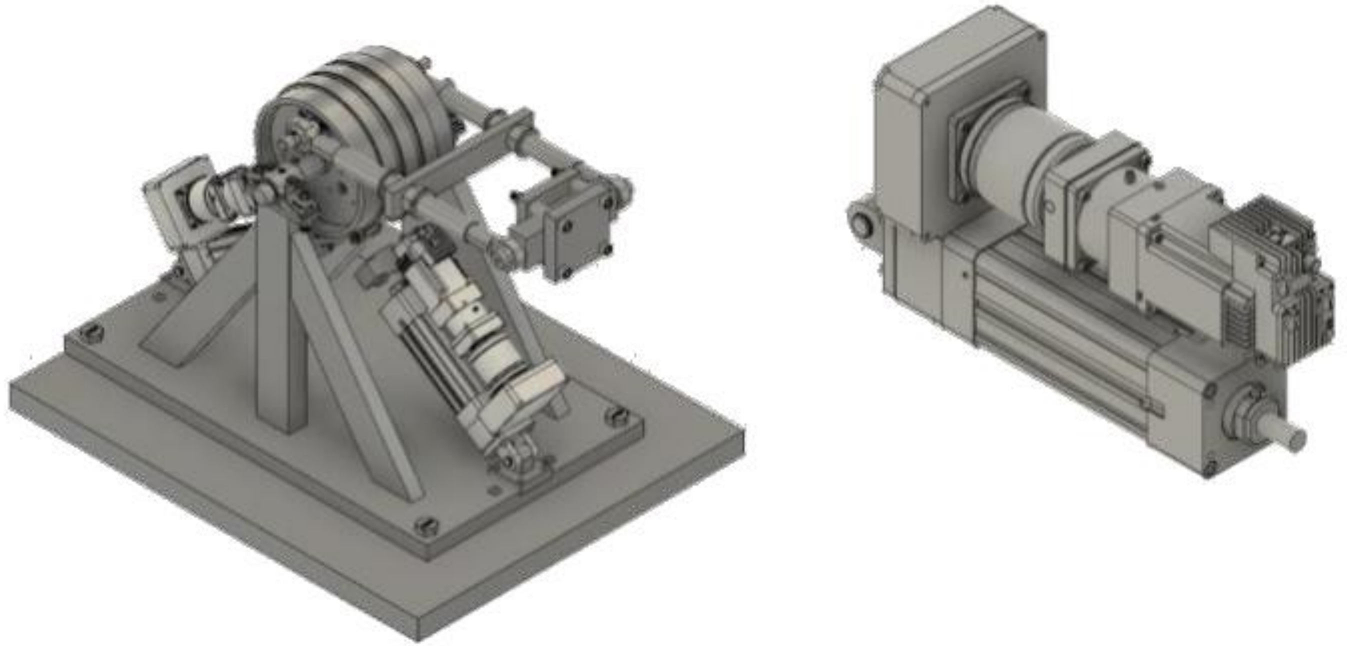
Expanding to Semi-active Device

New device is being engineered to create a stiffer design and incorporate electric actuators to create a semi-actively controlled friction damping device.



Rendering new Design

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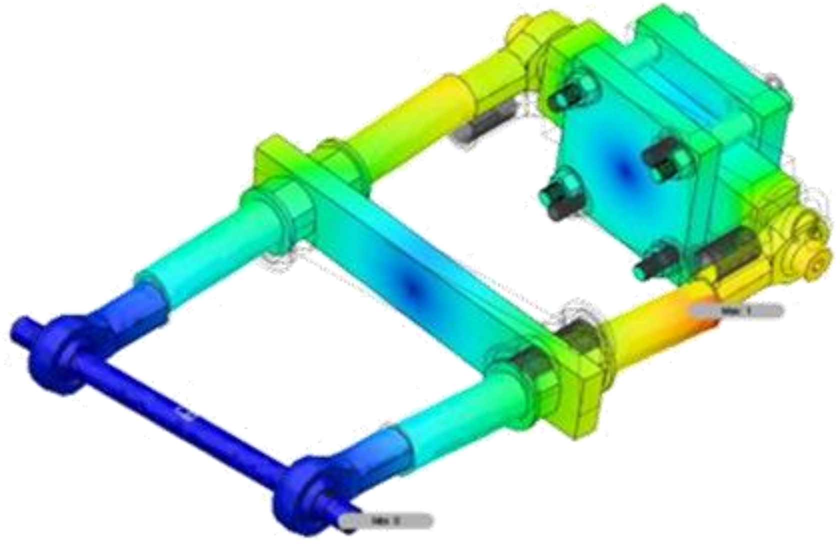
New Structure to Drum Connection

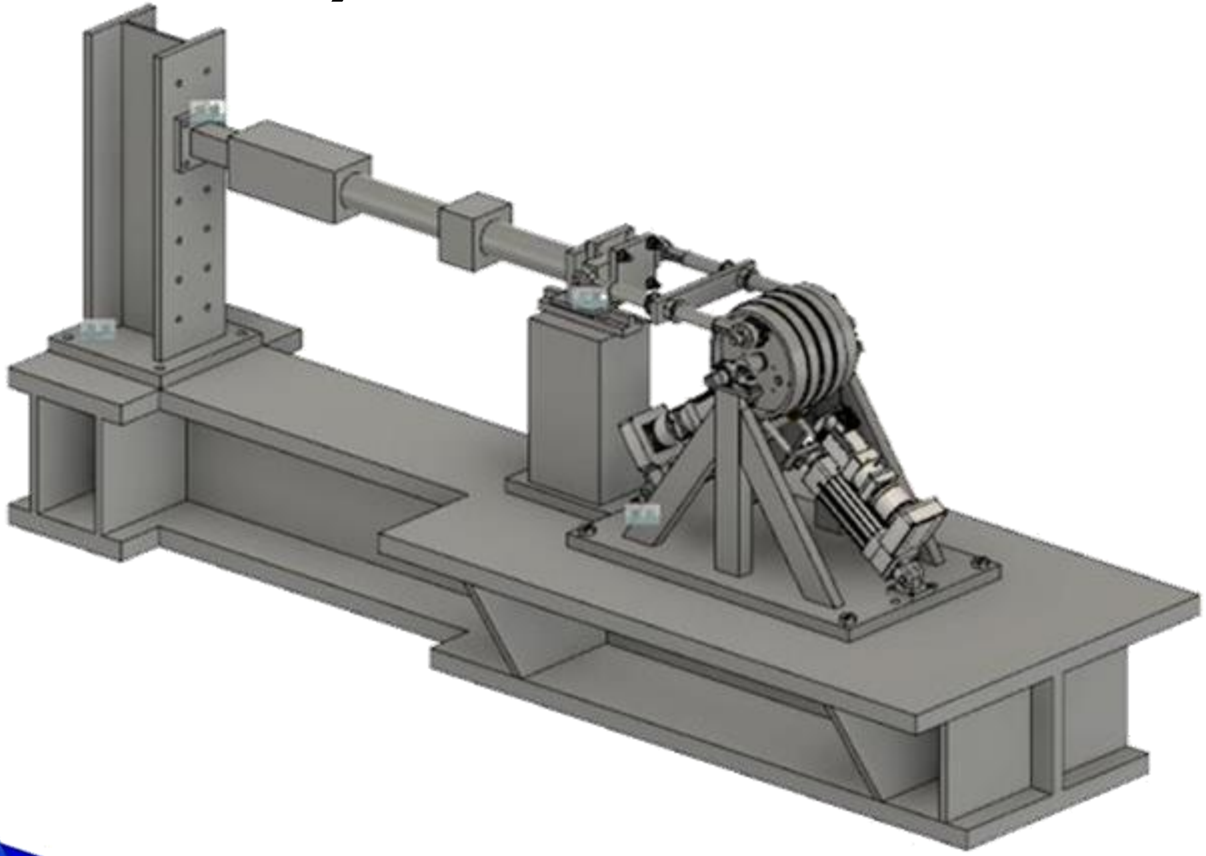
Old drum with previous connection



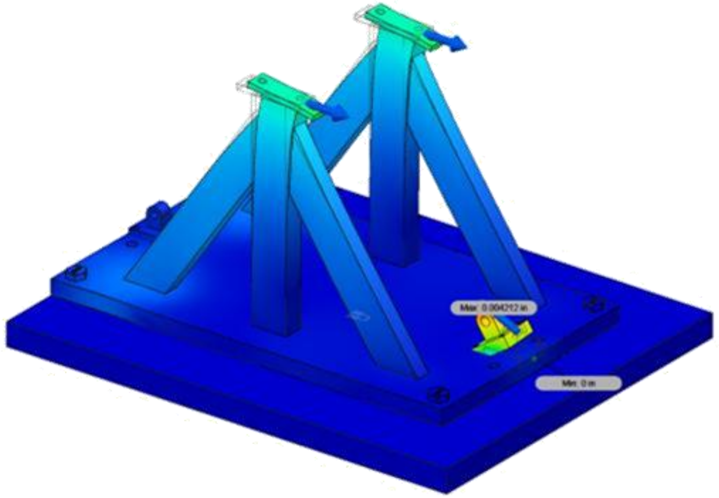
Mode Number	Frequency (Hz)
1	60.64
2	71.9
3	275.6
4	285.6
5	367.6

Methodology (Drawings and Simulation)

New steel drum

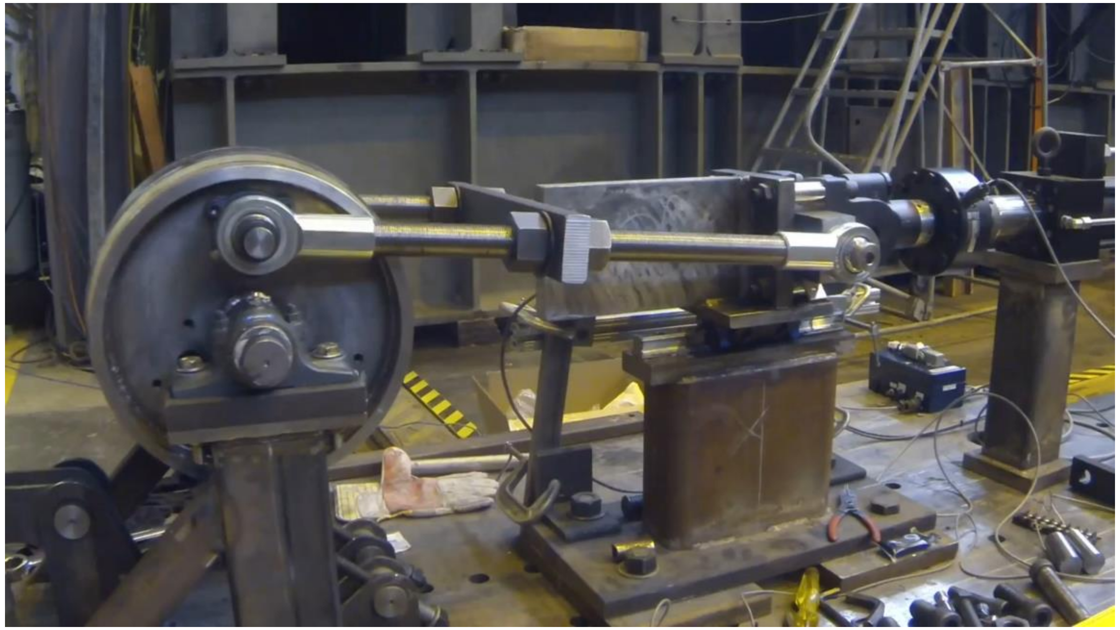


I-Beam Foundation with semi-active BRFD

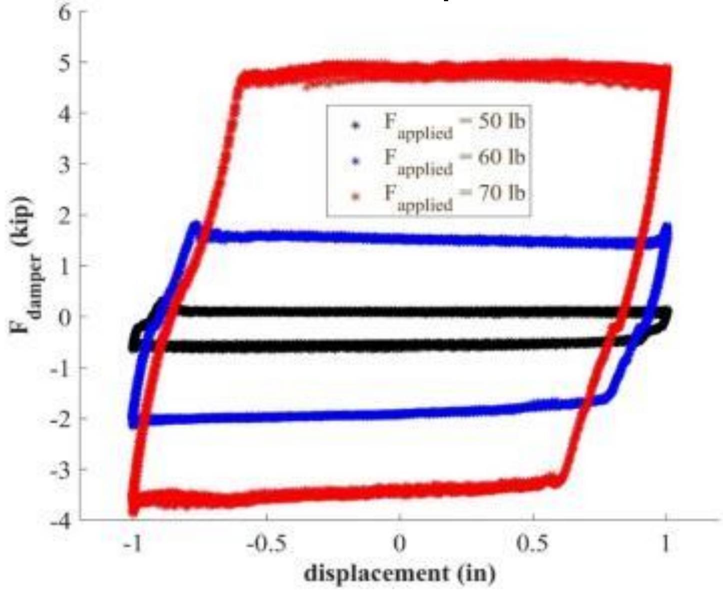


simulation is of the new frame and support struts

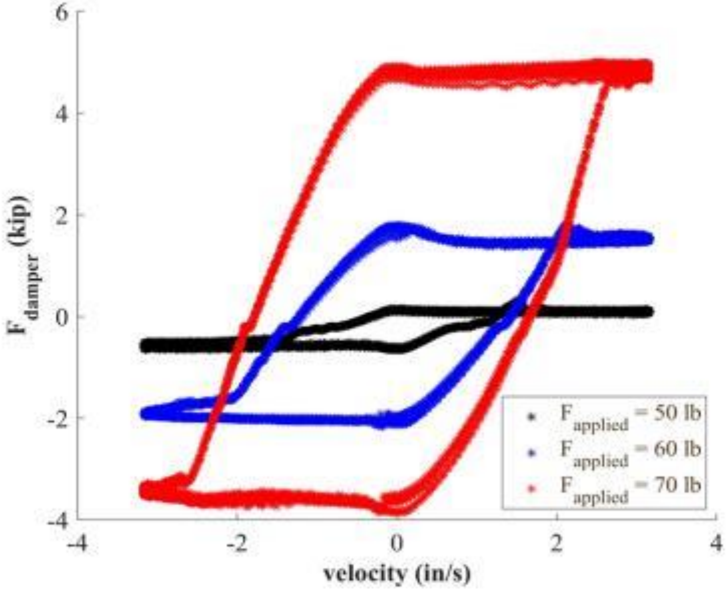
Preliminary Results



Force vs. displacement



Force vs. velocity



Daniel Coble – Friction Modeling using Physics Informed Machine Learning

Mitchell Stiles 2019	COVID-19 2020	Daniel Coble 2021	Parker Huggins 2022

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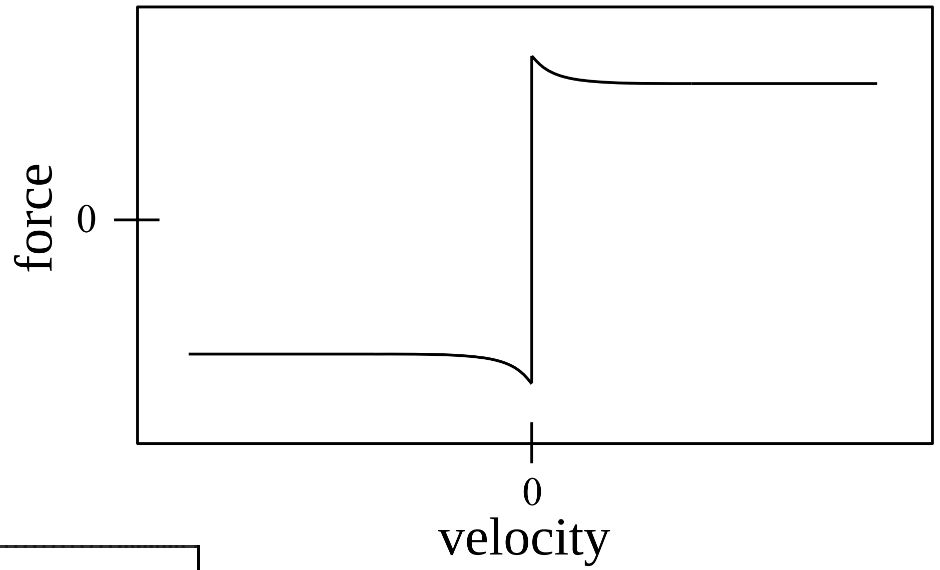
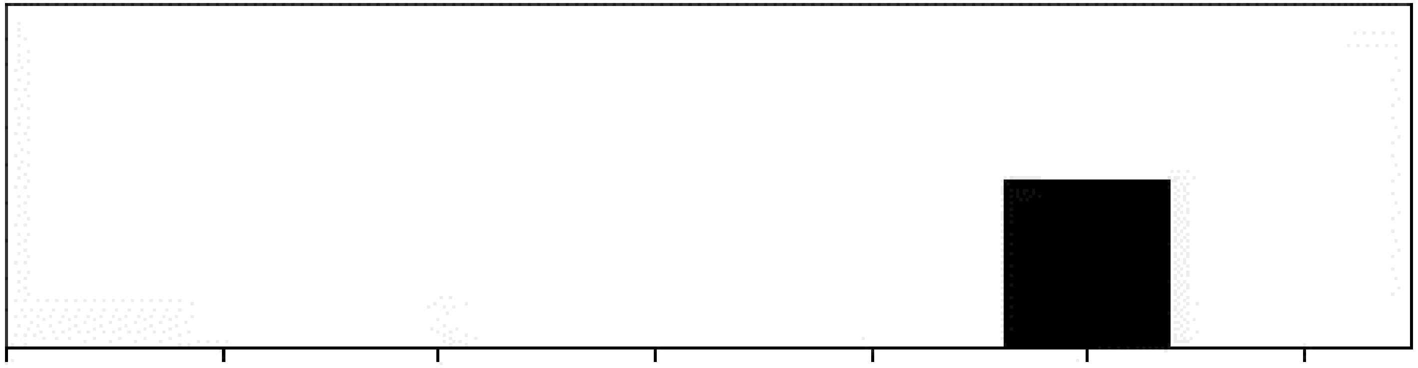
Problems in modeling friction

- Rate-dependent properties.
- Hysteretic behavior.
- Stribeck effect: static friction is greater than kinetic friction.
- Backlash: loss of friction during reversal of travel.





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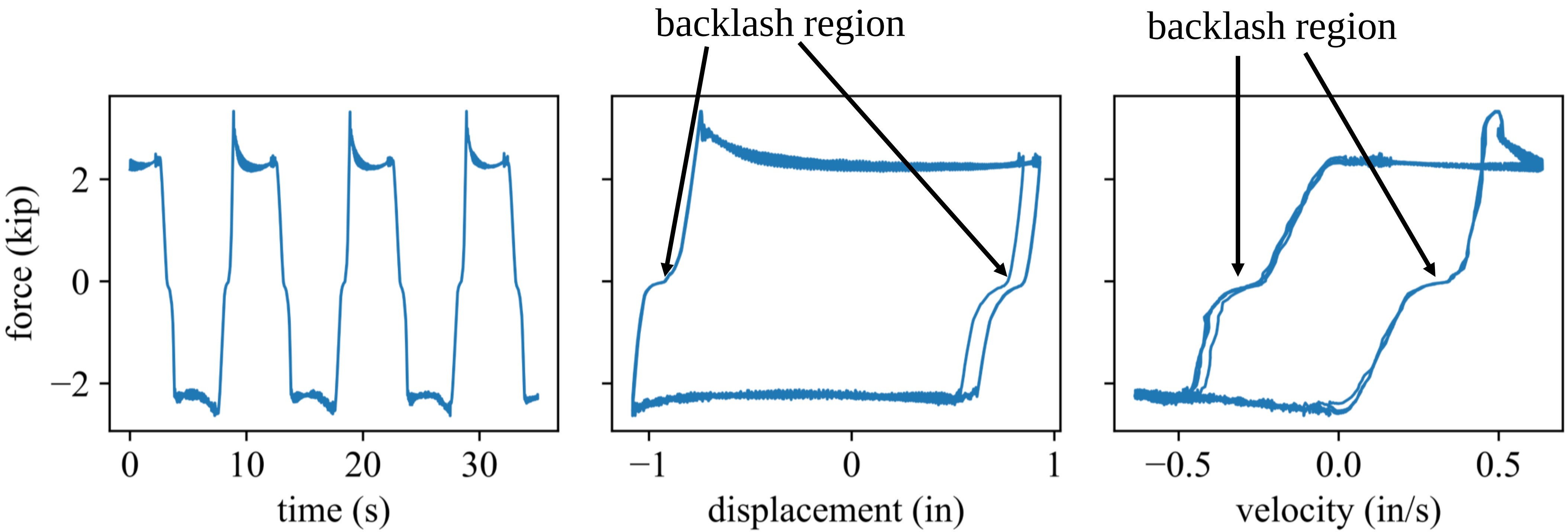
Device Characterization

- The device was characterized with four sinusoidal displacement tests with frequencies between 0.1 Hz and 1.0 Hz.
- The backlash effect: self-energizing effect depletes during reversal of travel.



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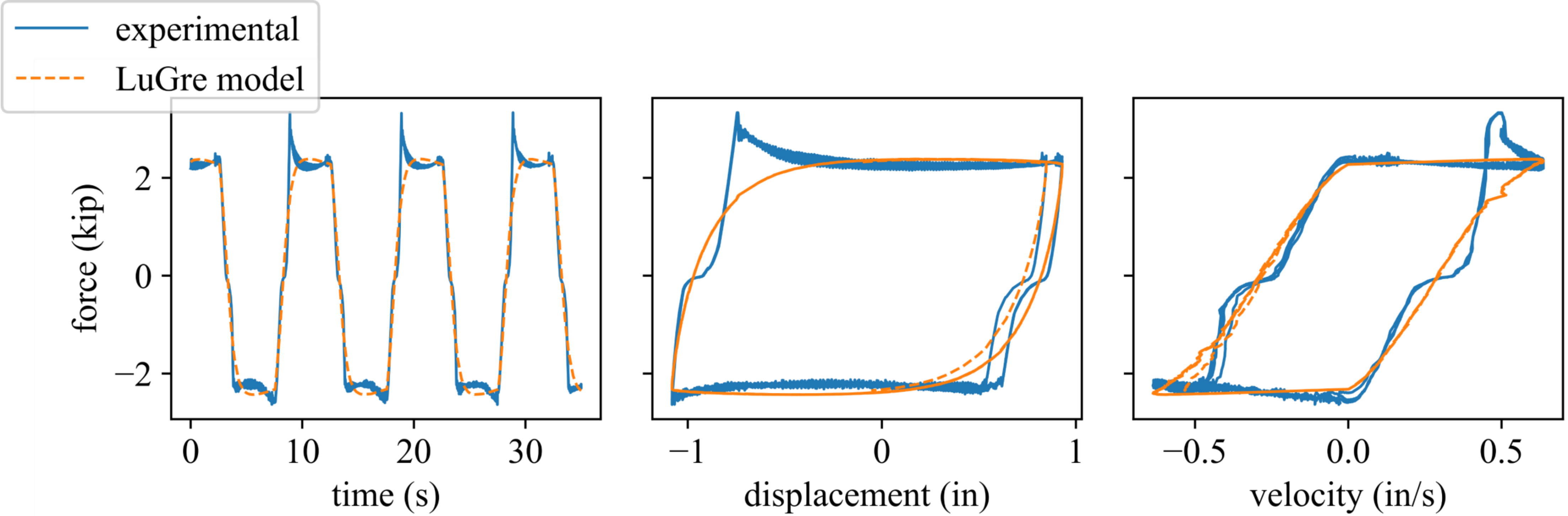
Problems using current models

- Standard dry friction models like the LuGre model cannot capture backlash.



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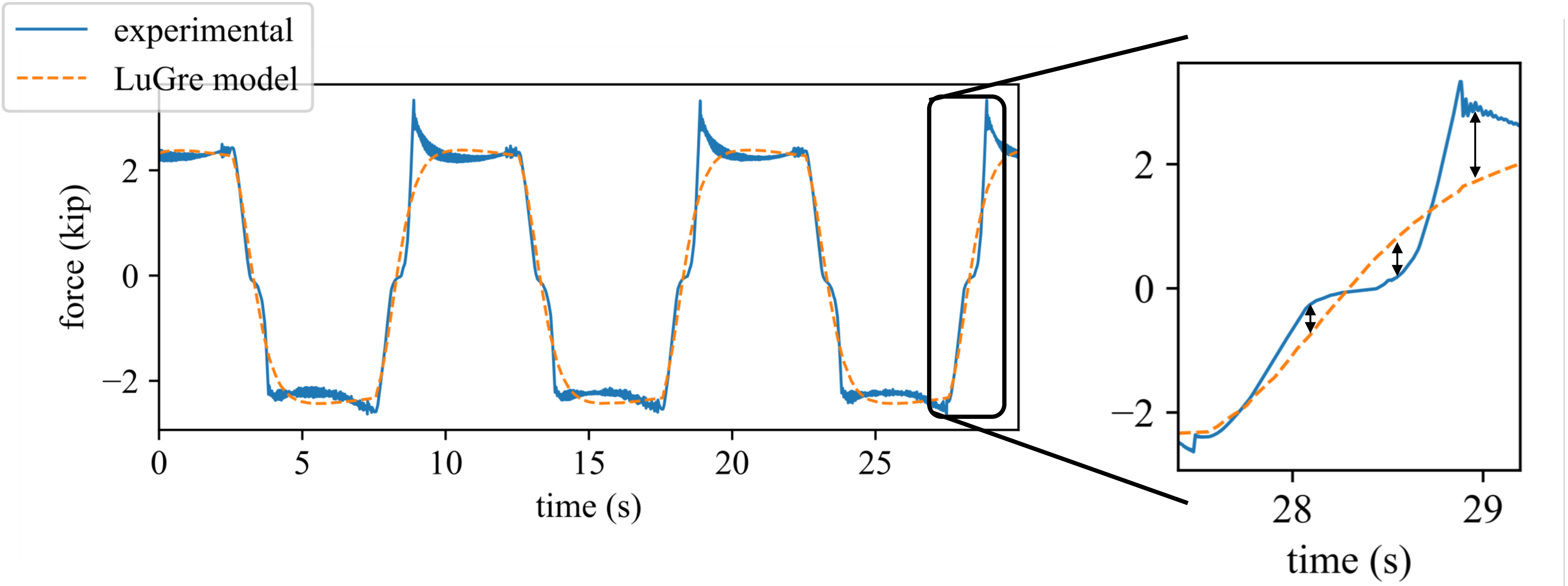

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Model Development

- Physics-informed component: the LuGre model.
- A ‘rate and state’ model with one state variable commonly used to describe dry friction systems.
- Physical interpretation of parameters:
  - Static parameters: F_c, F_s, v_s.
  - Dynamic parameters: σ_0, σ_1, σ_2.
- σ_0 controls hysteresis rate of change–backlash effect.

$$\dot{z} = v - \sigma_0 \frac{|v|}{g(v)} z$$

$$F = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 v$$

$$g(v) = F_c + (F_s - F_c)^{\left(\frac{v}{v_s}\right)}$$

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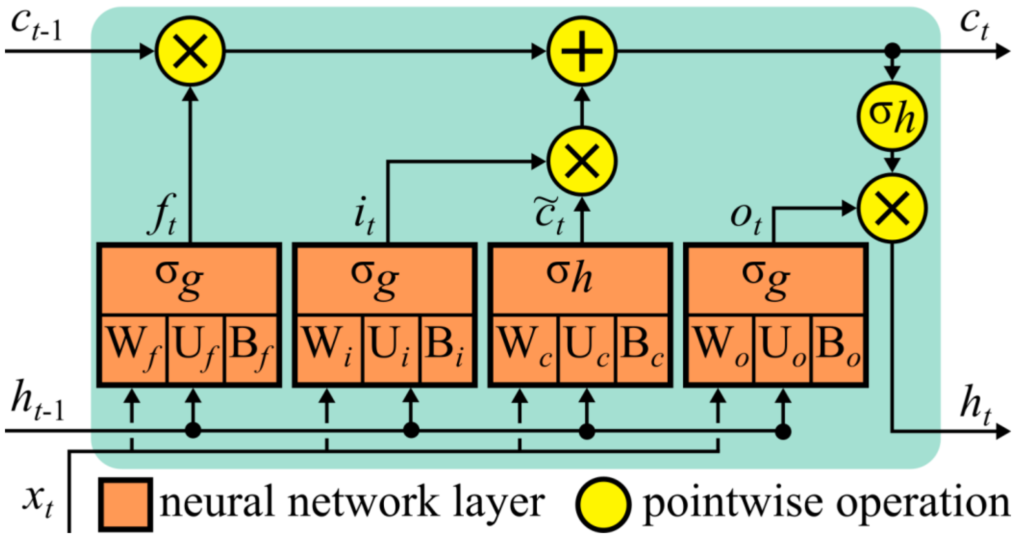
Model Development

- Machine-learning component: Long short-term memory.
- A class of recurrent neural network designed to detect longer time-series patterns than standard RNNs.
- State vectors h_t and c_t maintain state information.

$$f_t = \sigma_g\left(W_f x_t + U_f h_{t-1} + b_f\right)$$
$$i_t = \sigma_g(W_i x_t + U_i h_{t-1} + b_i)$$
$$o_t = \sigma_g(W_i x_t + U_o h_{t-1} + b_o)$$
$$\tilde{c}_t = \sigma_h(W_c x_t + U_c h_{t-1} + b_c)$$
$$c_t = f_t \circ c_{t-1} + i_t \circ \tilde{c}_t$$
$$h_t = o_t \circ \sigma_h(c_t)$$



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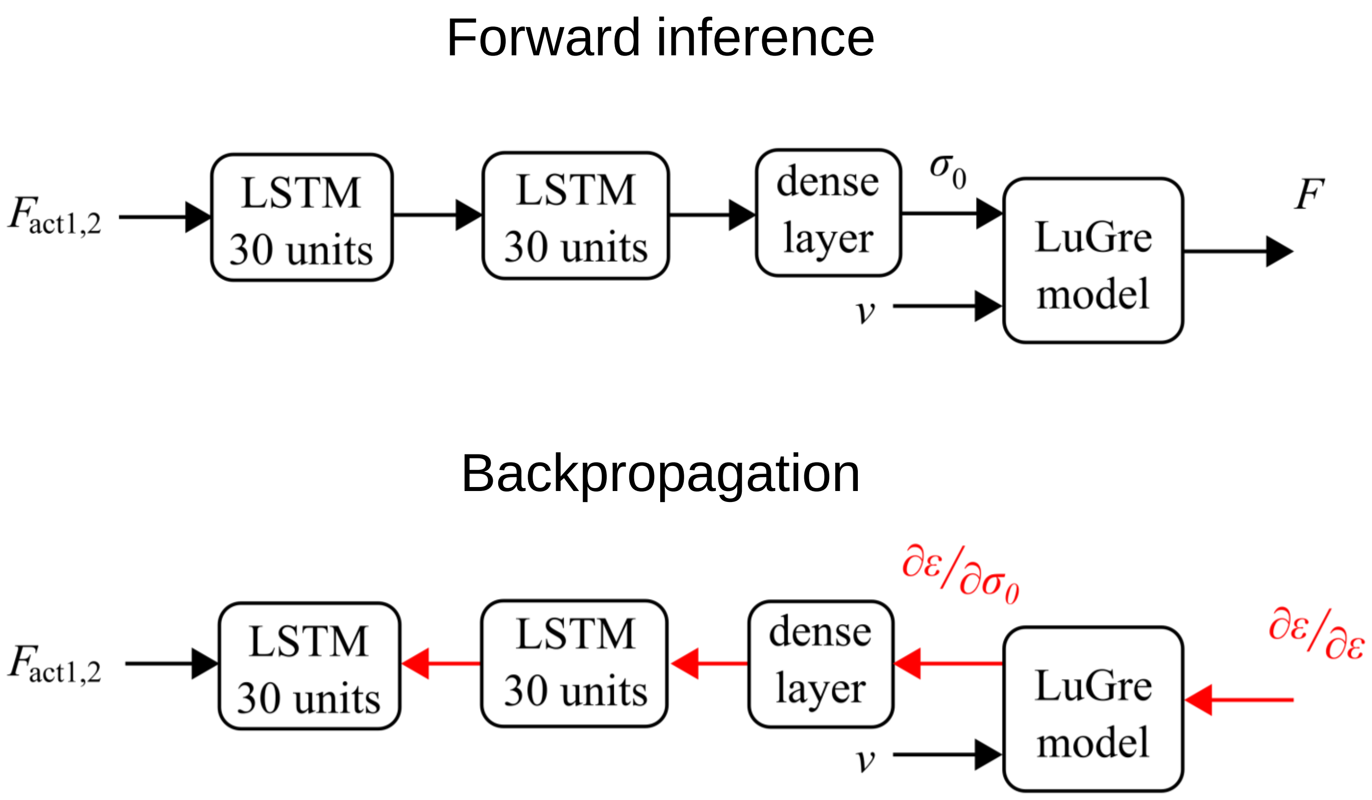
Model Training

- Static parameters F_c, F_s, and v_s found with a least-squares analysis.
- Supervised training procedure using damping force measured during characterization test.
- Backpropagation provides an error gradient $\partial\varepsilon/\partial\sigma_0$ as an intermediate value in updating weights.



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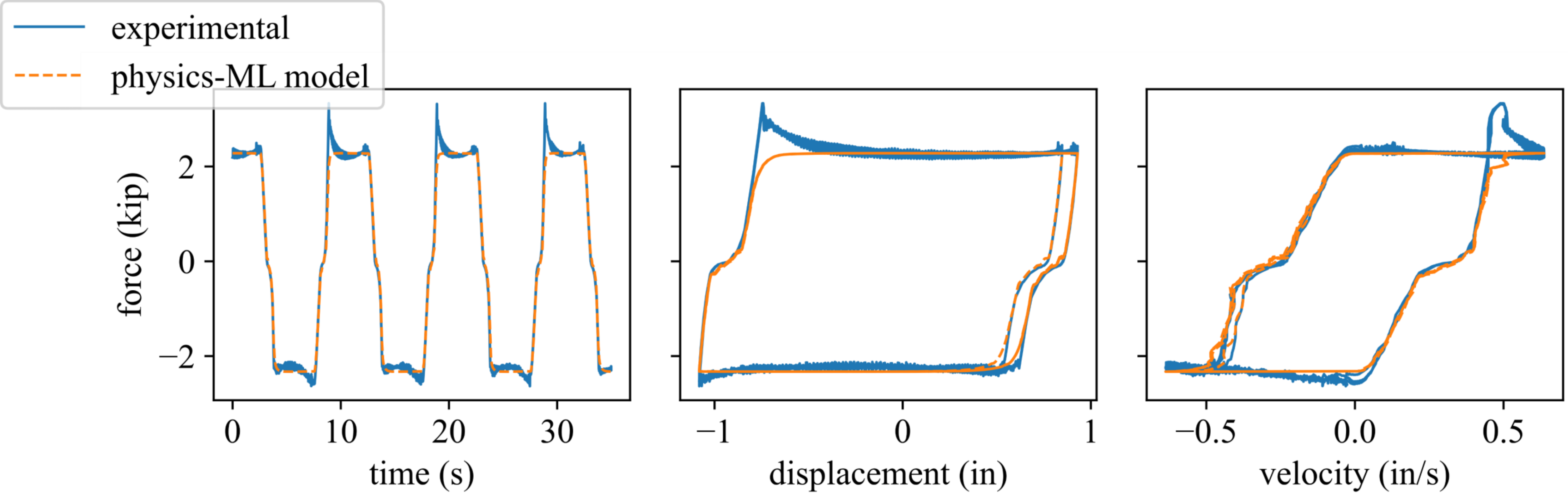
Results

- Compared against LuGre models found with least-squares fit.
- Normalized root mean squared error from 6.71% to 3.16%, a reduction of 53%.
- Most of the error reduction comes from the ability to reproduce the backlash effect.



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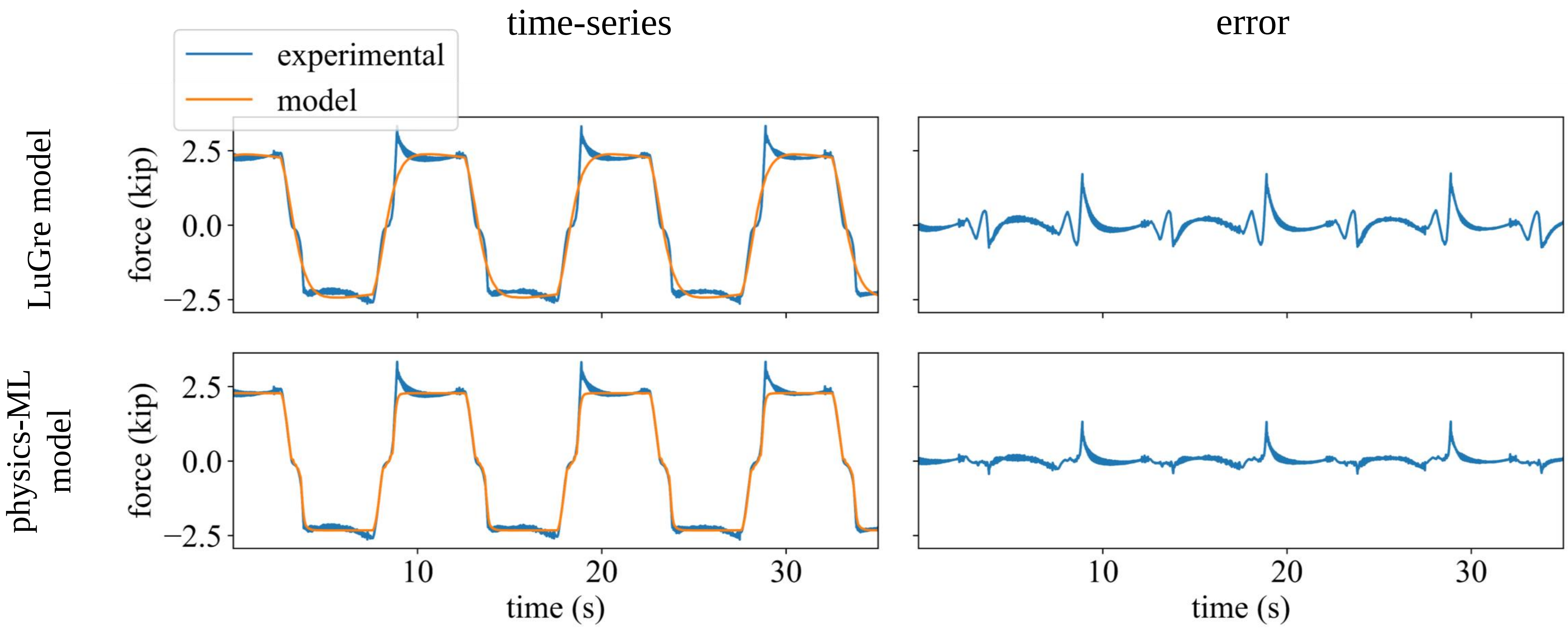
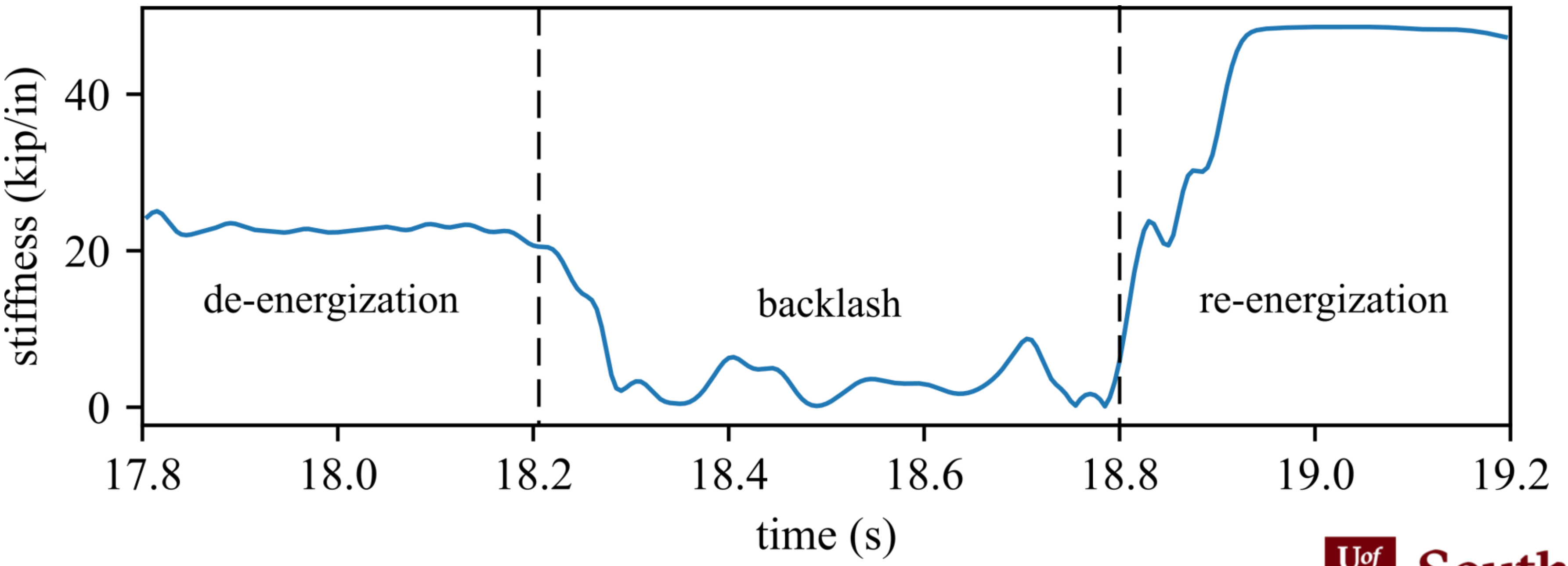
Results

Comparison between standard LuGre model and physics-ML model



Results

- The ML model produced a time-dependent function for σ_0—without any measurement of σ_0.
- Applications in ‘indirect measurement’ time-series characterization of physical systems.



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Parker Huggins – Characterization of a Semi-active Model

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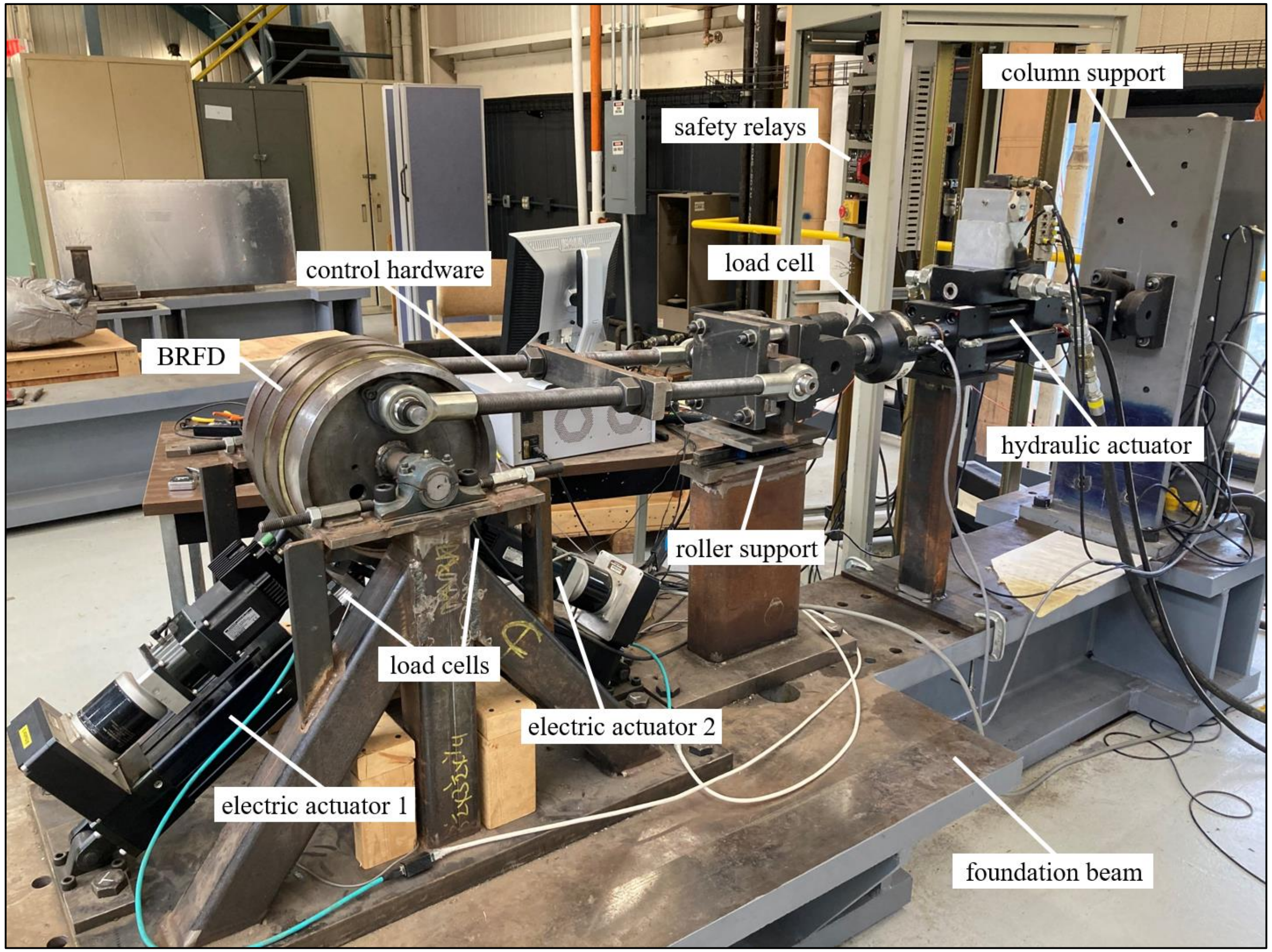
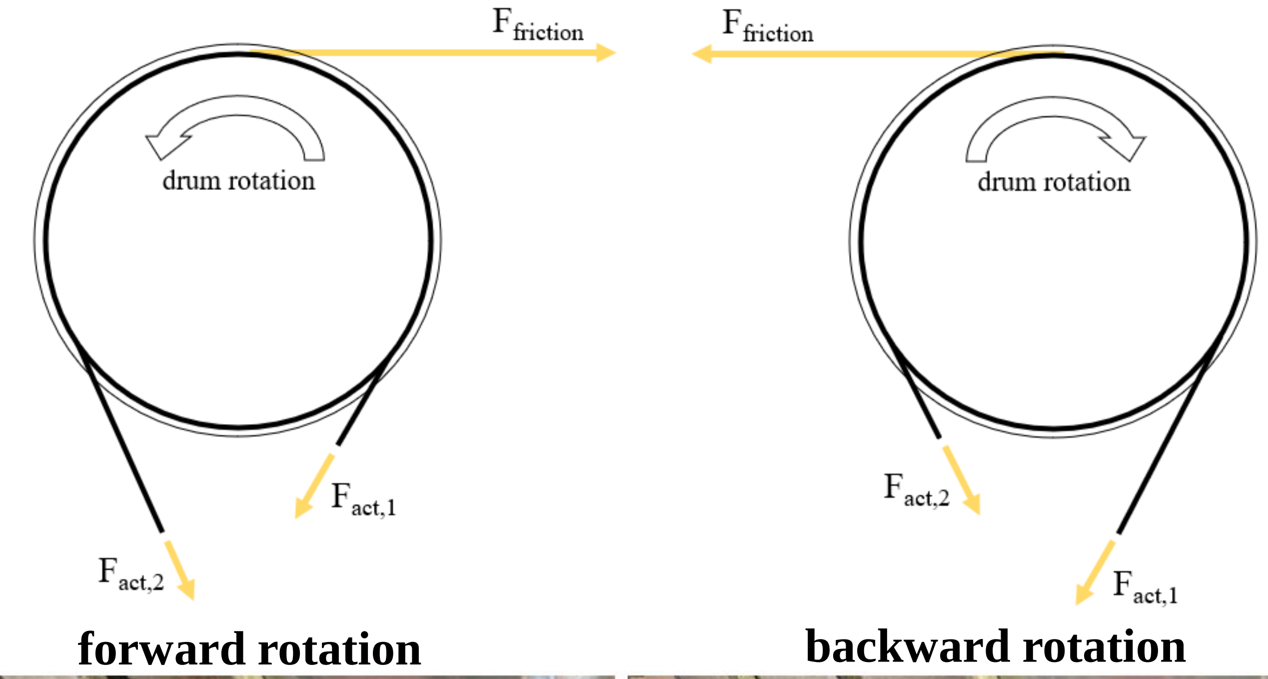
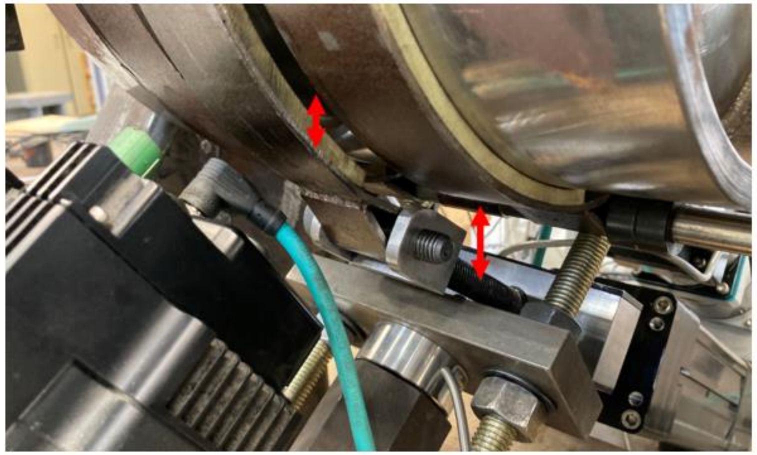
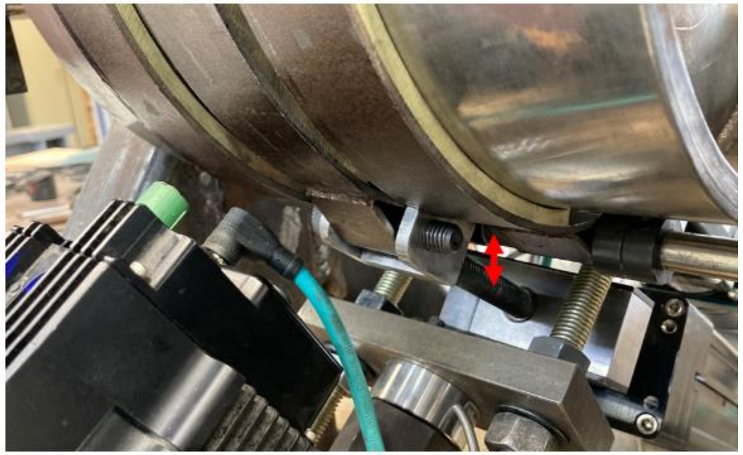
Test Setup


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

BRFD Modeling Difficulties







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

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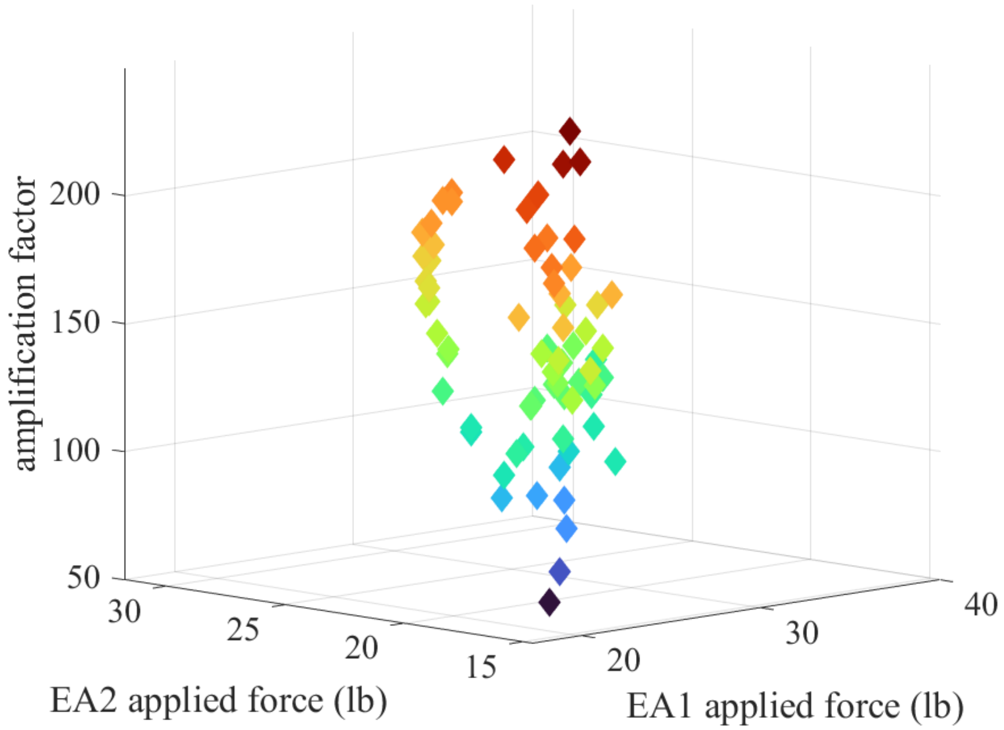
Damper Force Amplification



- 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 $\gg 1$
- Amplification **increases** with pretension forces

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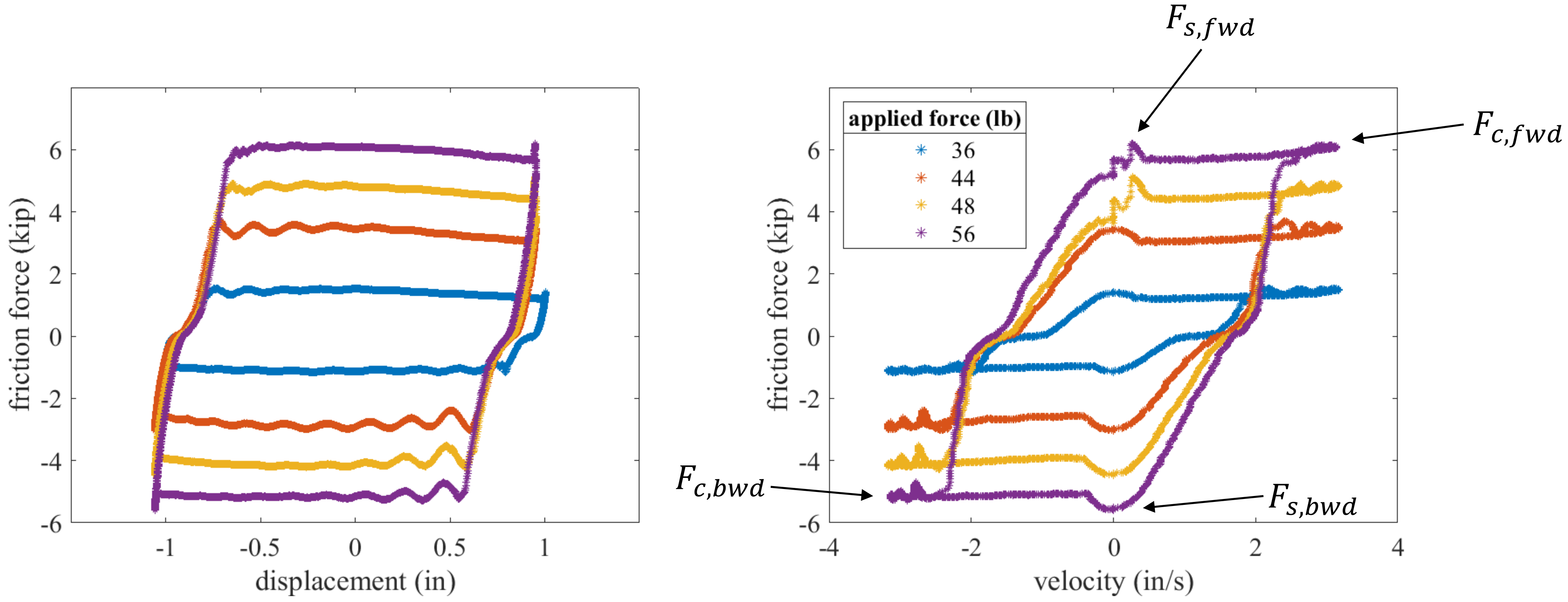
Passive to Semi-active



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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

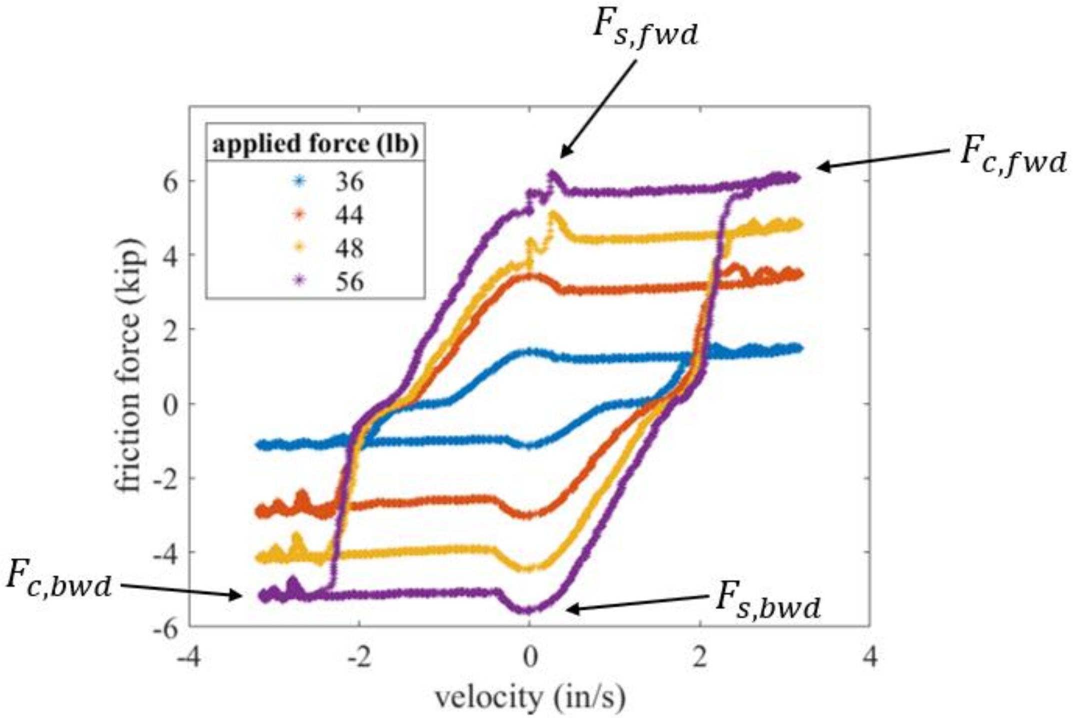
Actuator 1 position (in) / Actuator 2 position (in)

	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									

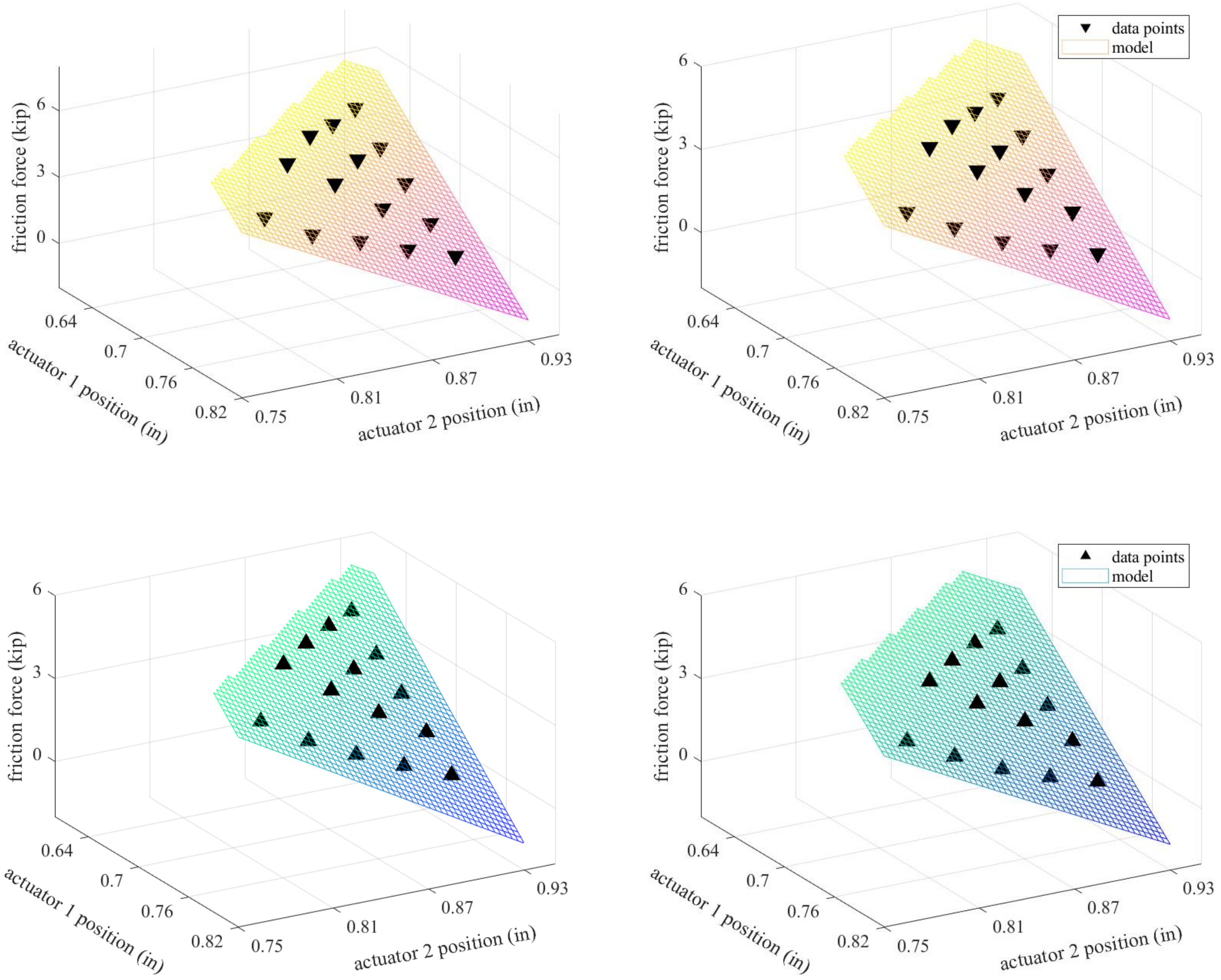
Full Test

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

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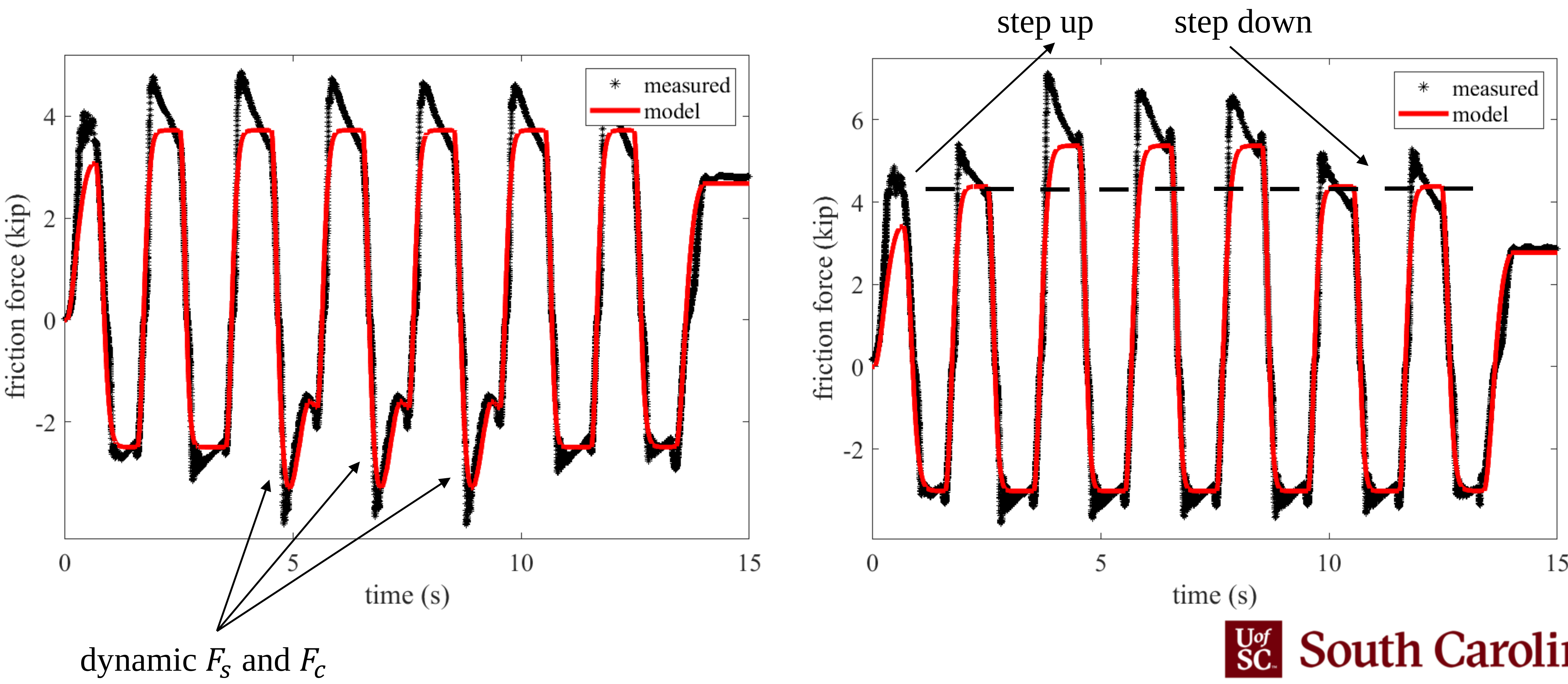
Results

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



THAT YOU!

WANT THE DATA?

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

Contact Information: Austin Downey
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Github: https://github.com/austindowney
Github-Lab: https://github.com/Arts-laboratory/

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