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Natural Hazards Engineering Research Infrastructure

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Characterization and Modeling of a Semi-active Rotary Friction Damper

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NHERI LEHIGH
Real-Time Multi-Directional Testing Facility

Structural Damping

Purpose: Reliably absorb and dissipate energy from dynamic loadings (i.e. earthquake, wind) to mitigate structural vibrations, displacements, etc.

Some common examples include:

- Tuned mass dampers
- Electromagnetic dampers
- Friction dampers

Fig. 1. Taipei 101.

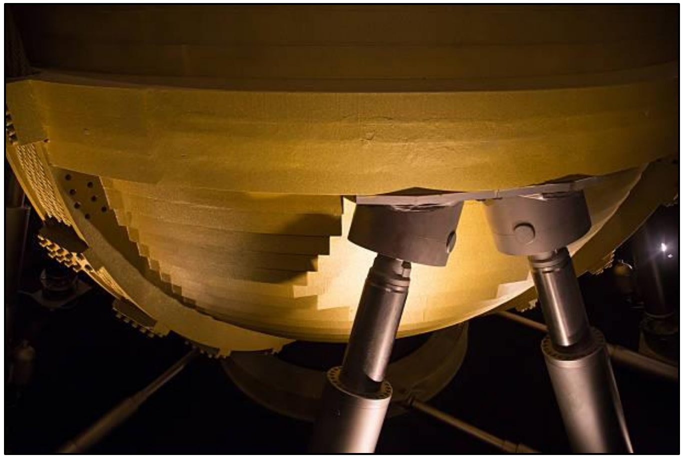


Fig. 2. Real-world TMD.

Damper Classes

Passive:

- Require no external power
- Limited functional bandwidth

Active:

- Adaptable/quick
- Require much external power

Semi-active:

- Purely reactive
- Require little external power

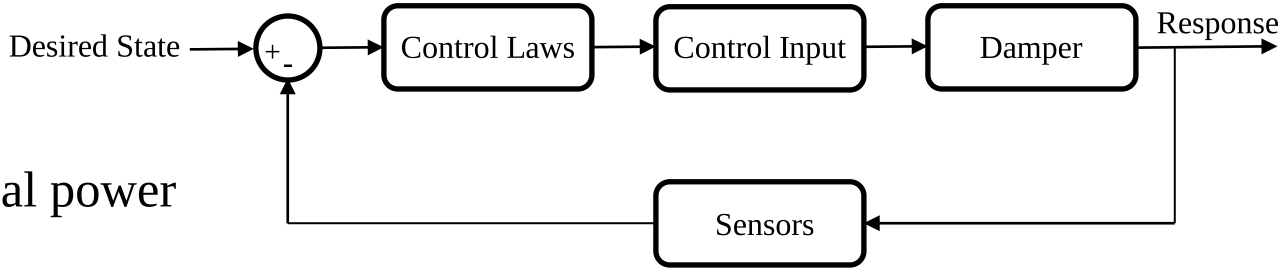


Fig. 3. Controlled damper block diagram.

Semi-active dampers **add no energy to the system** and are **fail safe**.

Banded Rotary Friction Device

- Novel variable friction damper inspired by band brake technology
- Drum rotates, friction develops between drum and elastic bands
- Electric actuators can adjust band tension → control damping

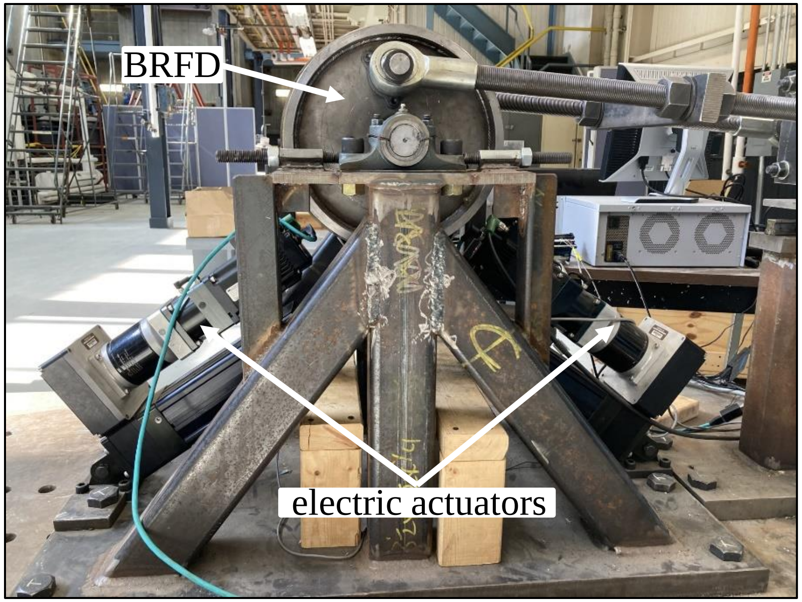


Fig. 4. BRFD side profile.

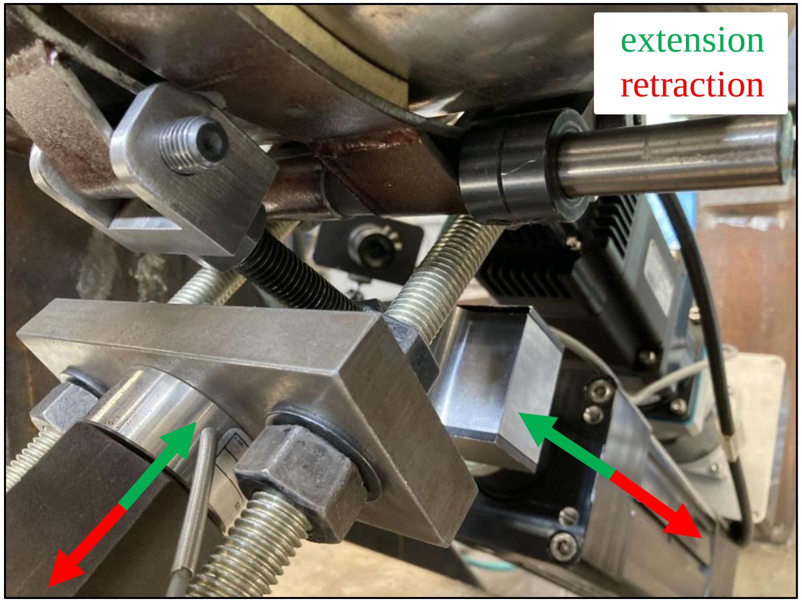


Fig. 5. BRFD electric actuators close up.

Test Setup

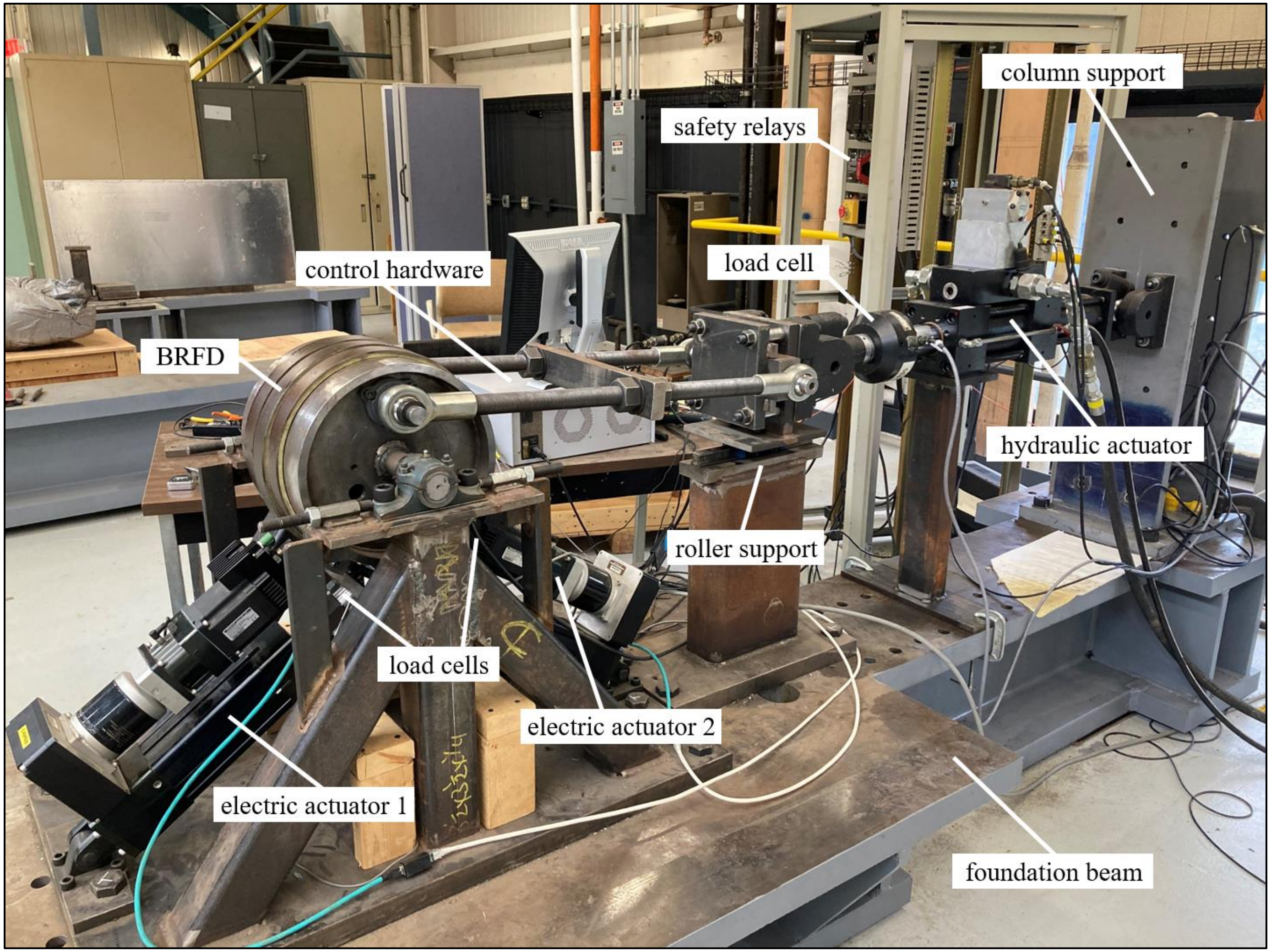


Fig. 6. BRFD and testbed.

Passive Operation

Vid. 1. BRFD passive mode operation.

Passive to Semi-active

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

Goal: Control kinetic friction with the electric actuators

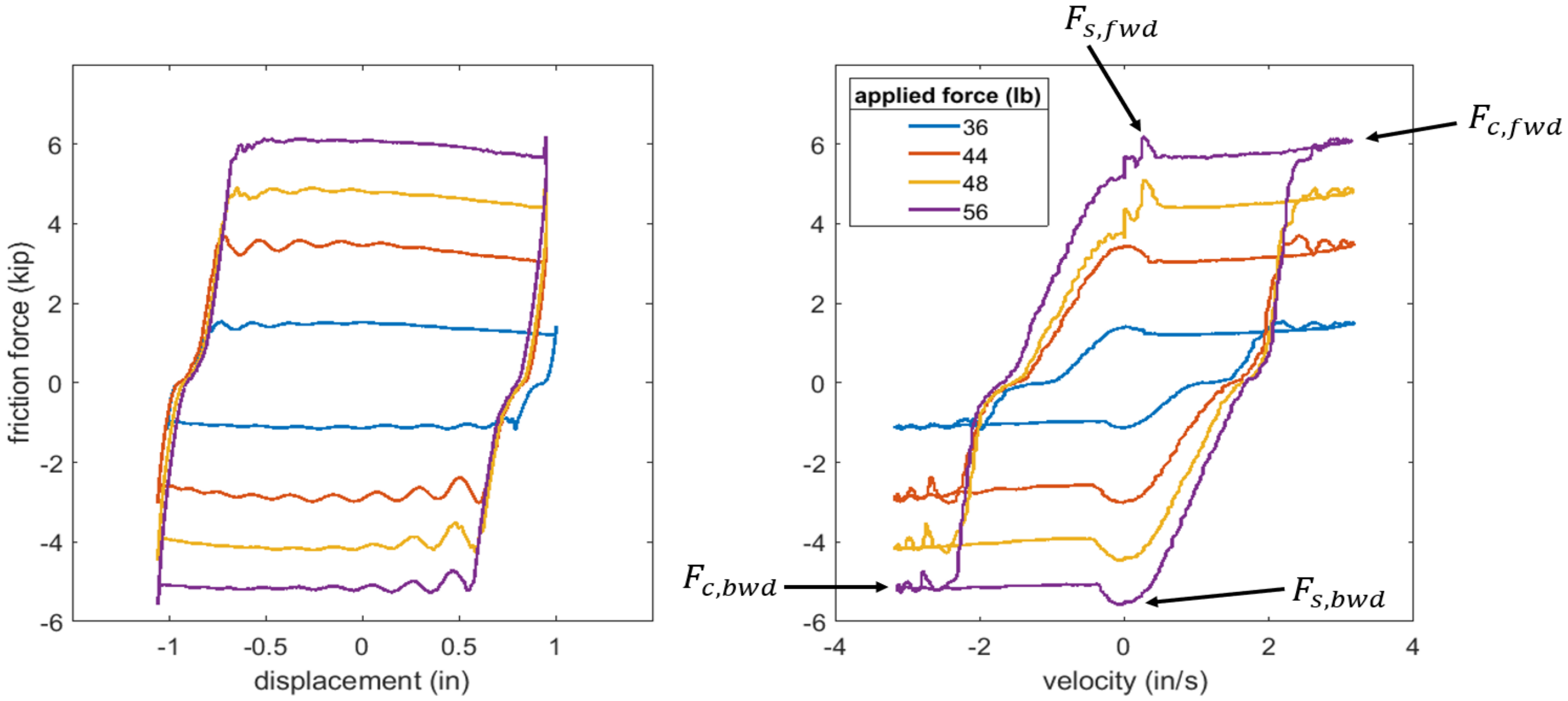
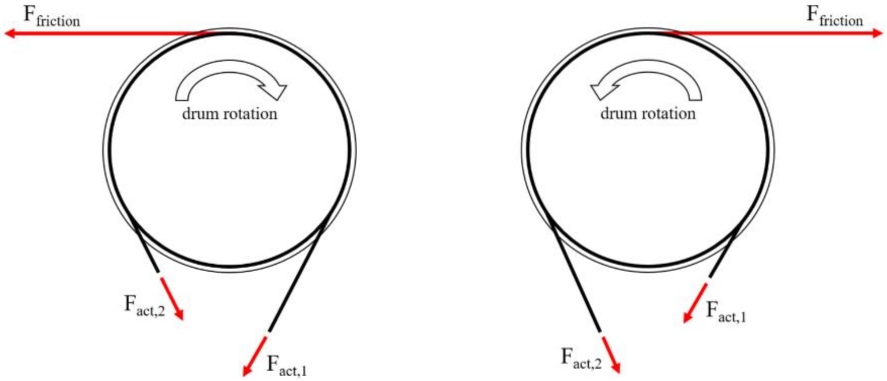


Fig. 7. BRFD passive response for various applied forces.

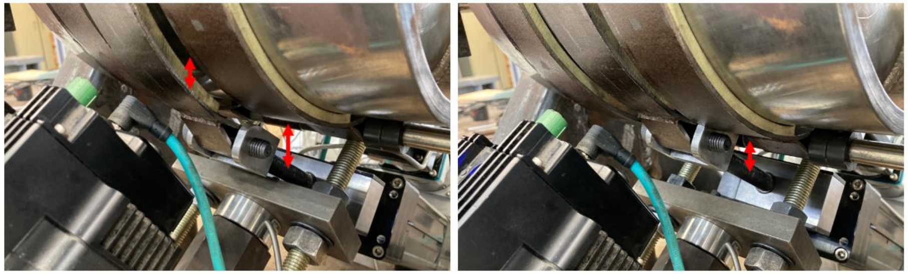
Semi-active Modeling Difficulties

1) **Friction**: stick-slip motion, Stribeck effect, hysteresis
2) **Self-energizing effect**: back-and-forth of energy stored and released
3) **Deflections**: electric actuators/elastic bands
4) **Sensitivity**: slight variations in setup conditions can vastly effect output



(a) forward rotation, $F_{act,2} >> F_{act,1}$ **(b)** backward rotation, $F_{act,1} >> F_{act,2}$

Fig. 8. Forces on the BRFD.



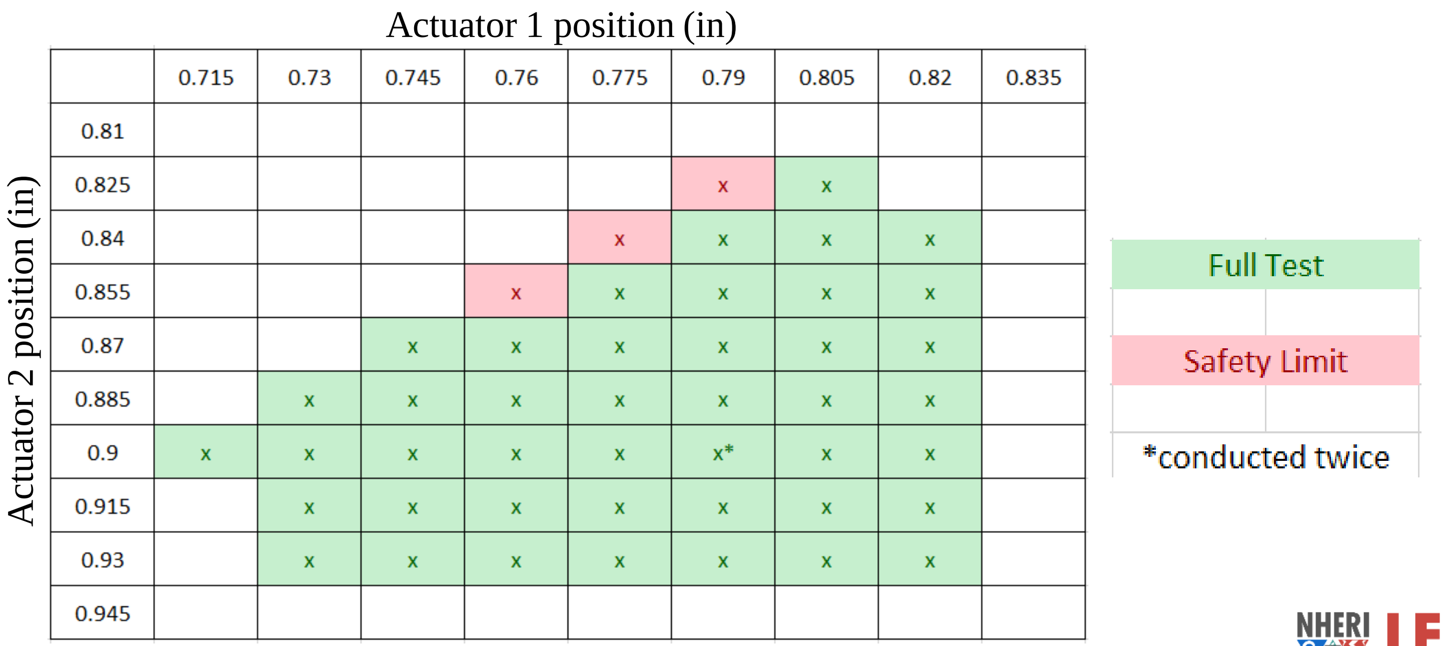
(a) slack **(b)** taut

Fig. 9. Electric actuator deflection.

Testing Procedure

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

Table 1. Passive tests conducted on 07/20.



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									

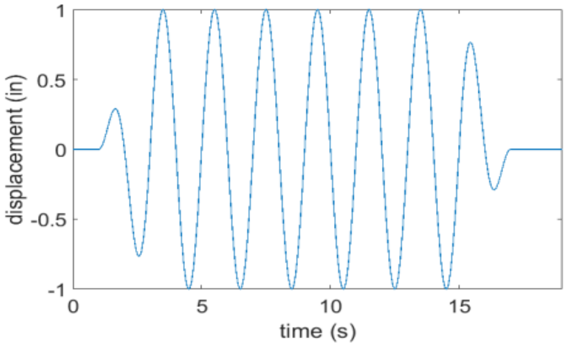
🟩 Full Test

🟥 Safety Limit

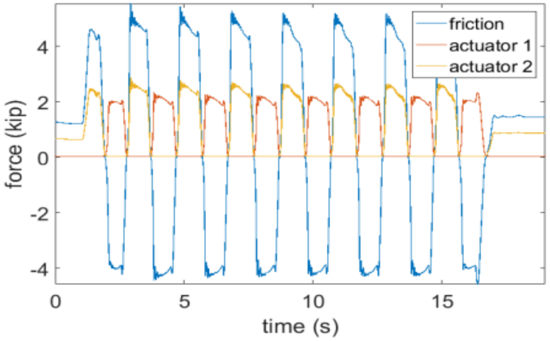
*conducted twice

Relationship Development

Question: How is damping related to electric actuator forces?

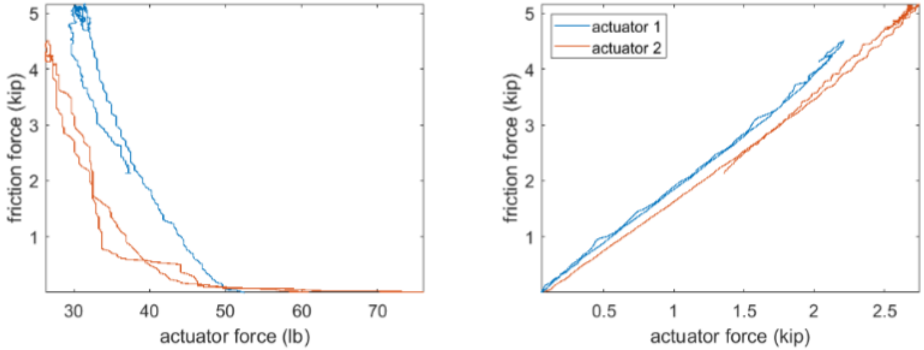


(a) displacement input



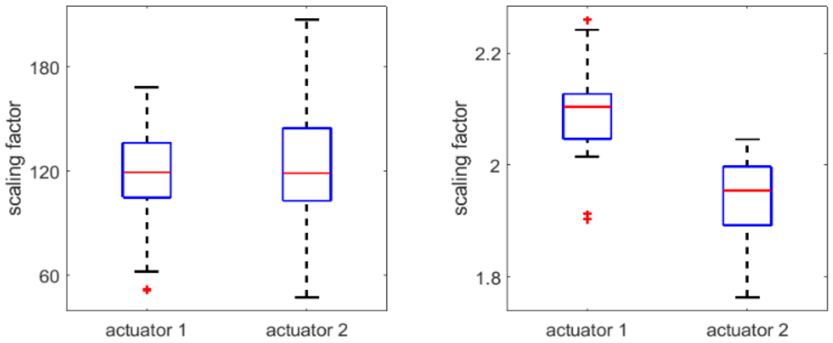
(b) damper response

Fig. 10. Example characterization data.



(a) slack **(b)** taut

Fig. 11. Friction-actuator force dependence.



(a) slack **(b)** taut

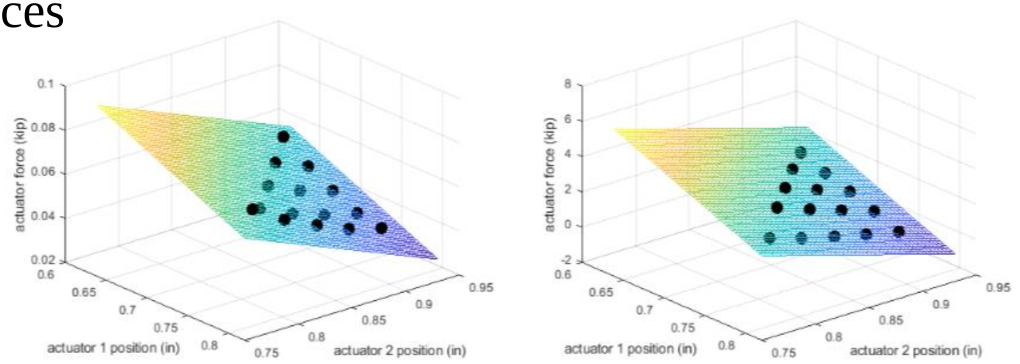
Fig. 12. Distribution of friction-actuator force slopes.

Answer: Damping is proportional to actuator forces.

Relationship Development

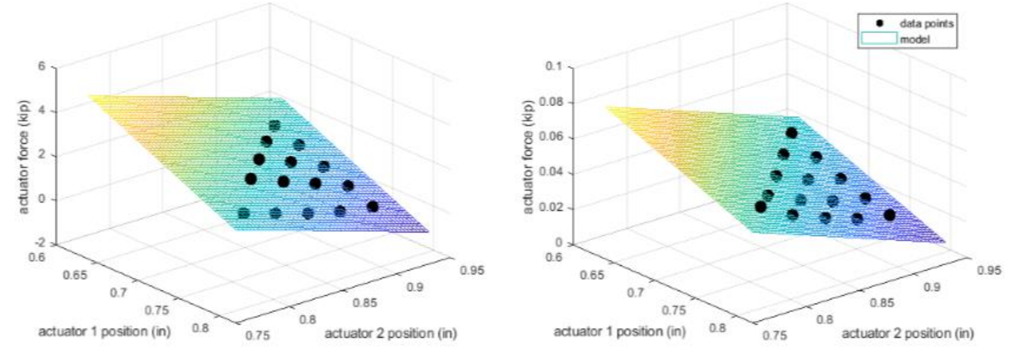
Question: How are electric actuator forces related to actuator displacements?

- Regressed actuator forces against positions
- Slopes capture rate at which actuator forces change with **displacements**
- Linear models ignore potential for coupling effect to exist



(a) forward, actuator 1

(b) forward, actuator 2



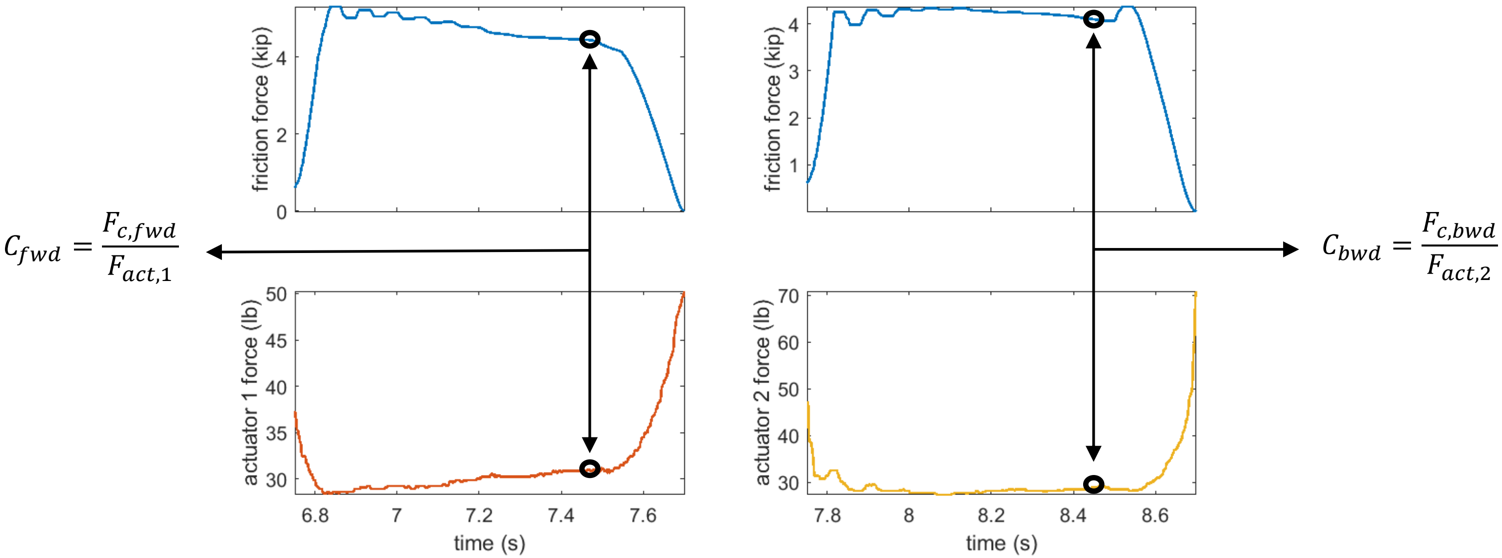
(c) backward, actuator 1

(d) backward, actuator 2

Fig. 13. Actuator force-position models.

Answer: Actuator forces are proportional to actuator positions.

Damper Force Amplification



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

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

(a) forward rotation **(b)** backward rotation

Fig. 14. Amplification factor computation.

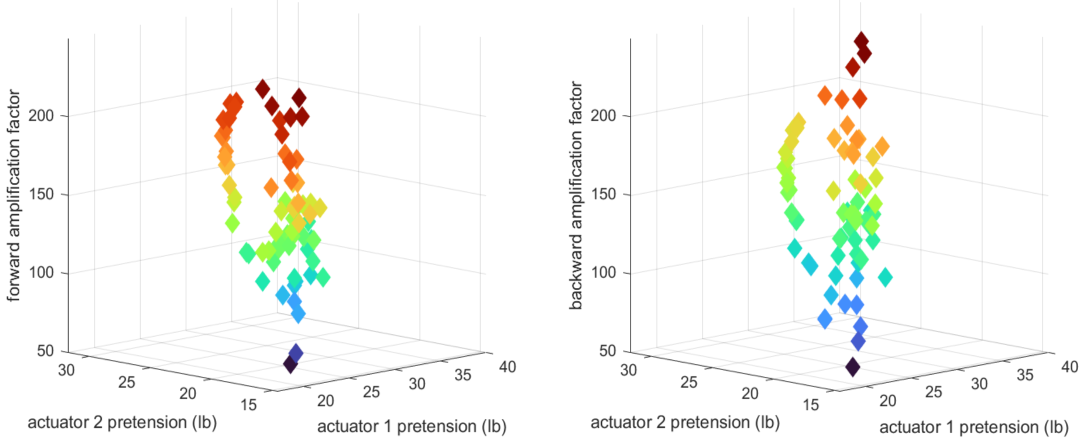


Fig. 15. Visualization of force amplification factors.

LuGre Model

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

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

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

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

- To solve Eq. 1, assumed that v is constant over each timestep Δt

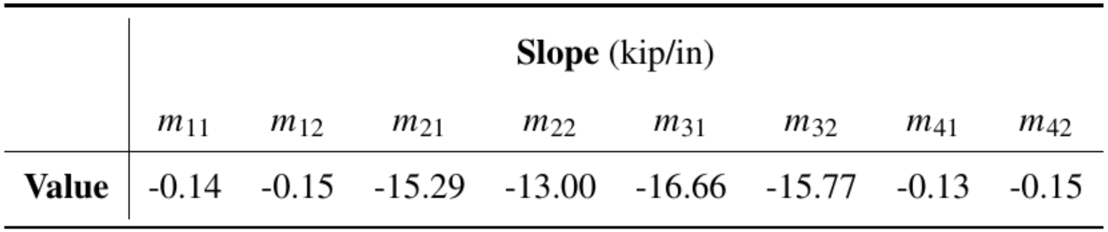
Semi-active Model

- Standard LuGre model serves as a baseline
- F_c modified to be function of electric actuator positions/drum velocity:

$$F_c(x_1, x_2, v) \qquad \text{Eq. 4}$$

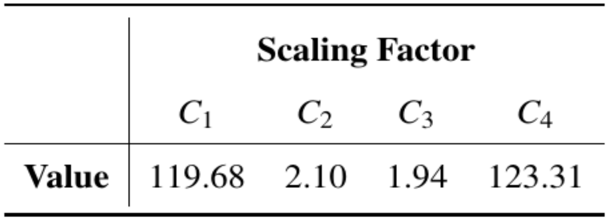
$$= \begin{cases} b + (C_1 m_{11} + C_2 m_{21})(x_1 - x_1') + (C_1 m_{12} + C_2 m_{22})(x_2 - x_2'), & v \geq 0 \\ b + (C_3 m_{31} + C_4 m_{41})(x_1 - x_1') + (C_3 m_{32} + C_4 m_{42})(x_2 - x_2'), & v < 0 \end{cases}$$

Table 2. Identified model scaling factors.



	Slope (kip/in)							
	m_{11}	m_{12}	m_{21}	m_{22}	m_{31}	m_{32}	m_{41}	m_{42}
Value	-0.14	-0.15	-15.29	-13.00	-16.66	-15.77	-0.13	-0.15

Table 3. Identified model slopes.



	Scaling Factor			
	C_1	C_2	C_3	C_4
Value	119.68	2.10	1.94	123.31

Validation Tests

- Semi-active validation tests devised that run hydraulic/electric actuators simultaneously

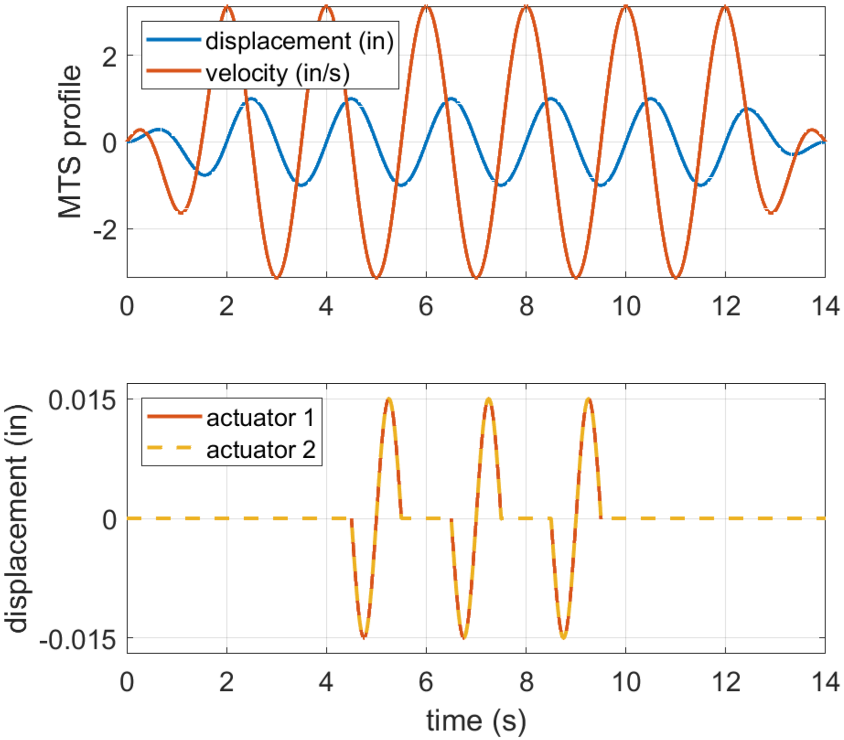
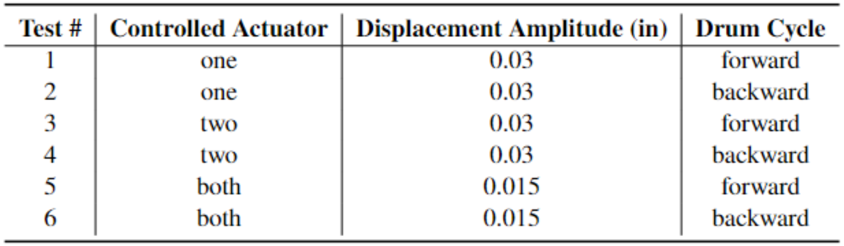


Fig. 15. Example validation profile.

- **12** validation tests conducted in total
- **6** with harmonic actuator displacements
- **6** with step actuator displacements

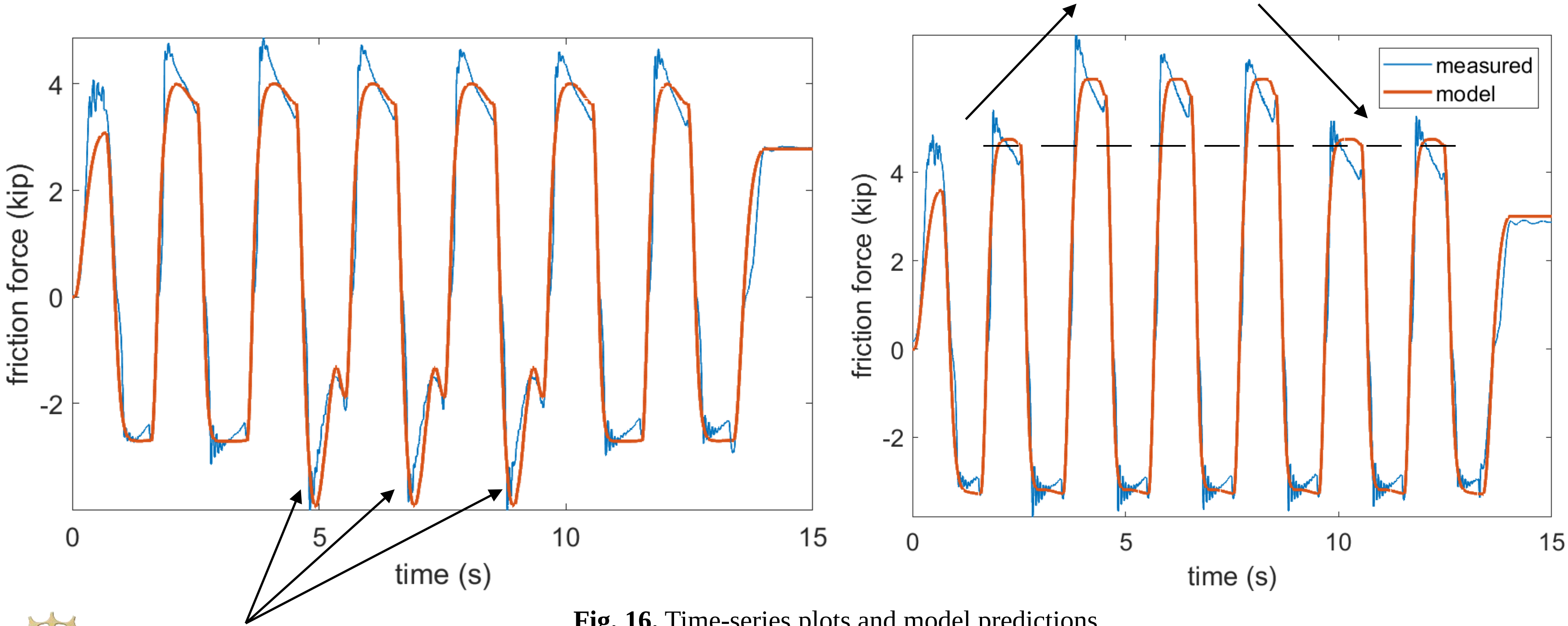
Table 4. Electric actuator displacement parameters for validation tests.



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

Validation Results

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



step up

step down

dynamic F_c

Fig. 16. Time-series plots and model predictions.

Validation Results

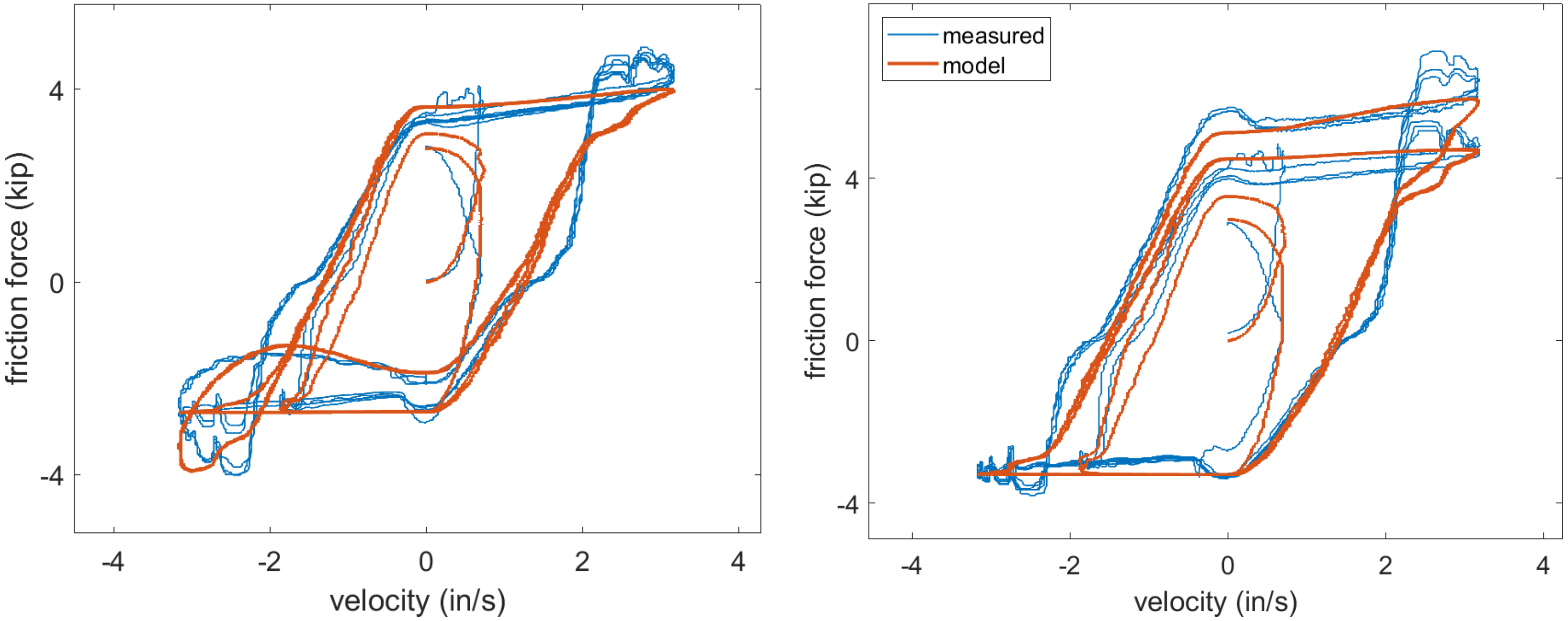


Fig. 17. Hysteresis plots and model predictions.

(f) test 6

Discussion

- With just **0.03in** actuator displacements, damper amplification factors saw a **33%** increase
- Much model error stems from backlash and residual static forces

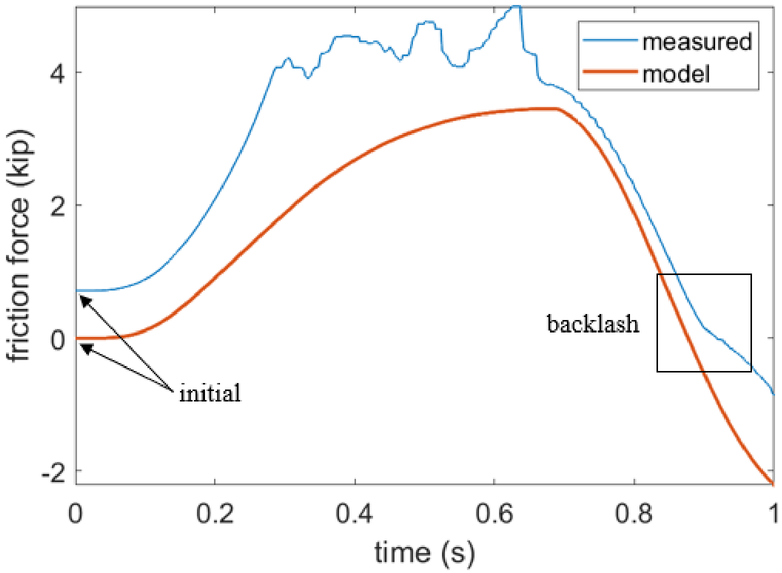
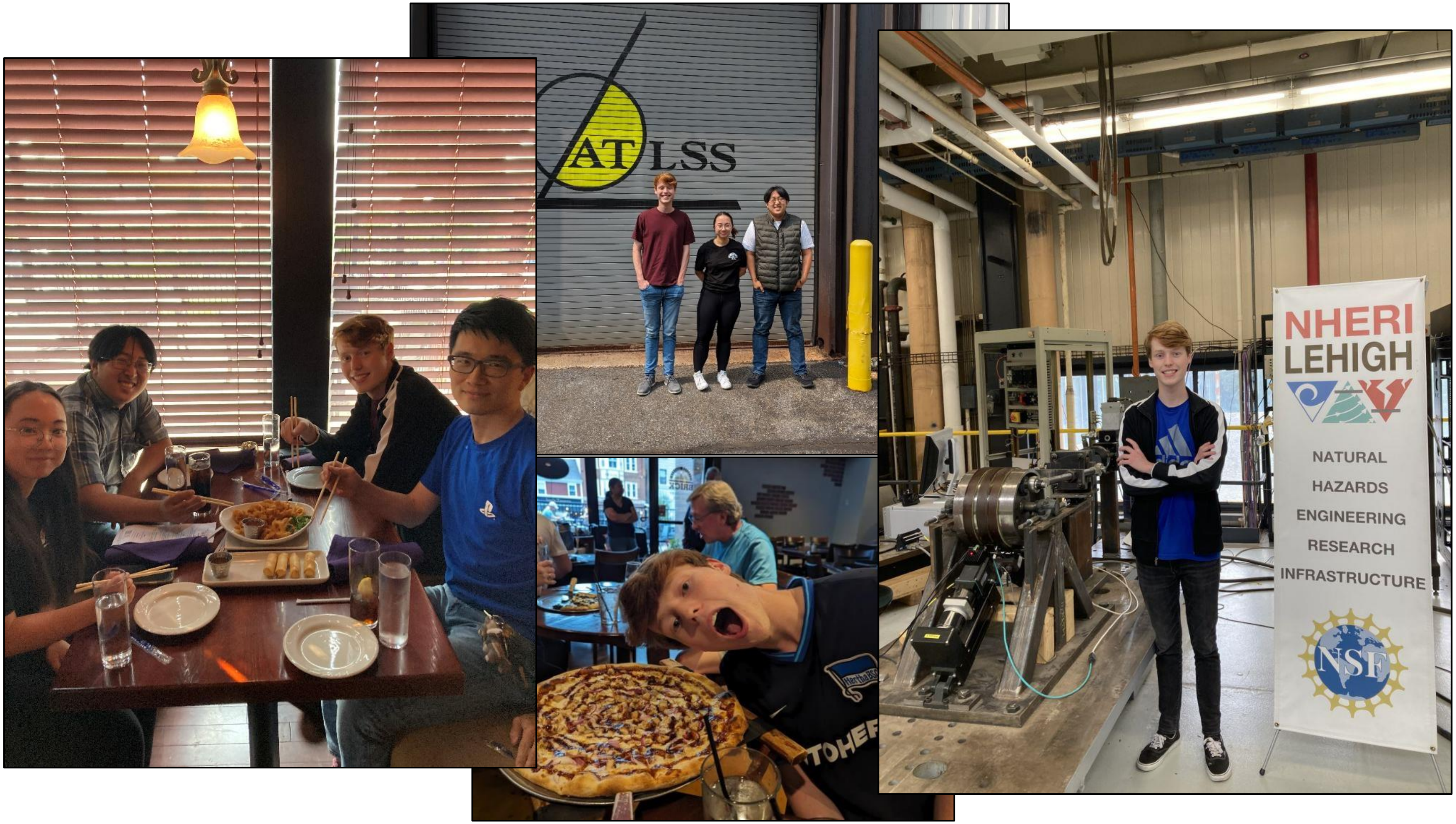


Fig. 18. Visualization of model error modes.

Table 5. Model error on validation data.

	NRMSE	
Test #	Harmonic	Step
1	0.1988	0.1766
2	0.2070	0.1794
3	0.1971	0.1684
4	0.1939	0.1792
5	0.1984	0.1768
6	0.1908	0.1717

My Experience at Lehigh



Learning Outcomes

Takeaways:

- Damping/friction knowledge
- Dissemination experience
- Connections/friends

Future work:

- Semi-active control
- Paper

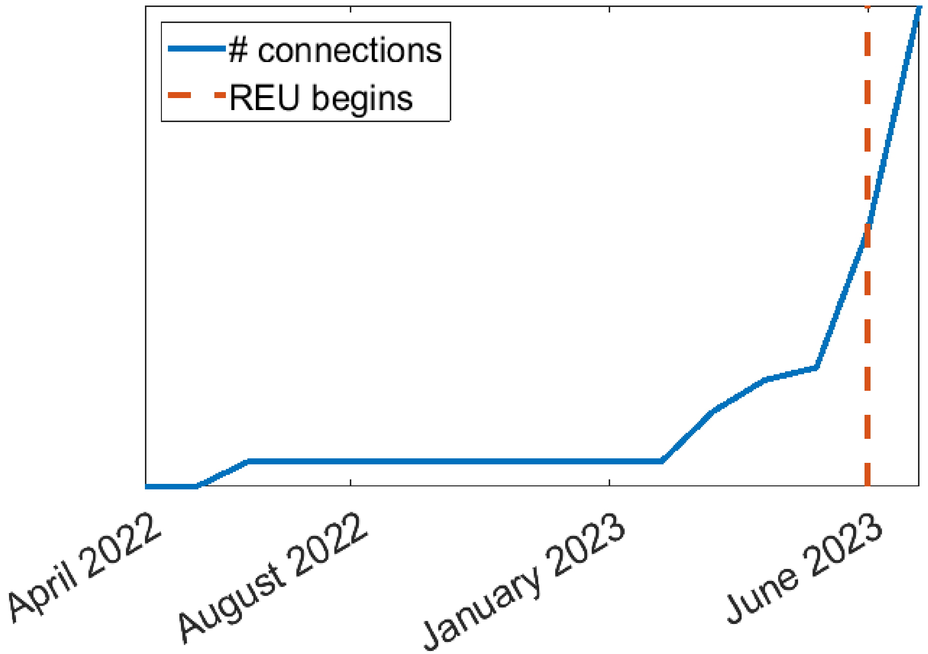


Fig. 19. LinkedIn connections through time.

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