Practical Considerations for Generating Nonlinear Dynamic Blackbox Models using Neural Networks

A. J. Barber, Gary Sandlass
MTS Systems Corporation

Contents

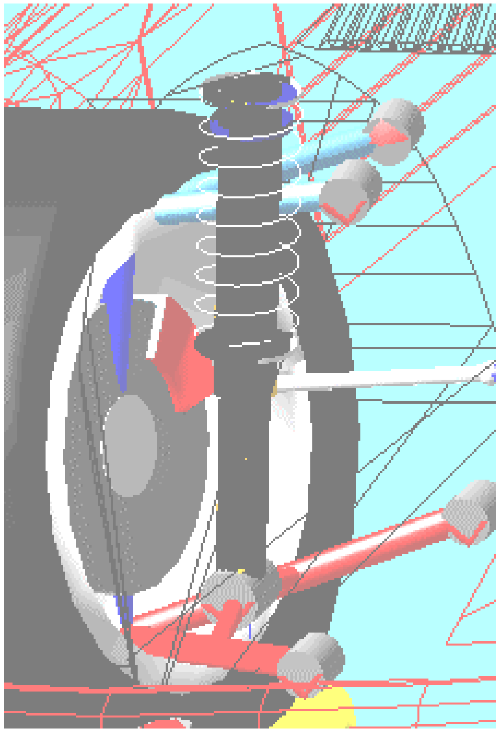
- **Review of Empirical Dynamics Modeling**
  - **Status of Adams/EDM Interface development**
- Choice of Model Input
  - Displacement
  - Velocity
- Representation of Inertial Forces
- Choice of Blackbox Boundaries

Empirical Dynamics Modeling

- **Blackbox**
- **Nonlinear, Amplitude-dependent**
- **Dynamic, Frequency-dependent**
  - **Exhibits Hysteresis or Memory**

Blackbox Models

- **Obtained from experimental data**
- **Inputs & outputs alone**
- **Little or no physical detail**



Whitebox Modeling

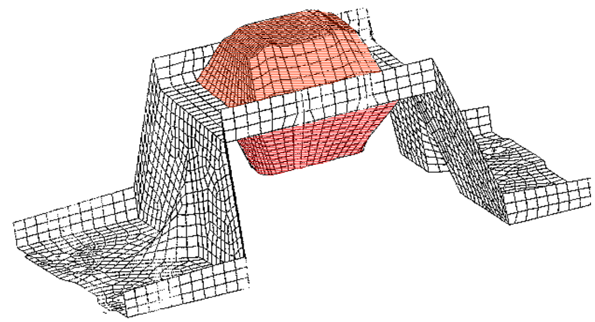
- Uses information about the system
  - Geometry
  - Physical properties
  - Physical laws

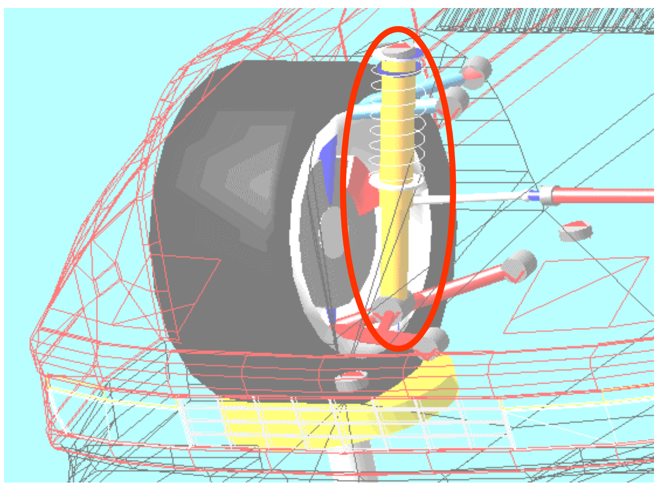
- Uses differential equations

- Examples: ADAMS, FEM, CFD

Why is blackbox modeling needed ?

- Too many variables
- Slow to solve



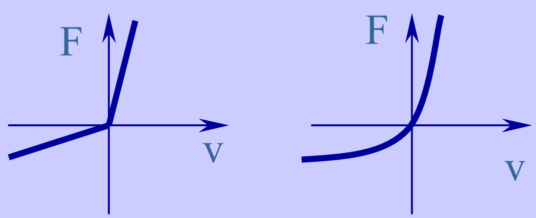


- Complex physics or math
- Expertise unavailable

Conventional Blackbox Methods

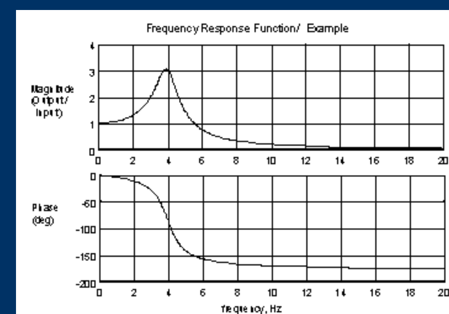
Amplitude Dependent Models

- Splines
- Polynomials



Frequency Dependent Models

- Frequency Response Functions (FRFs)



- ARMA Models

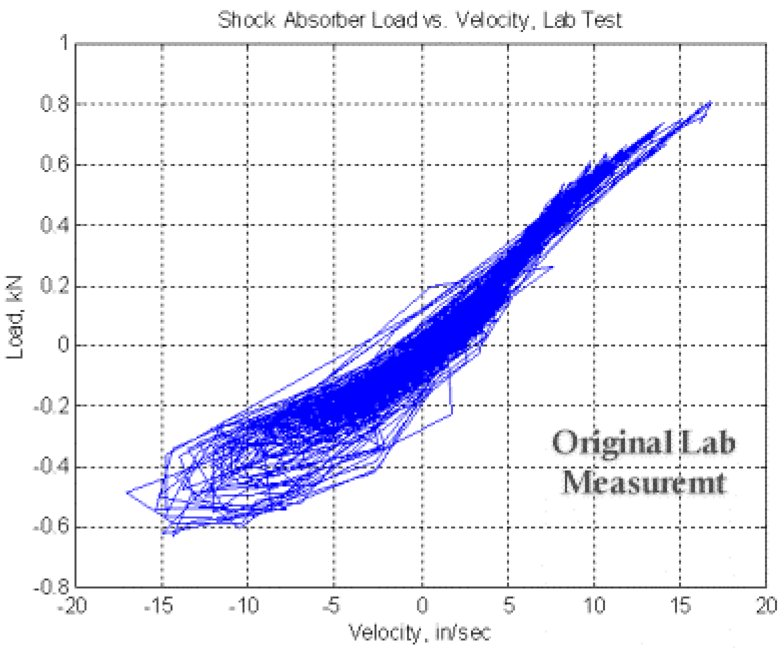
Conventional Blackbox Methods

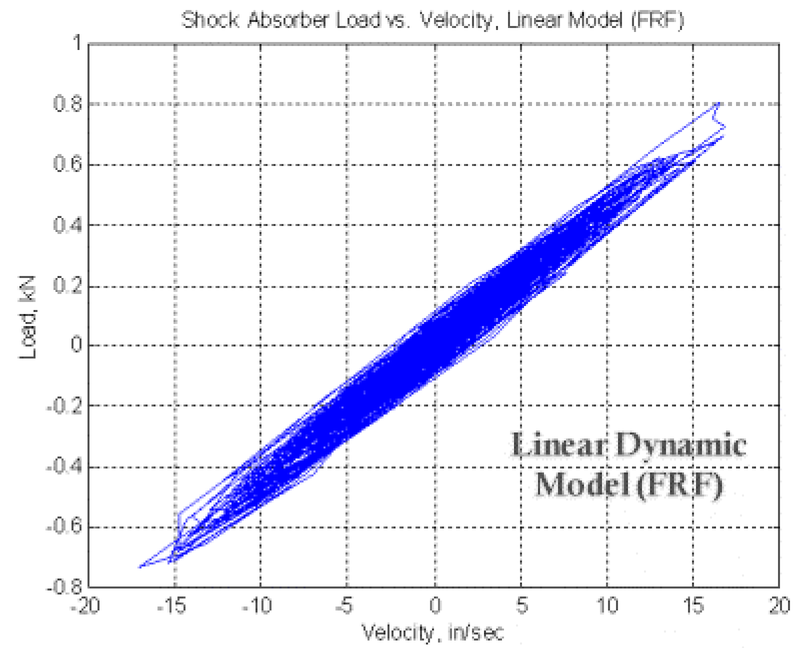
Amplitude Dependent Models

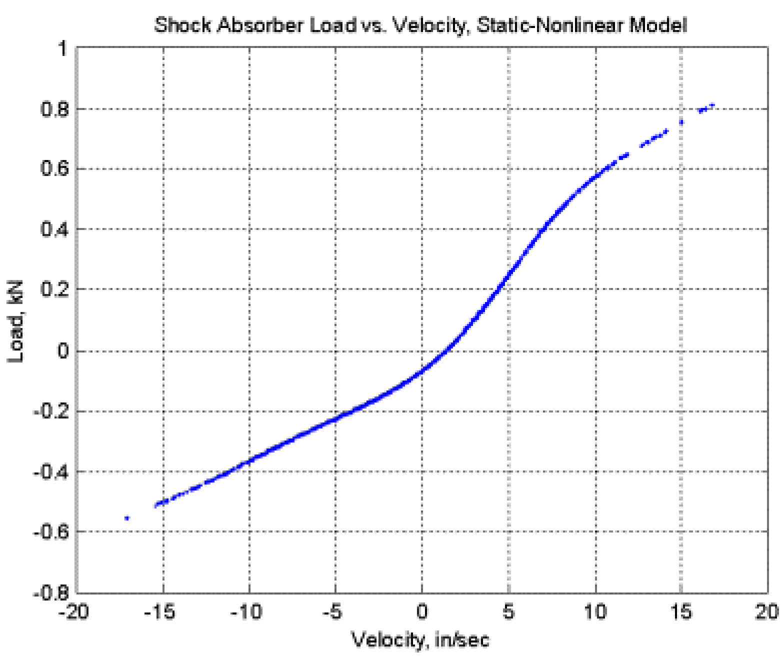
- nonlinear systems
- without hysteresis
- small number of inputs

Frequency Dependent Models

- linear systems
- with hysteresis
- many inputs

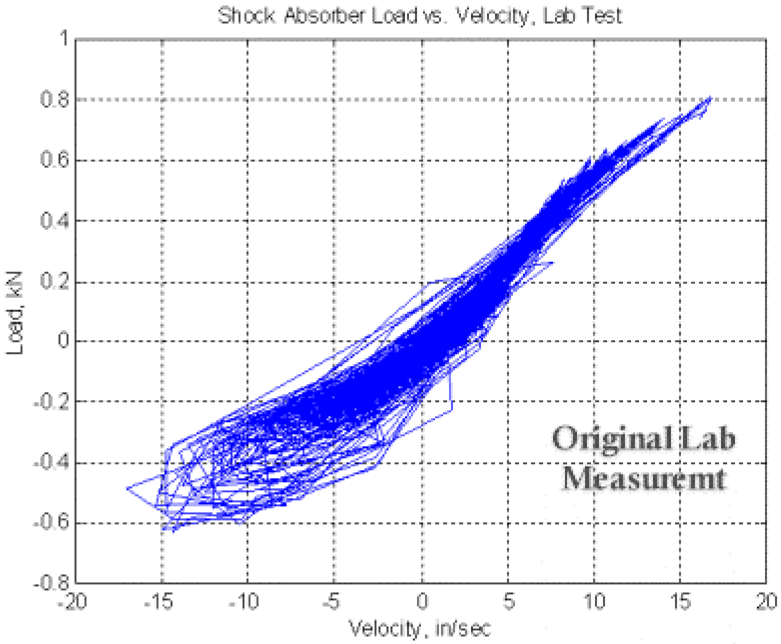


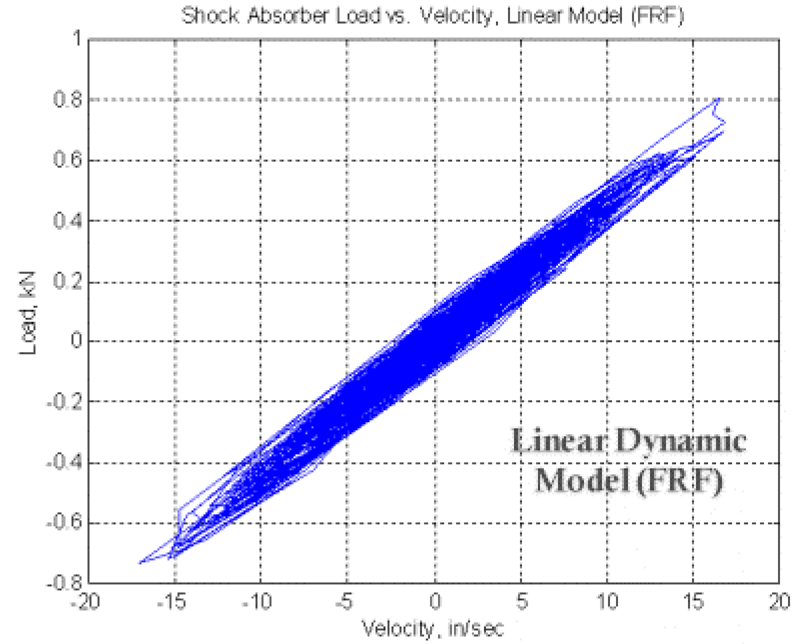


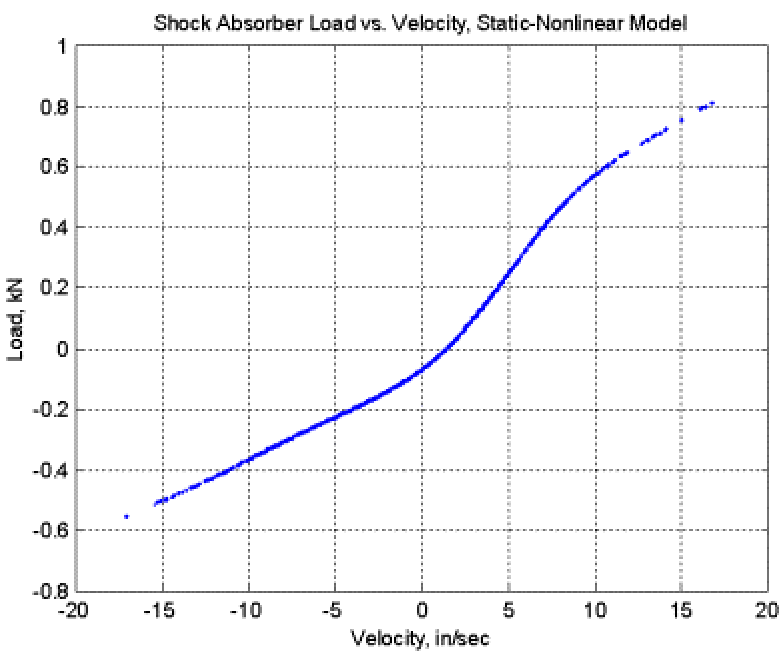


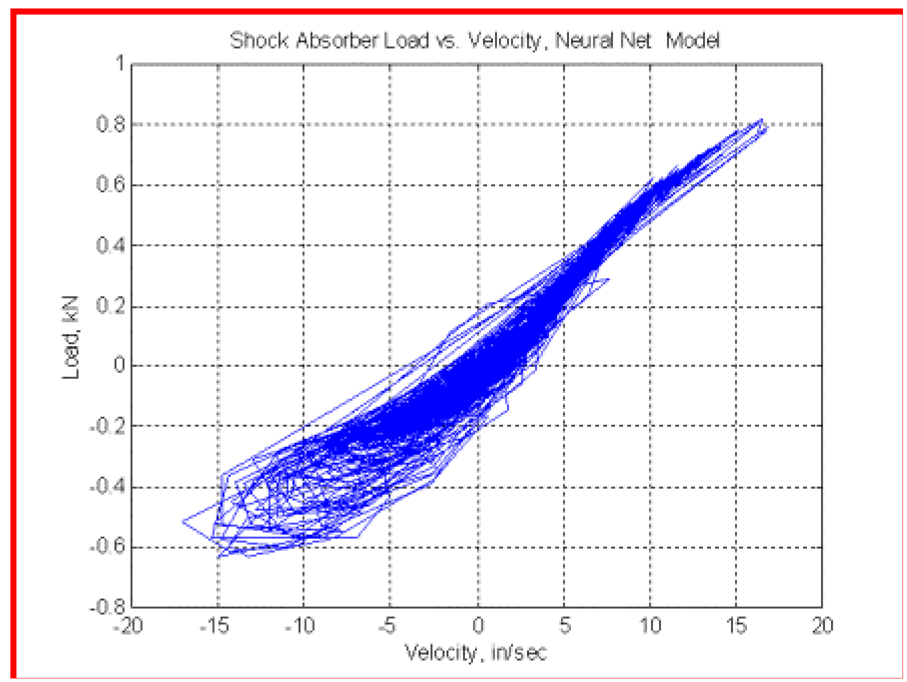
Mathematical Complexity

CPU Power


Shock Absorber Load vs. Velocity, Lab Test
Load, kN
Velocity, in/sec
Original Lab Measuremt


Shock Absorber Load vs. Velocity, Linear Model (FRF)
Load, kN
Velocity, in/sec
Linear Dynamic Model (FRF)


Shock Absorber Load vs. Velocity, Static-Nonlinear Model
Load, kN
Velocity, in/sec


Shock Absorber Load vs. Velocity, Neural Net Model
Load, kN
Velocity, in/sec

Empirical Dynamics Modeling

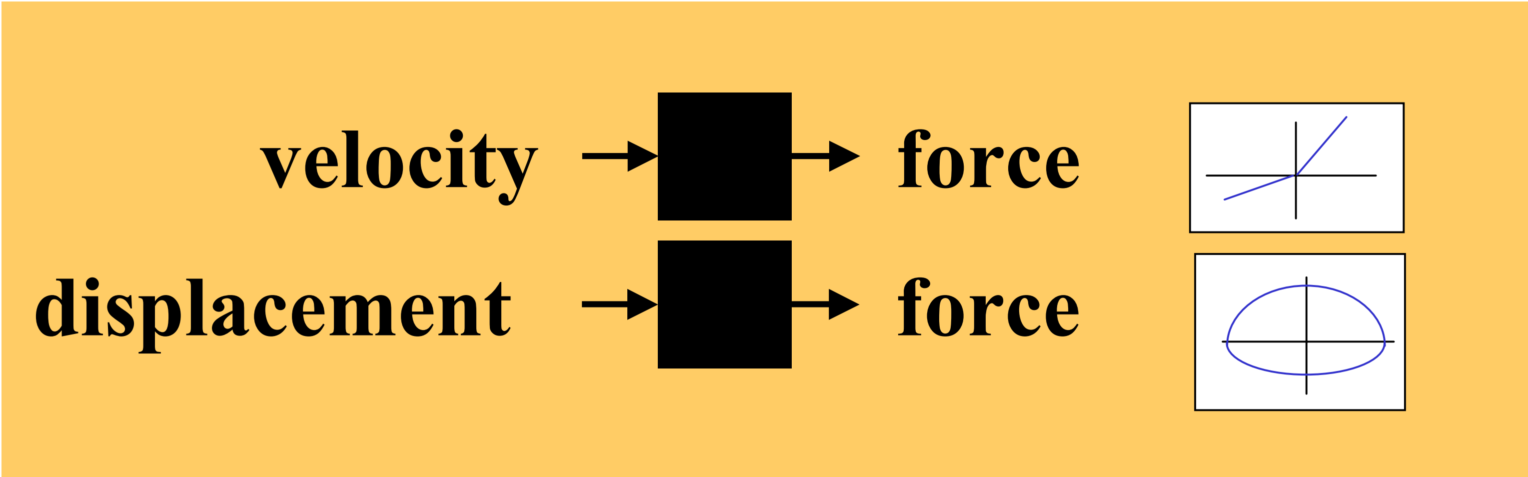
- Blackbox
- Amplitude-dependent
- Frequency-dependent

- Random Waveform
- Multiple Input and Output
- Wide Class of Systems

- Review of Empirical Dynamics Modeling
- **Choice of Model Input**
  - **Displacement**
  - **Velocity**
- Representation of Inertial Forces
- Choice of Blackbox Boundaries

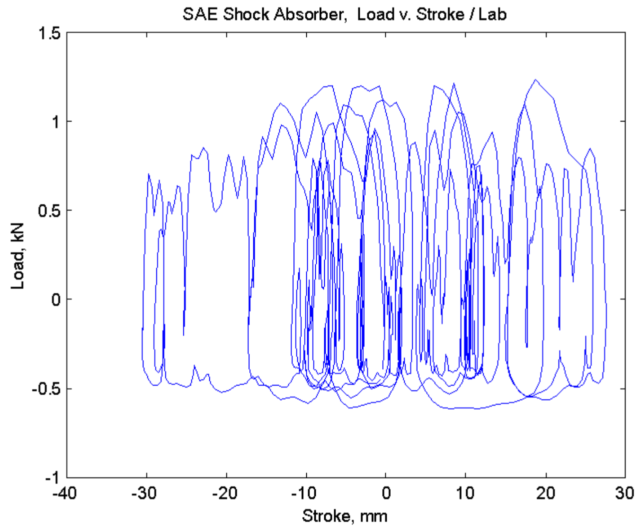
Choice of Model Input

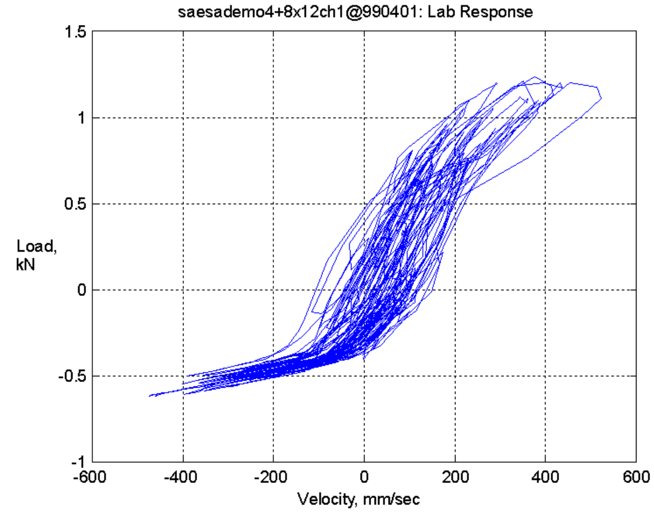
- **Even a simple damper can be modeled several ways as a blackbox, by using different input and output signals:**



Choice of Model Input

- **Damper: Displacement v. Velocity Input**





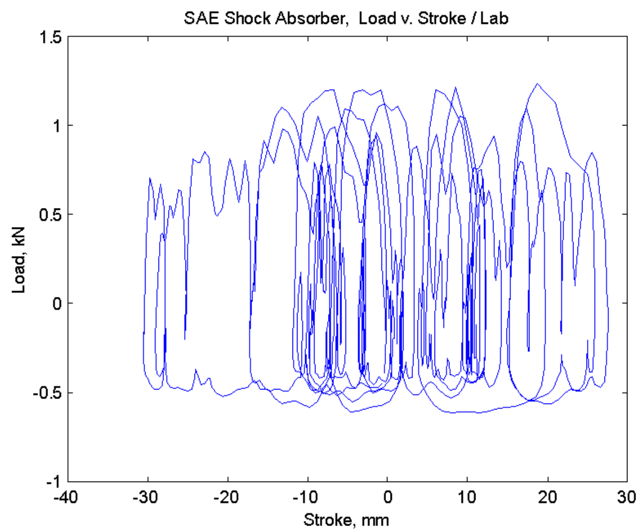
Choice of Model Input

- **Empirical Dynamics *damper* models use displacement input, force output:**

displacement → EDM → force

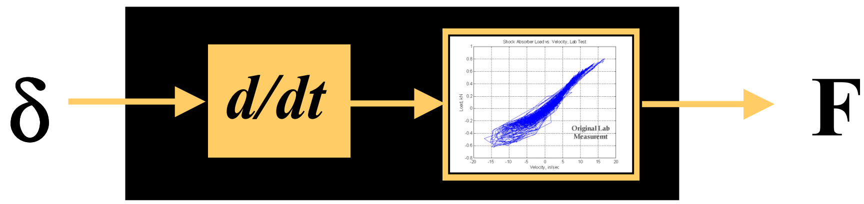
Modeling Dampers with Displacement Input

Normally, it's not feasible to fit curves to random force-displacement data

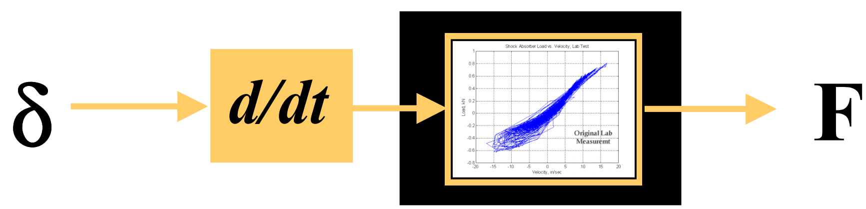


Modeling Dampers with Displacement Input

- The EDM blackbox is equivalent to differentiator and a force-velocity function



Empirical Dynamics damper model

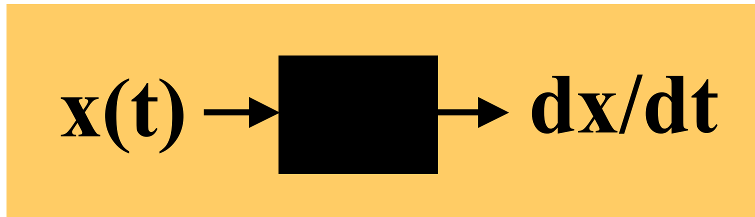


conventional damper model

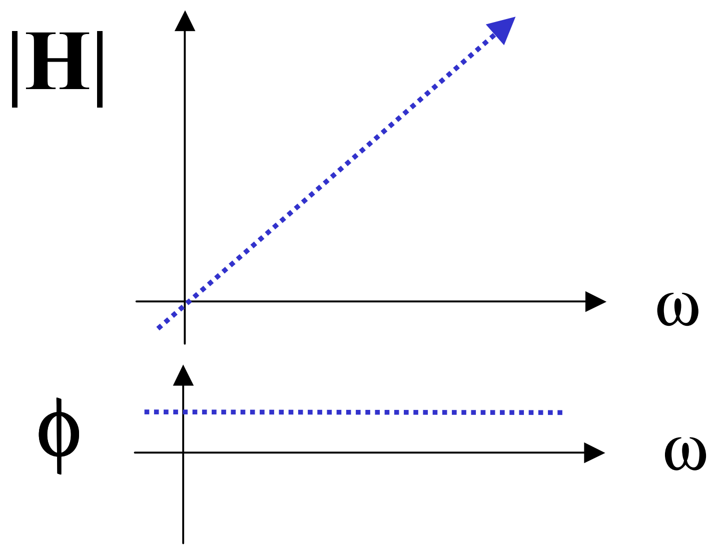
EDM Differentiation

- **Benefits**
  - Reduce differentiation errors
  - Noise immunity
  - Model different types of derivatives.

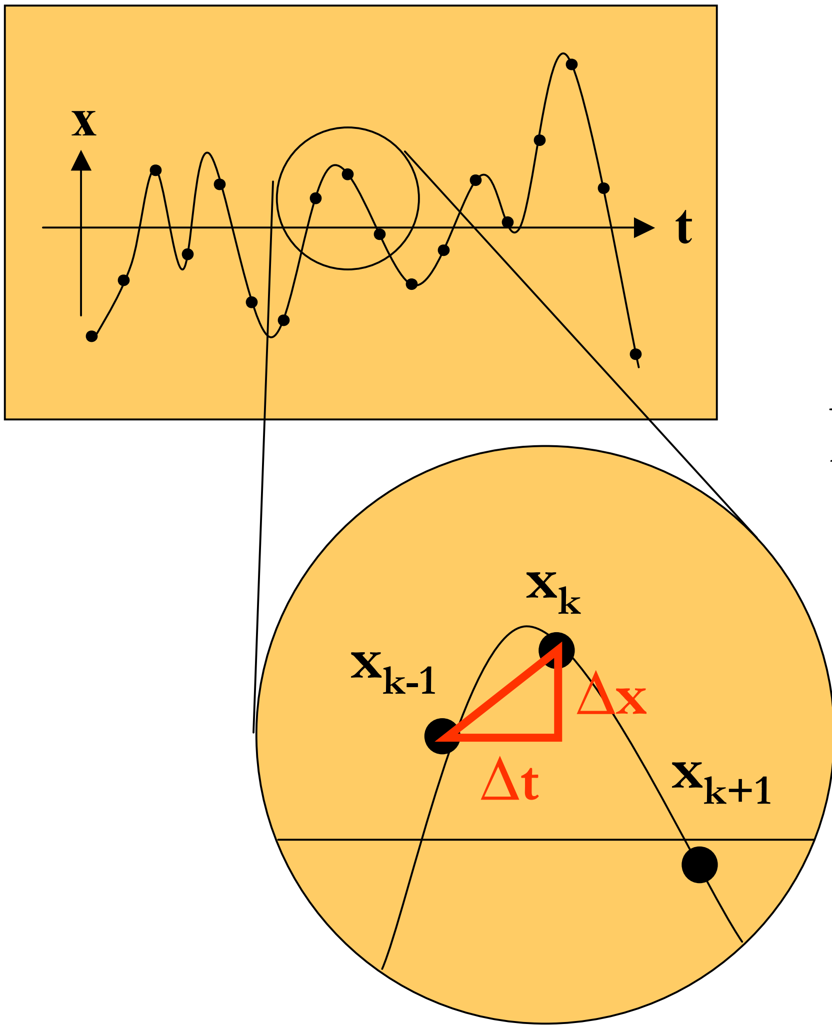
Ideal Differentiator



- **Frequency response:** **dx/dt ⇔ jωX = H**



Finite Difference Differentiator

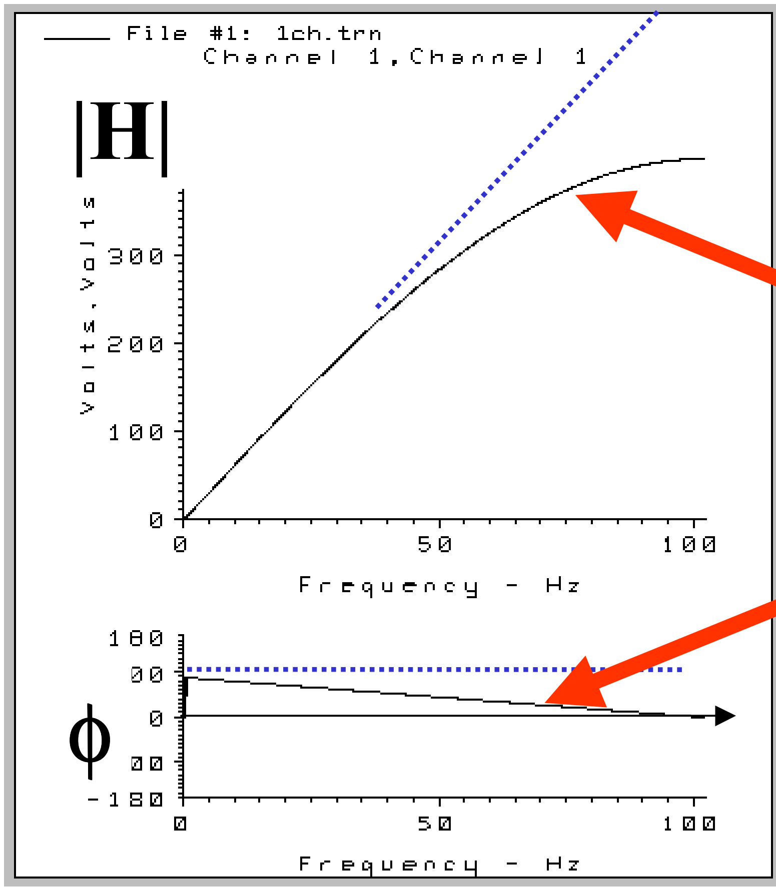


Backward Difference:

$$\dot{x}_k = \frac{x_k - x_{k-1}}{\Delta t}$$

Finite Difference Differentiator

Frequency Response



Ideal

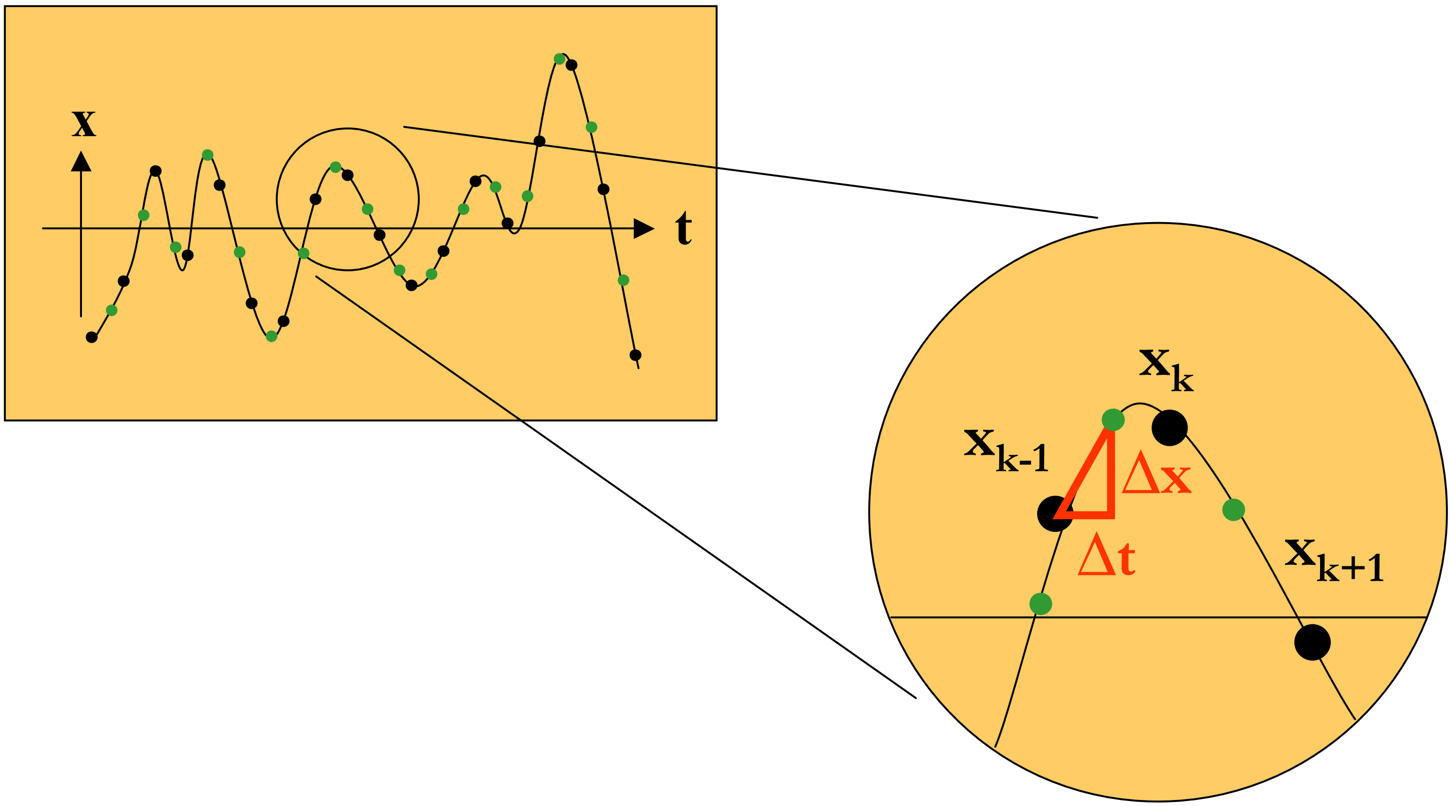
Finite Diff.

High frequency attenuation

Large phase shift

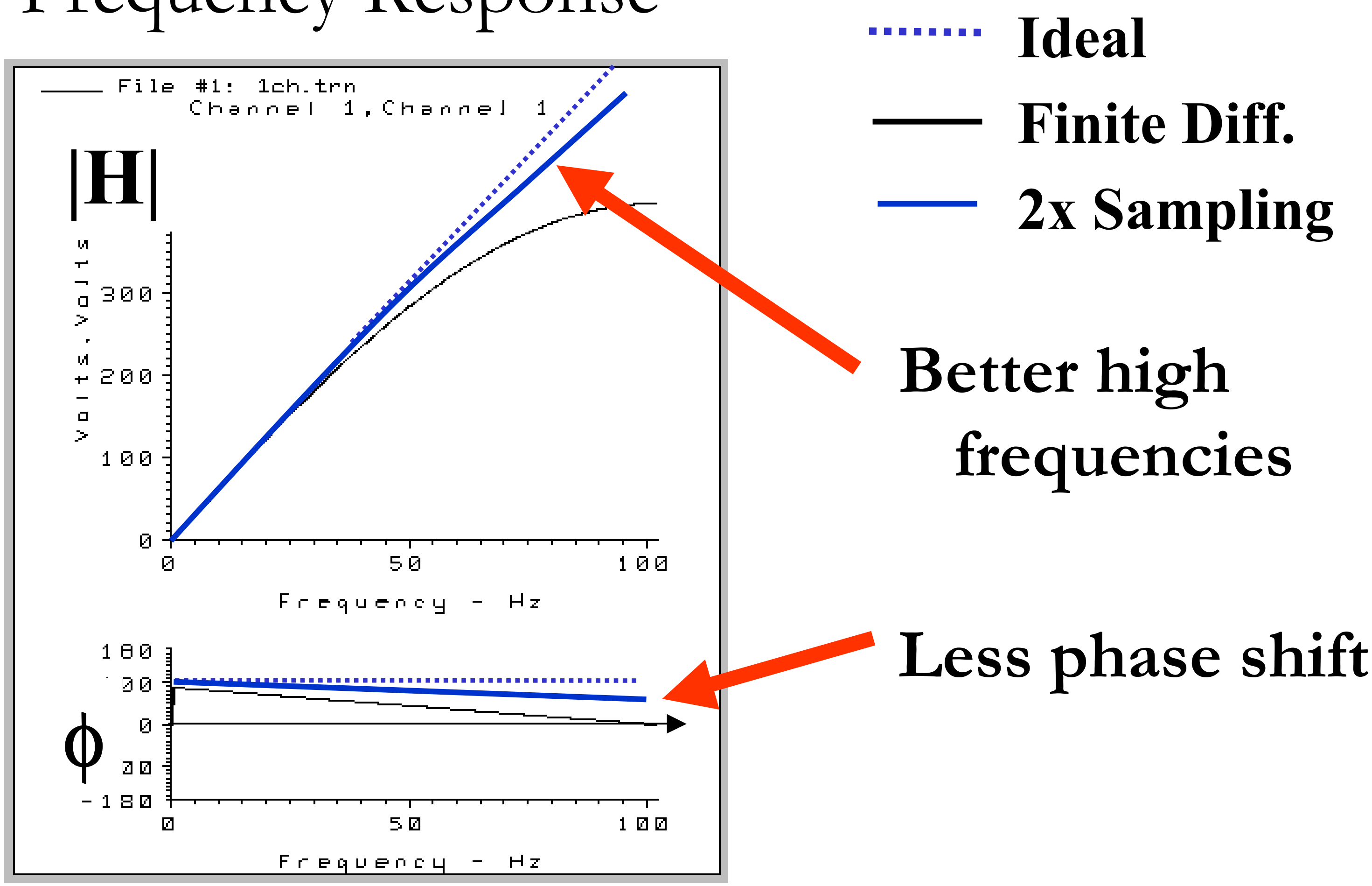
Improved Differentiator

- Use higher sample rate



2x Upsampled Differentiator

Frequency Response

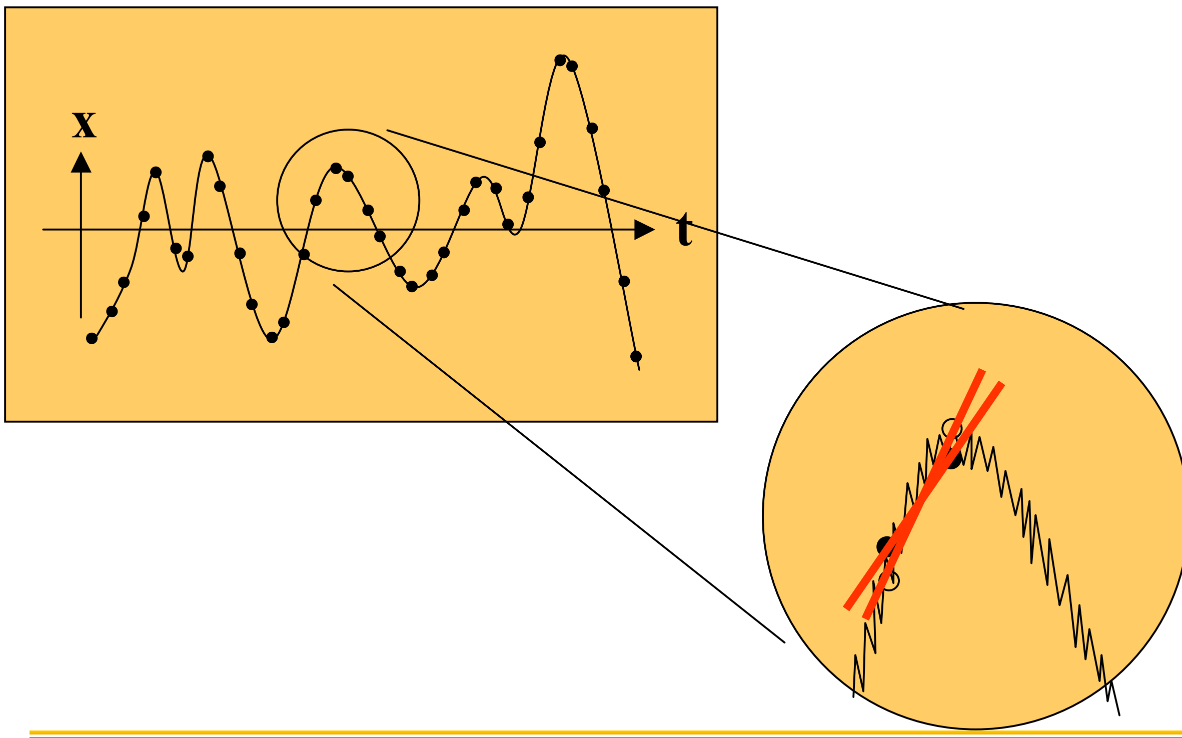


Higher Sample Rate Differentiation

- Shortcomings
  - More samples => more calculations
  - Improved high frequencies => more susceptible to noise

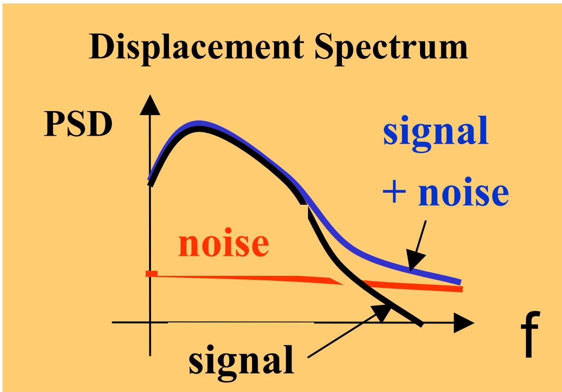
Differentiators: Dealing with Noise

- **typically, noise problems occur at higher frequencies**

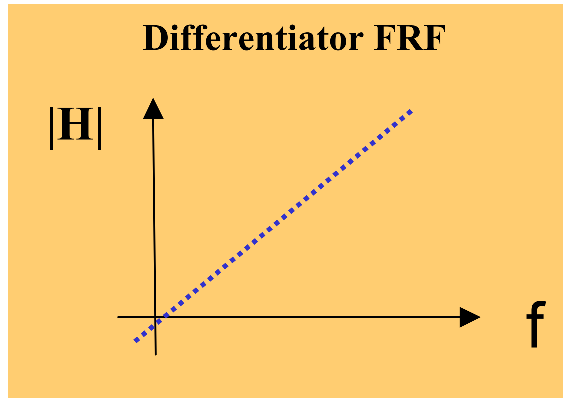


Differentiators & Noise

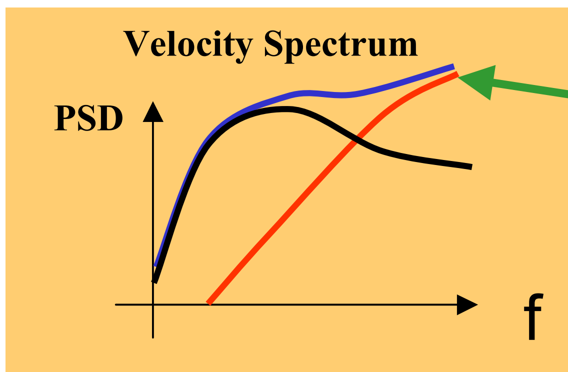
- **Frequency Domain Effects**



*



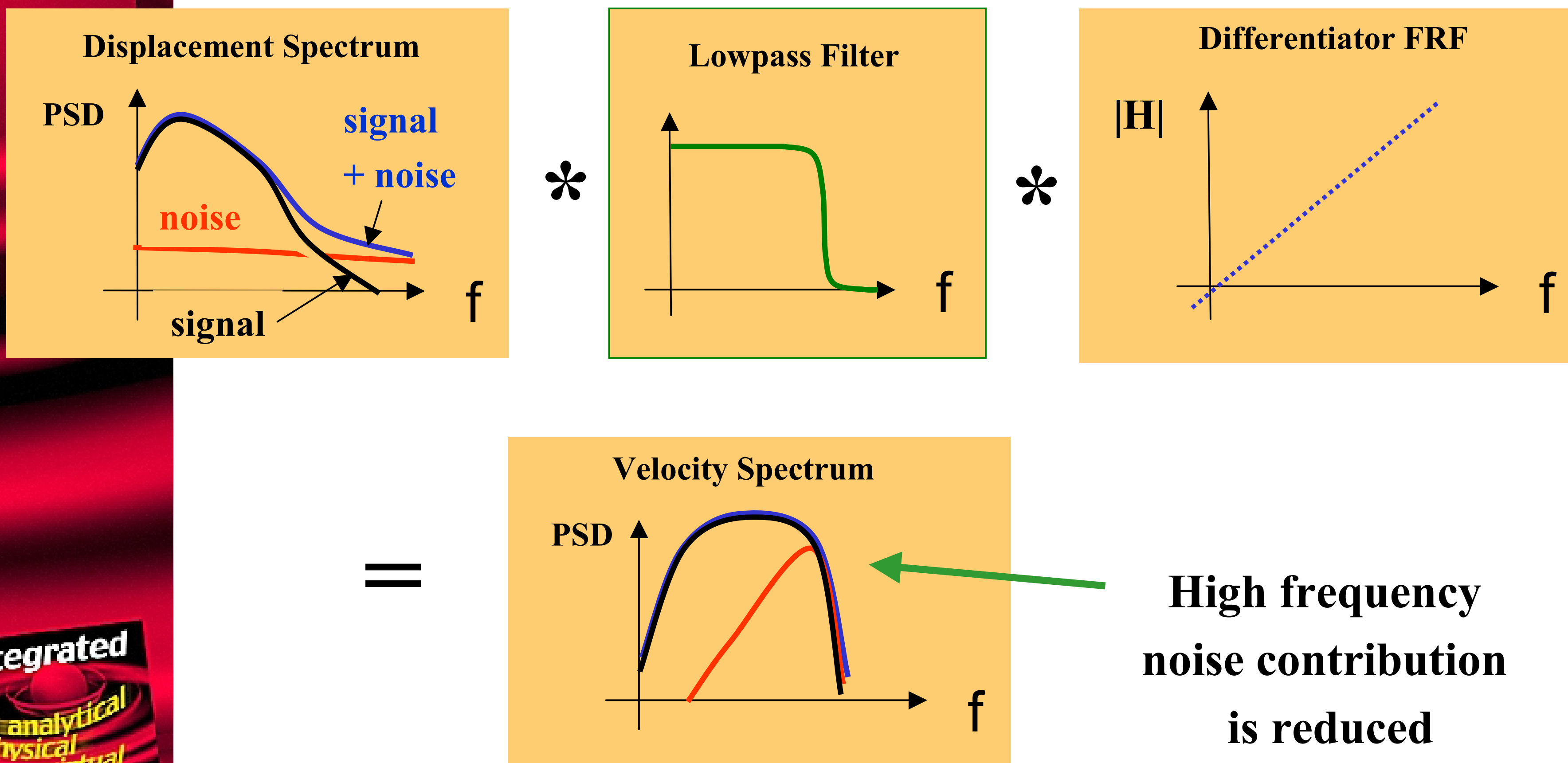
=



High frequency noise dominates the differentiated signal

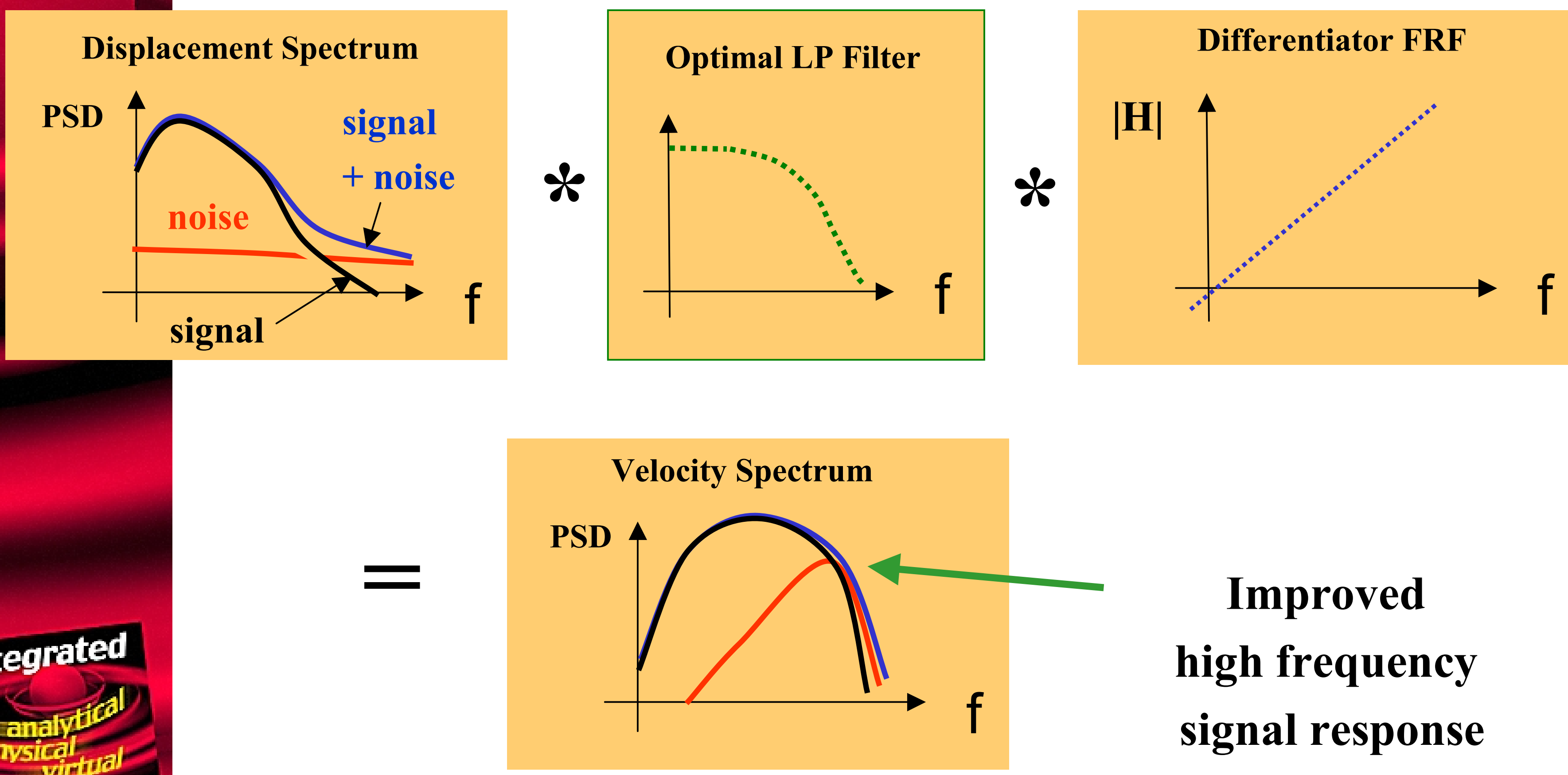
Differentiators & Noise

- Use of Lowpass Filter

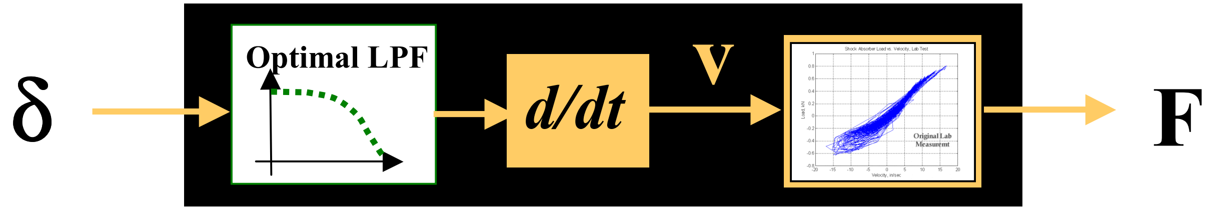


Differentiators & Noise

- Use of <u>Optimal</u> Lowpass Filter



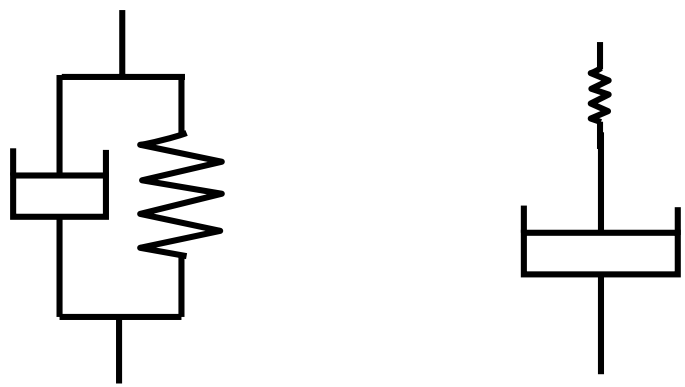
Differentiation using EDM



- **EDM differentiation effectively includes upsampled, optimal LPF**

Alternate Derivatives

- **Higher order derivatives (d^k/dt^k)**
- **Derivative + proportion**



Choice of EDM Damper Input

- **EDM differentiation**
  - more effective than typical finite difference, LPF schemes
  - ability to handle complex phenomena
  - no additional modeling cost

- ~~**Conclusion: For dampers, displacement input is preferred over velocity.**~~-----------

- **Stop the press !!**
- **For using EDM in ADAMS, a better choice is a <u>combination of displacement & velocity</u>**

- Review of Empirical Dynamics Modeling
- Choice of Model Input
  - Displacement
  - Velocity
- **Representation of Inertial Forces**
- Choice of Blackbox Boundaries

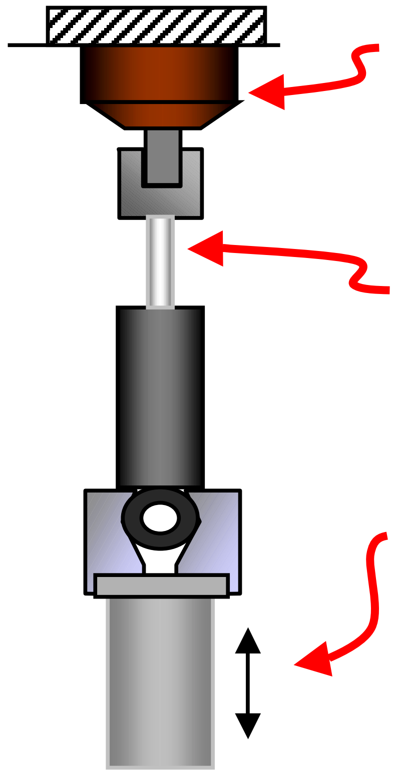
Representation of Inertial Forces

- **A mechanical lab test may exclude important inertial force components**

- **These components may affect ED model accuracy at high frequencies**

Representation of Inertial Forces

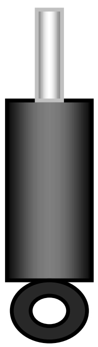
- Example: Std damper test rig

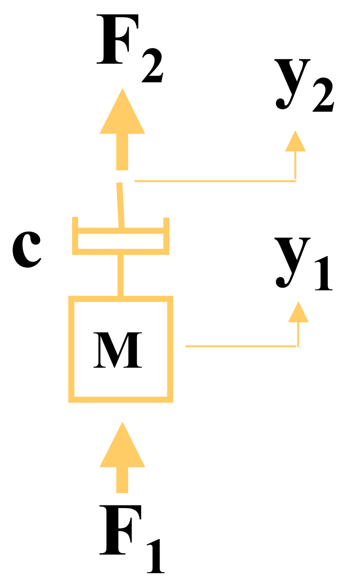


- Load cell between specimen and ground
- Typically, low mass end (rod) attaches to load cell
- Actuator attaches to opposite end

Representation of Inertial Forces

- Equations of Motion



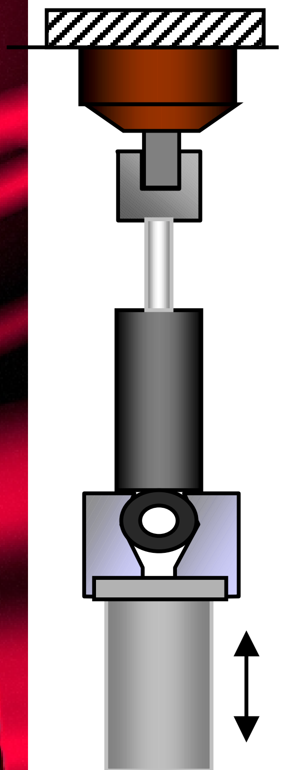


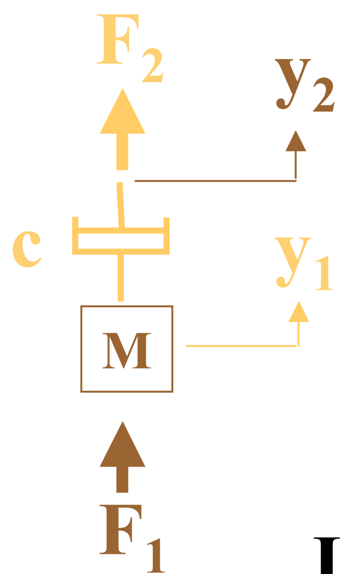
$$\Sigma F = M\ddot{y}_1 = F_1 + F_2$$

$$F_2 = c\,(y_1 - y_2)$$

Representation of Inertial Forces

- Equations of Motion





Damper Test:

$y_2 = 0$

F_1 is not measured

$$\Sigma F = M\ddot{y}_1 = F_1 + F_2$$

$$F_2 = c\,(y_1 - y_2)$$

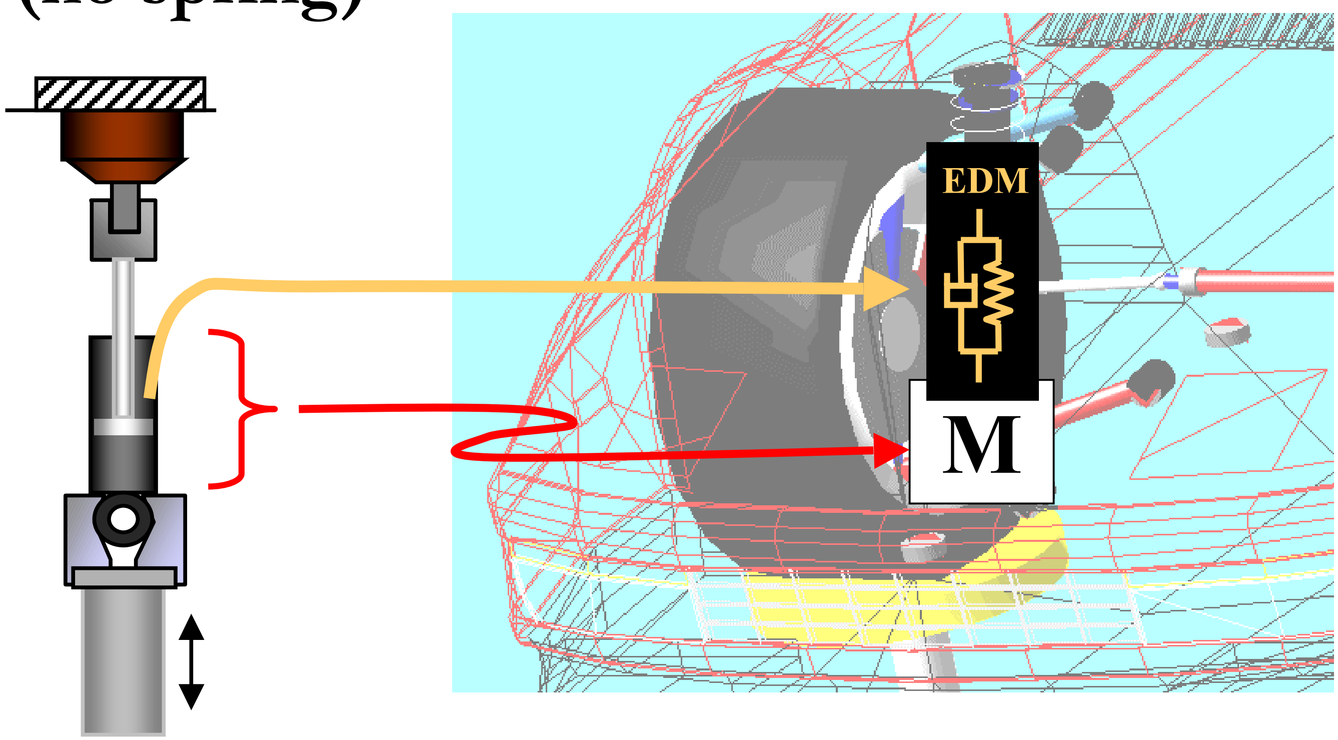
Inertial force $M\ddot{y}_1$ is ignored

Only damping is modeled

Inertial Forces, Modeling Workarounds

Simple Damper (no spring)

Add lumped mass of s/a body to one end

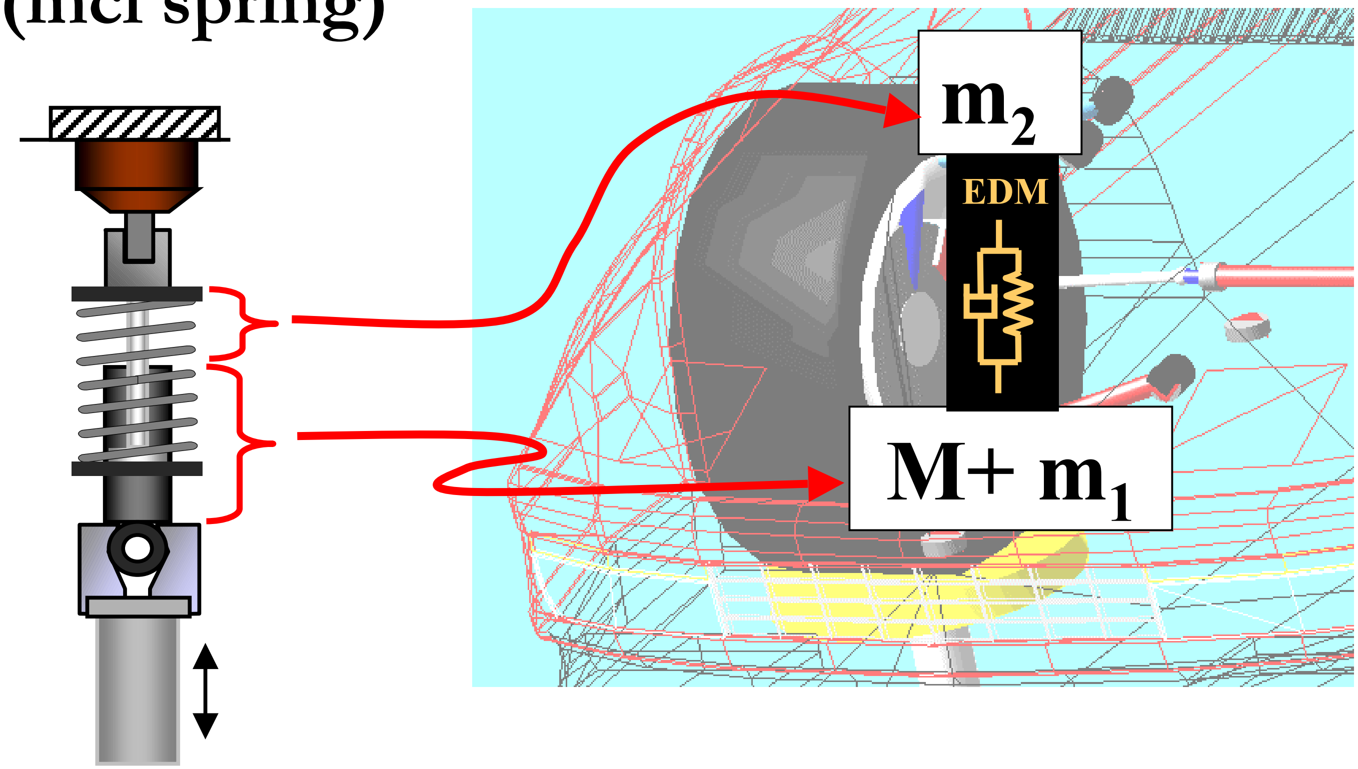


Inertial Forces, Modeling Workarounds

Strut

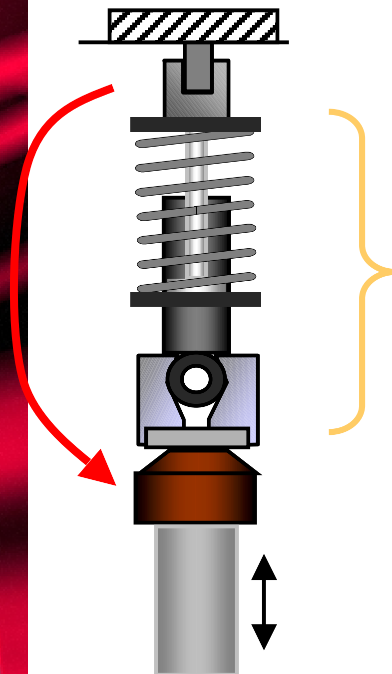
(incl spring)

Assign a fraction of mass to each end

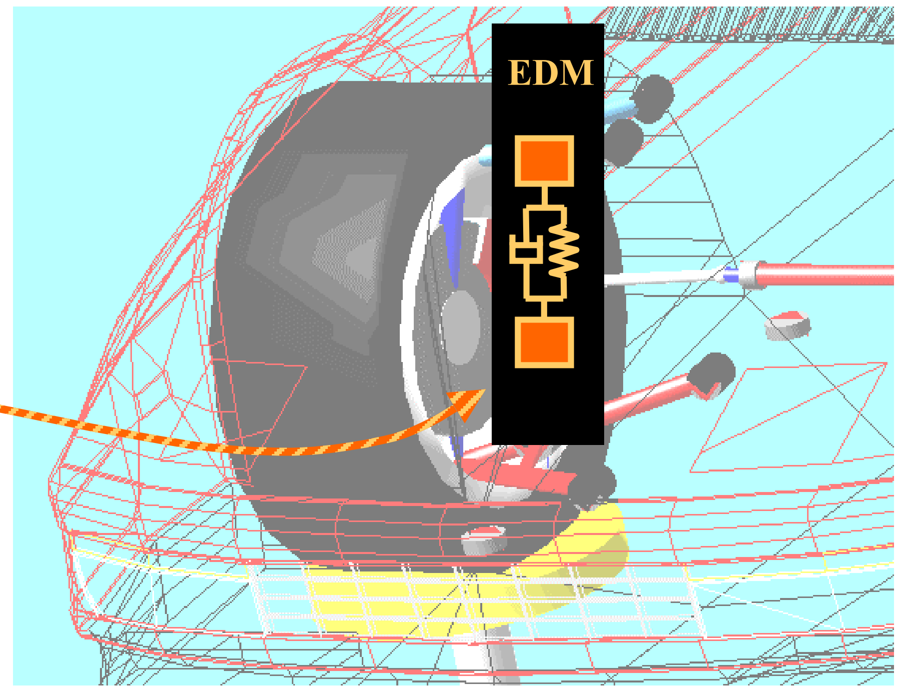


Inertial Forces, Modeling Workarounds

Damper or Strut



Use load cell at the active end

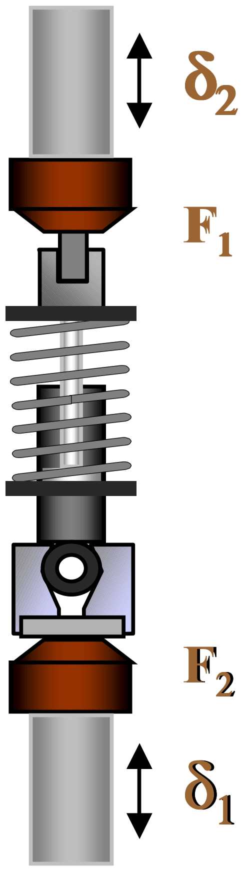


(+) Some inertia forces are included in the blackbox

(-) Difficult to measure - moving load cell

Inertial Forces, Modeling Workarounds

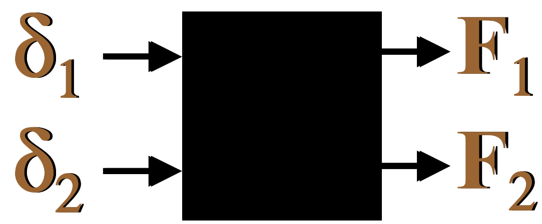
Damper or Strut



Use alternative test rig

- two actuators
- two load cells

=> 2 input, 2 output blackbox



(+) Inertial forces are included in the blackbox

(-) Excess inertia from grips

(-) Difficult to measure - moving load cell

EDM Representation of Inertial Forces

- **Other specimens => similar issues**

- **<u>Problem is inevitable</u> at sufficiently high accelerations**

Inertial Forces and EDM

Summary

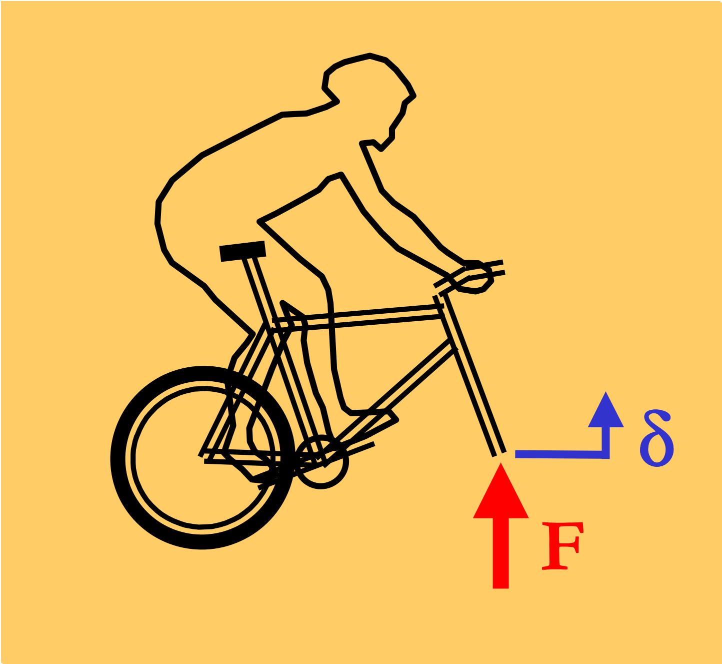
- For accurate EDM characterization at high frequencies, a special test rig may be necessary
- Remember to consider the test rig used to generate ED model and include the "effective" mass in your Adams simulation.

- Review of Empirical Dynamics Modeling
- Choice of Model Input
  - Displacement
  - Velocity
- Representation of Inertial Forces
- **Choice of Blackbox Boundaries**

Choice of Blackbox Boundaries

- System = bicycle w/ suspension fork, + rider

- ED model : predict vertical force into fork, for any road profile input

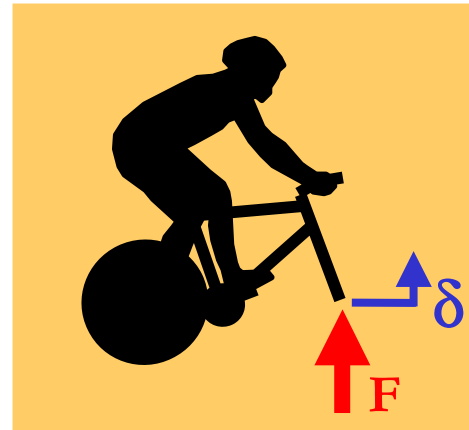


Choice of Blackbox Boundaries

Scenario 1

Blackbox =

Bike + Rider combination

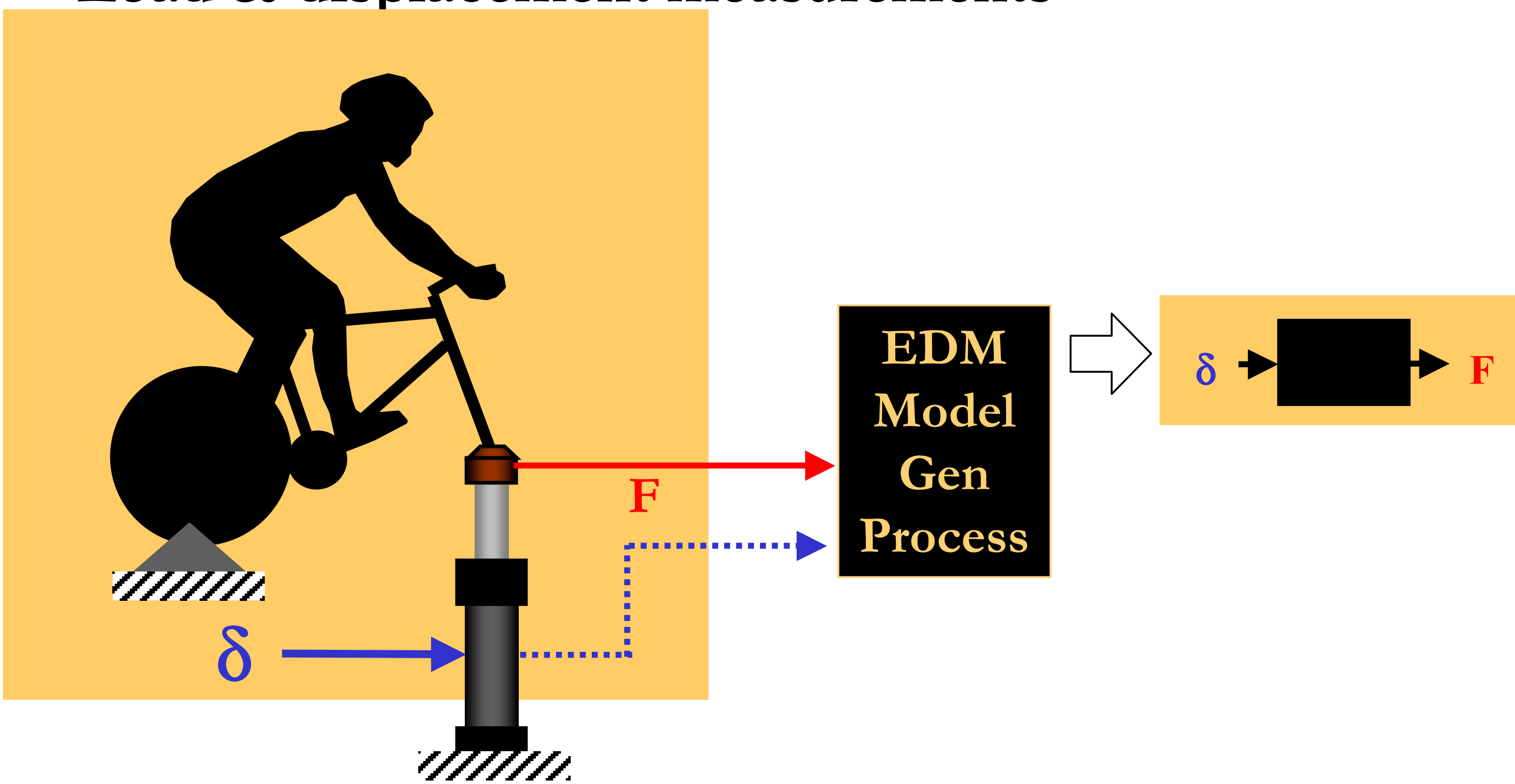


(+) can model displacement
=> force directly
(SISO model)

(-) model is valid only for
one particular Rider

Lab Test Proposal

- Single Actuator
- Rider (mechanically consistent !)
- Load & displacement measurements



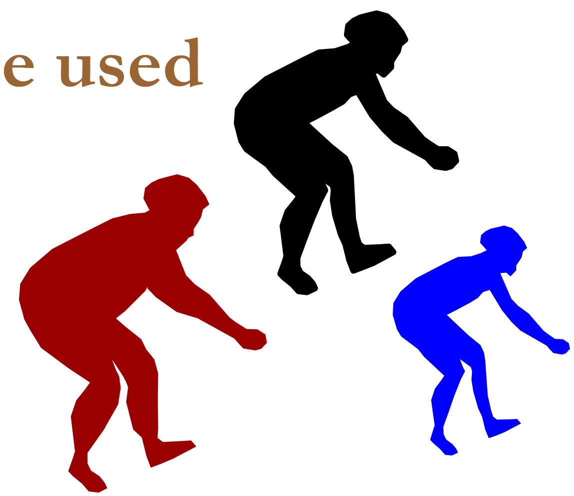
Choice of Blackbox Boundaries

Scenario 2

1 Blackbox = Bike

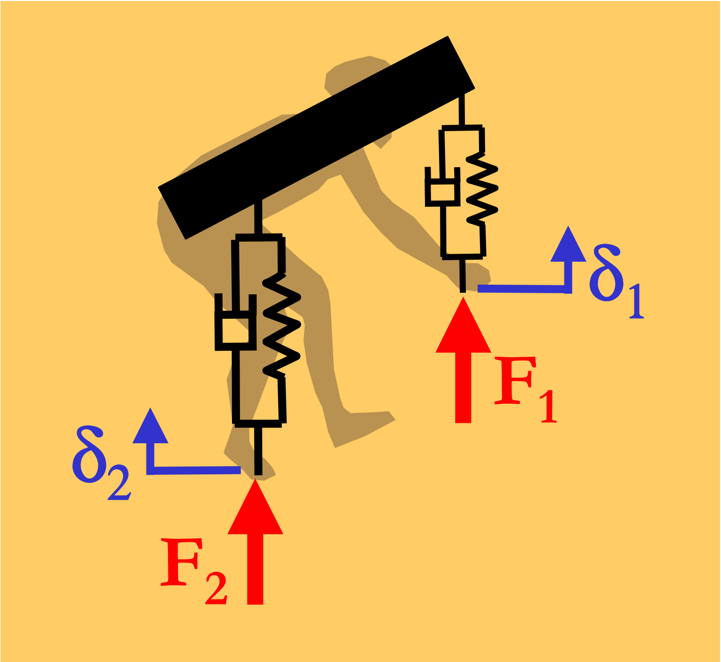
1 Other model = Rider

(+) Different Riders can be used



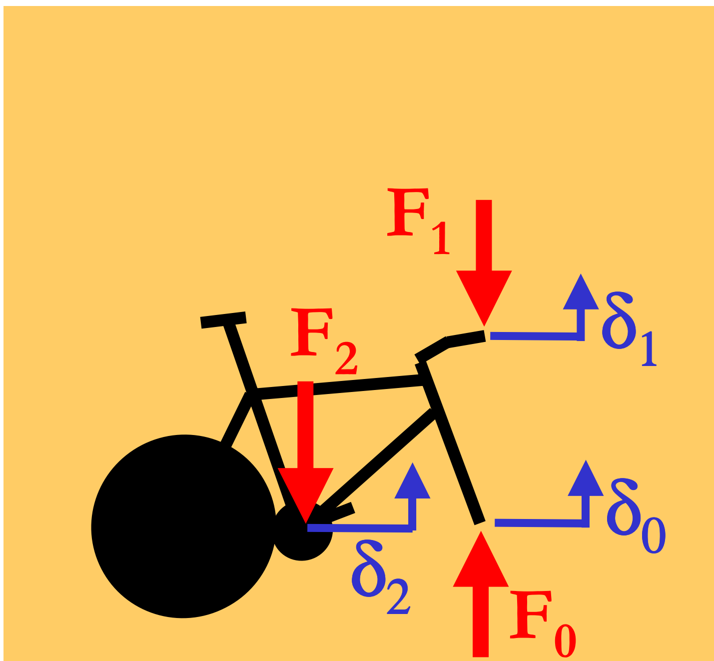
Rider Model

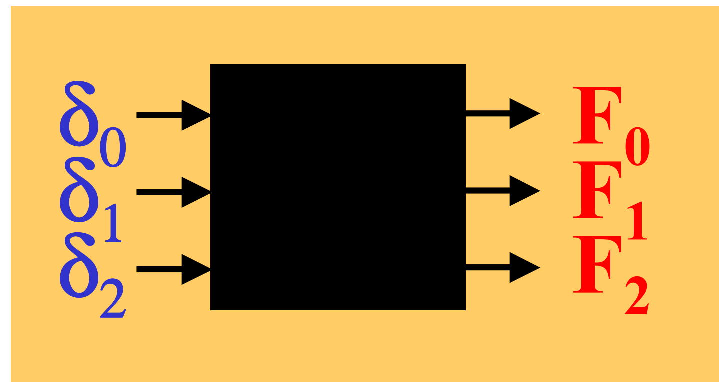
- **Simple:**
  - mass
  - bio-suspension (arm & knee compliance)



Choice of Blackbox Boundaries

Blackbox = Bike

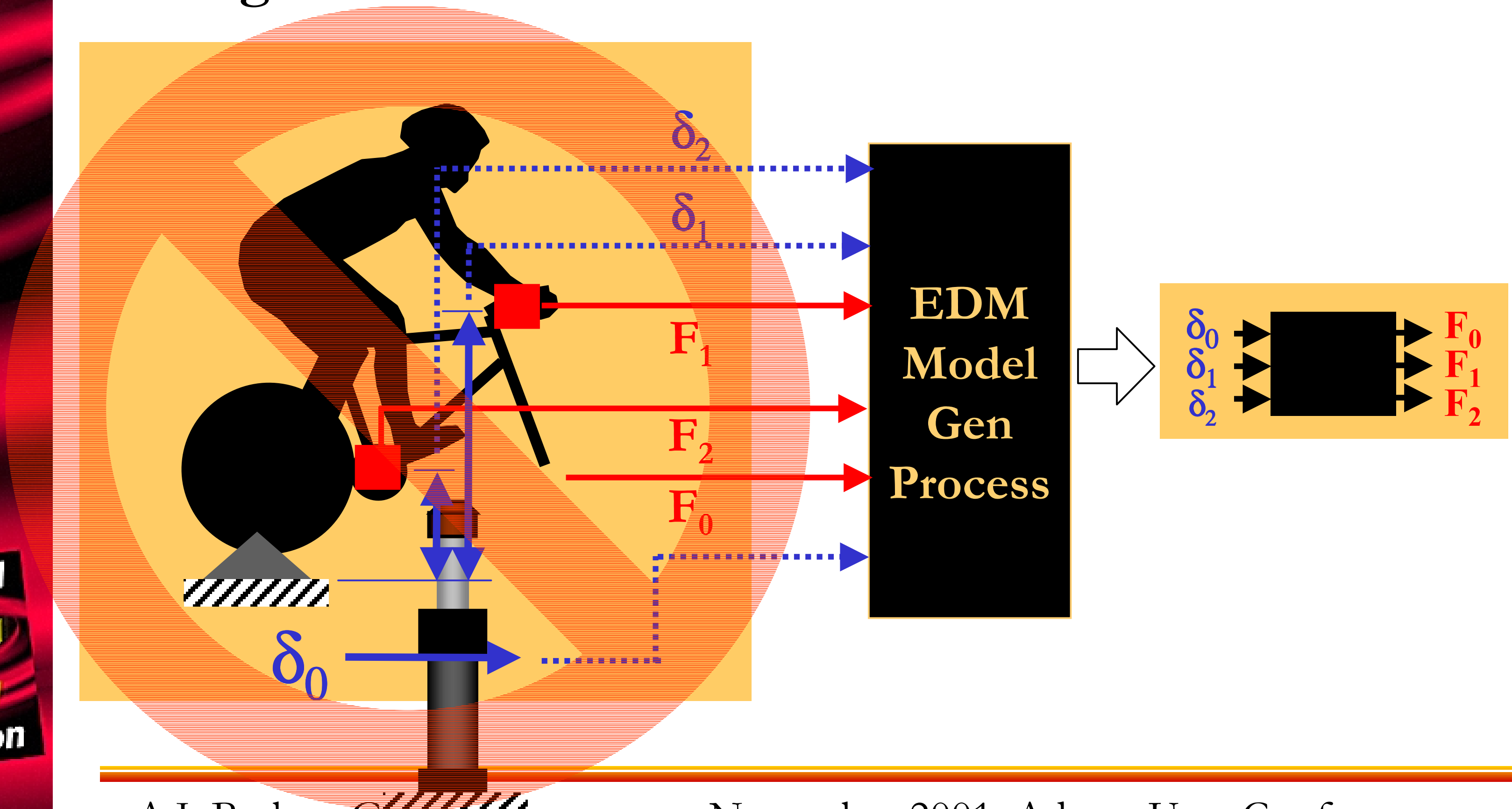




(-) Requires more blackbox inputs !

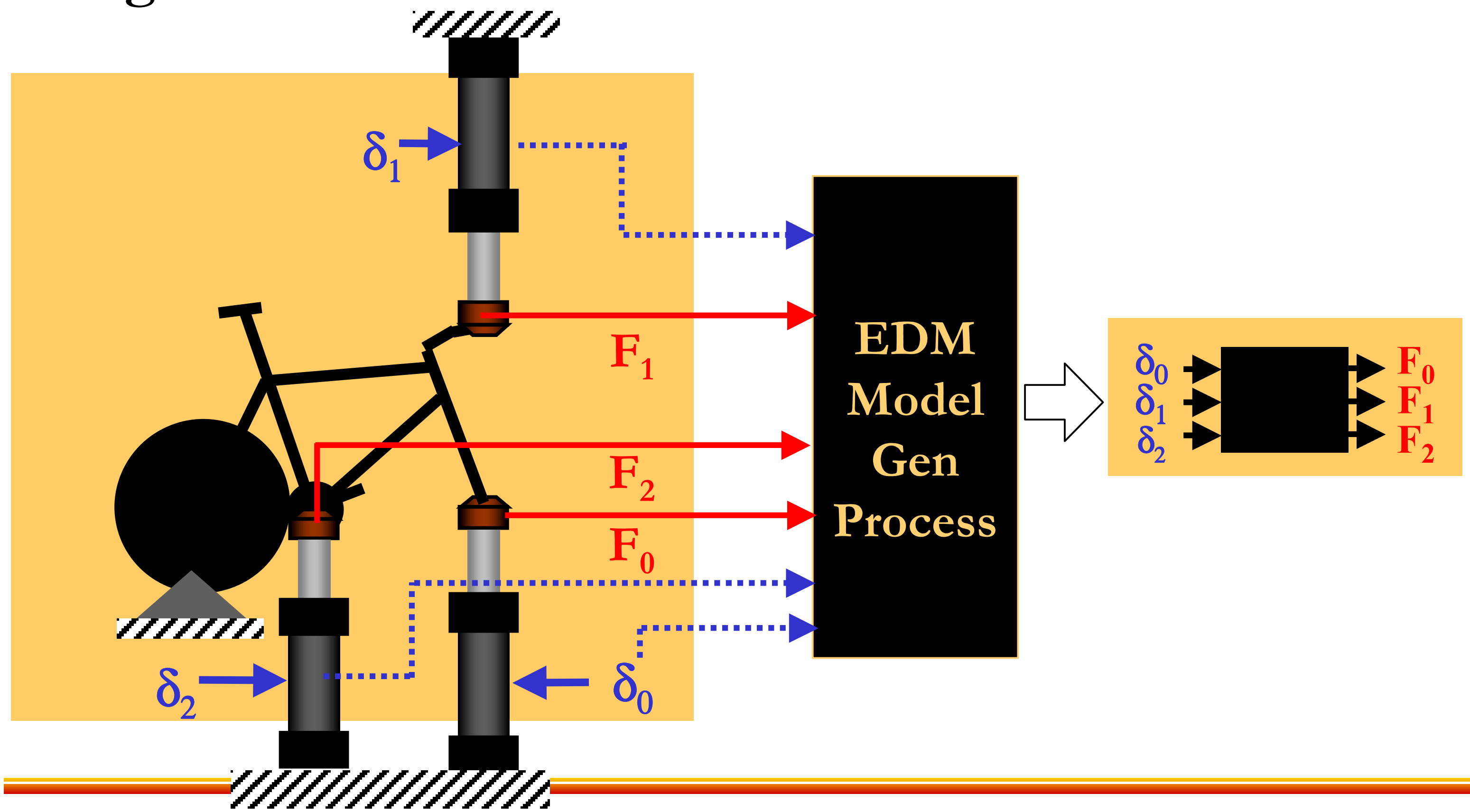
Lab Test Proposal

- Single Actuator
- Rider
- 6 signal measurements



Lab Test Proposal 2

- 3 actuators, independently controlled
- No rider !
- 6 signal measurements



Lab Test Requirement

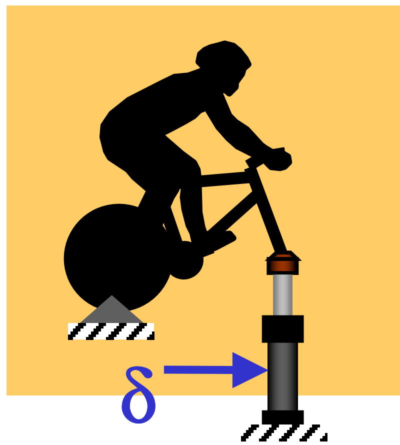
Number of independently controlled actuators

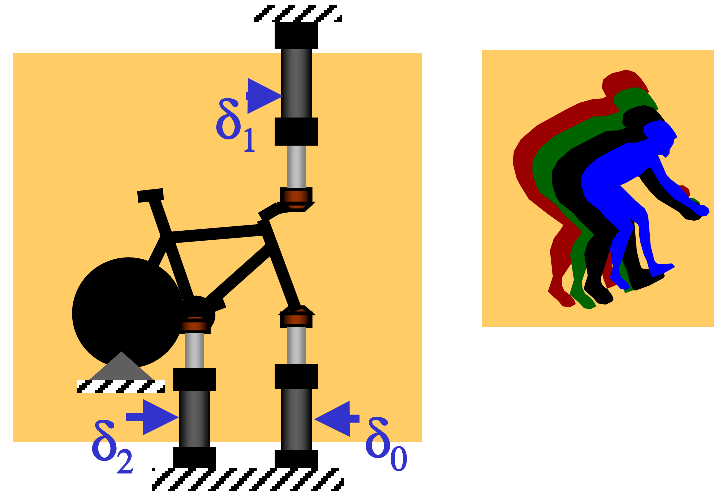
=

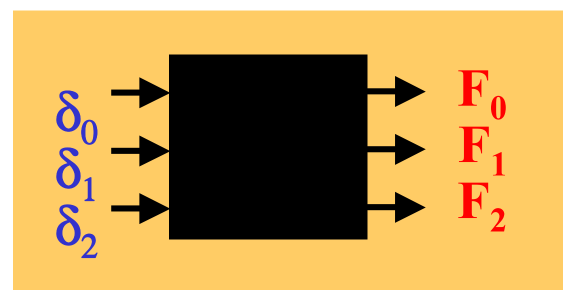
Number of ED model inputs.

Choice of Blackbox

- **Simplicity vs. Adjustability**







Choice of Blackbox Boundaries

- **Apply same thinking to more advanced systems**

Choice of Blackbox Boundaries

Summary

- **Choice of blackbox boundaries determines:**
  - the adjustability of a model
  - the number of model inputs
  - the number of independent actuators for the lab test

Summary

- **For successful nonlinear blackbox modeling, understand the limitations:**
  - **Choice of model input**
  - **Inertial force measurement**
  - **Blackbox boundaries**

Reference

A. J. Barber,

Accurate Models for Bushings and Dampers using the Empirical Dynamics Method,

ADAMS International Users Conference, 1999 (Berlin)

http://support.adams.com/usercon/euc99/euc99-thu.htm