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# Practical Considerations for Generating Nonlinear Dynamic Blackbox Models using Neural Networks

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# Contents

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- **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

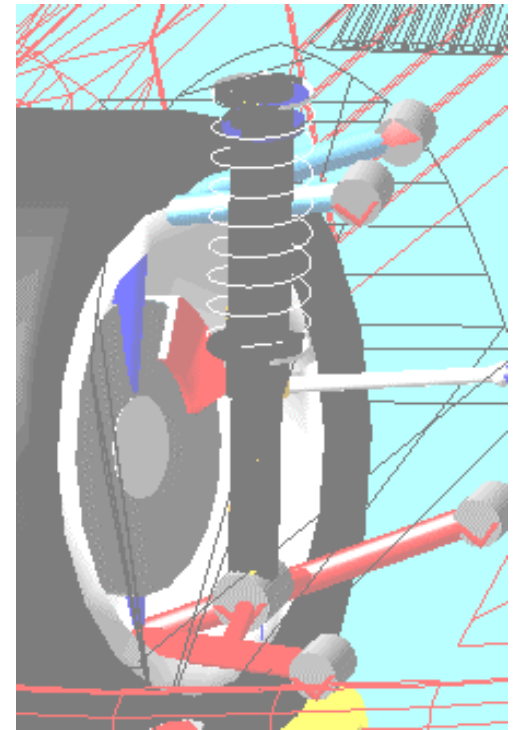
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- **Blackbox**
- **Nonlinear, Amplitude-dependent**
- **Dynamic, Frequency-dependent**
  - Exhibits Hysteresis or Memory

# Blackbox Models

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



# Whitebox Modeling

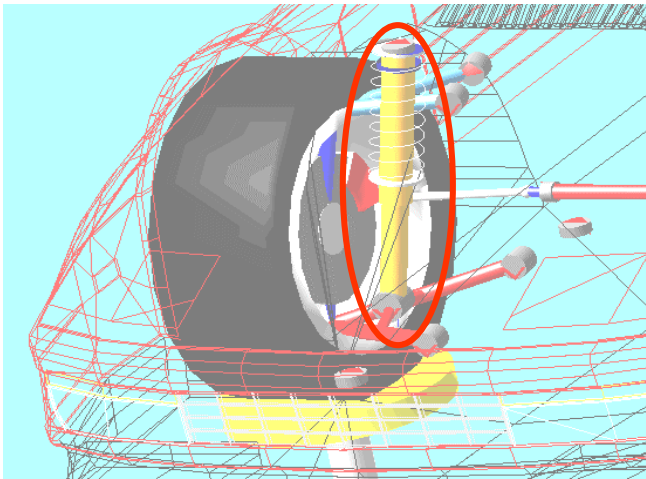
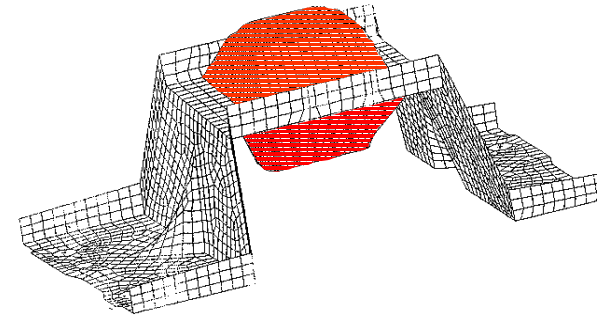
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- **Uses information about the system**
    - **Geometry**
    - **Physical properties**
    - **Physical laws**
  - **Uses differential equations**
  - **Examples: ADAMS, FEM, CFD**
-

# Why is blackbox modeling needed ?

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- Too many variables
- Slow to solve

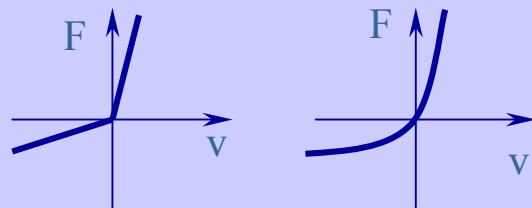


- Complex physics or math
- Expertise unavailable

# Conventional Blackbox Methods

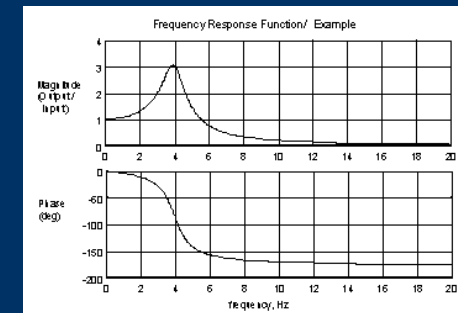
## Amplitude Dependent Models

- Splines
- Polynomials



## Frequency Dependent Models

- Frequency Response Functions (FRFs)



- ARMA Models

# Conventional Blackbox Methods

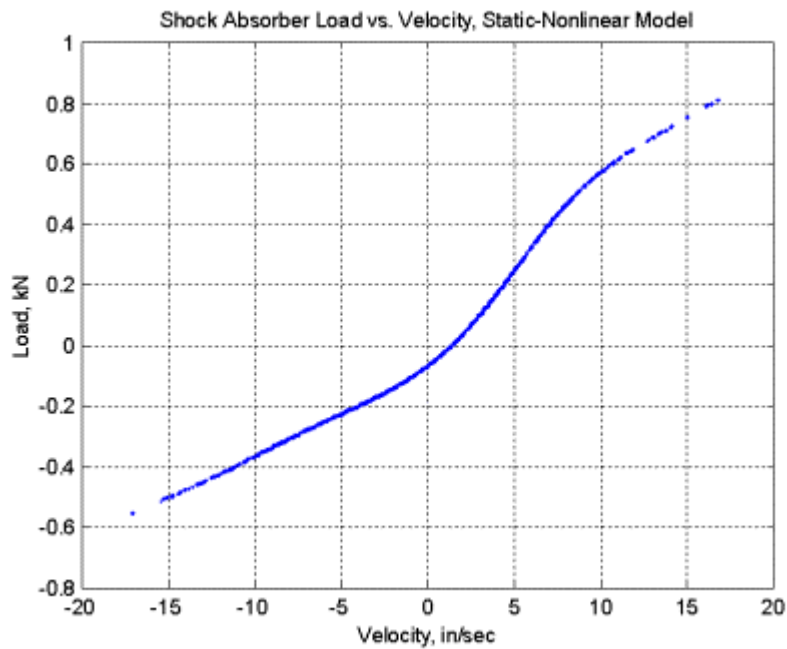
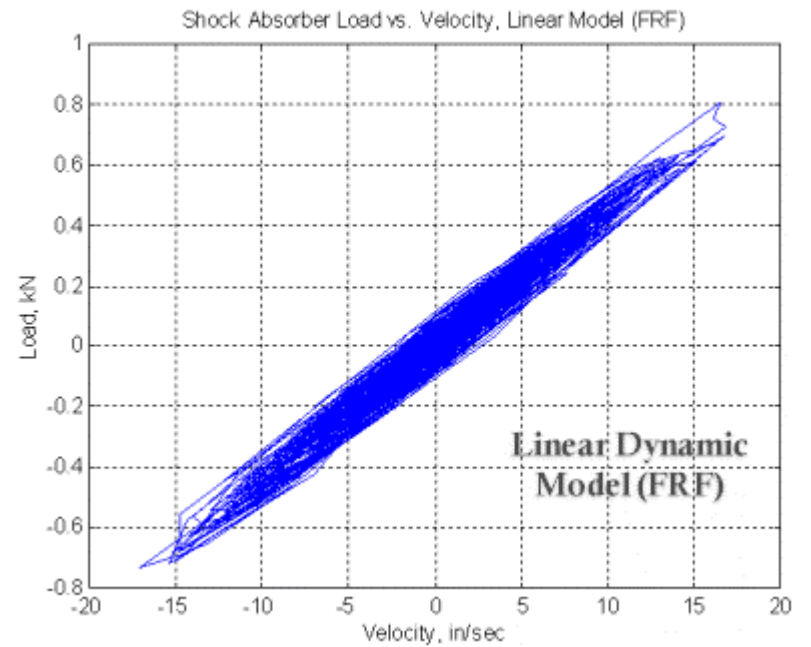
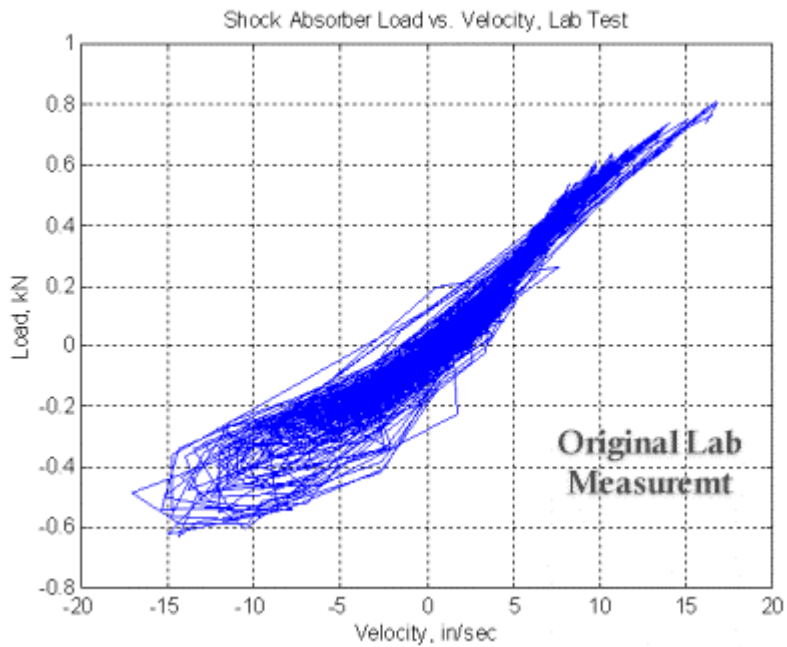
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## Amplitude Dependent Models

- nonlinear systems
- without hysteresis
- small number of inputs

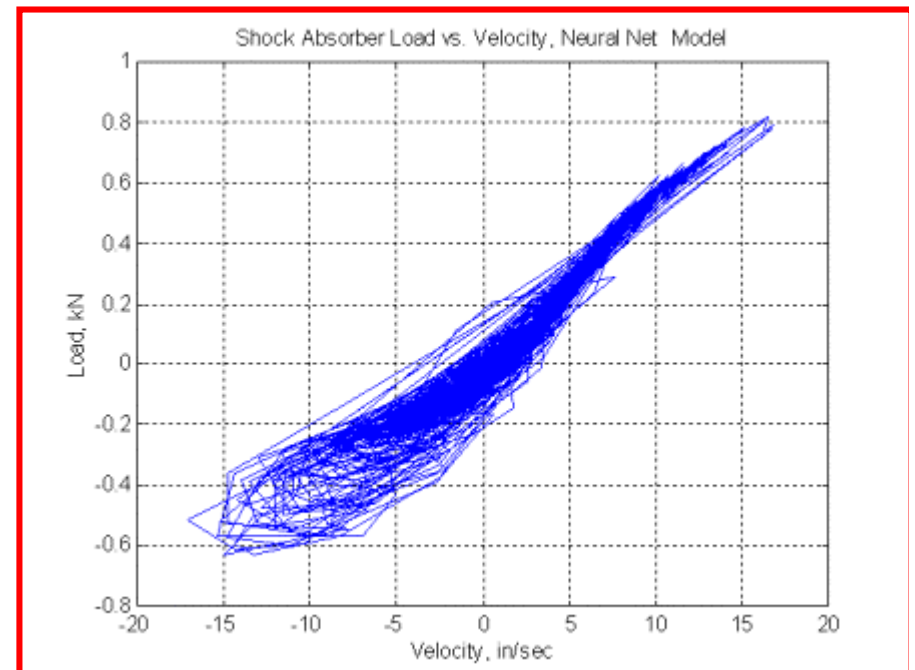
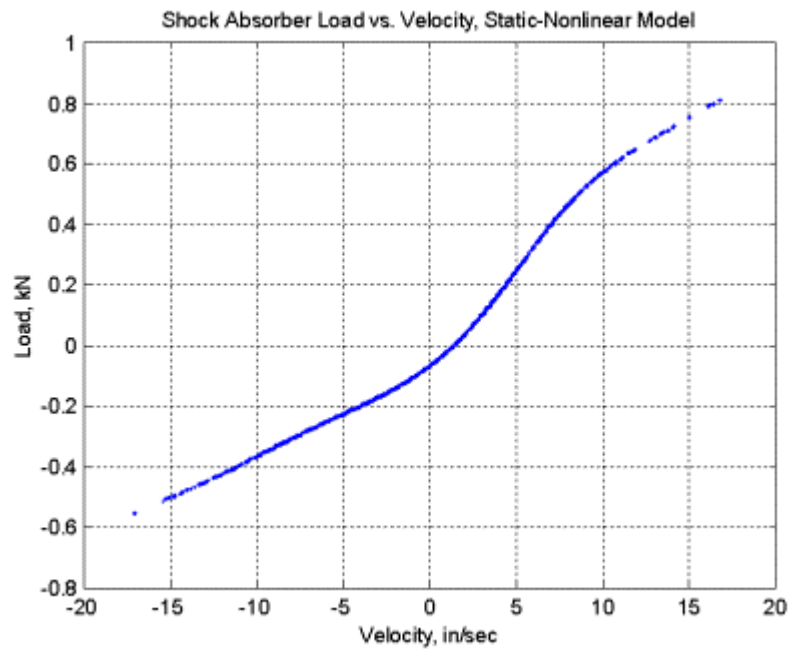
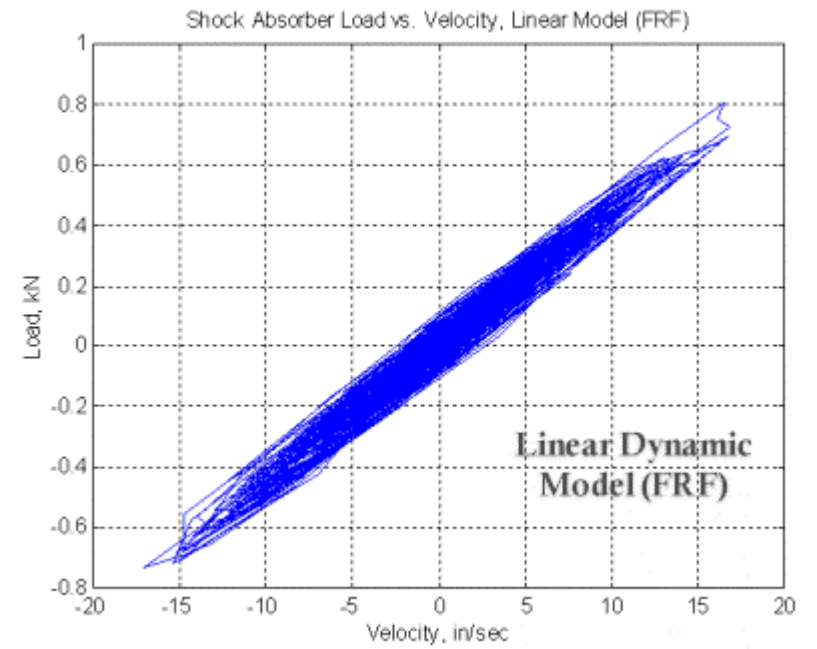
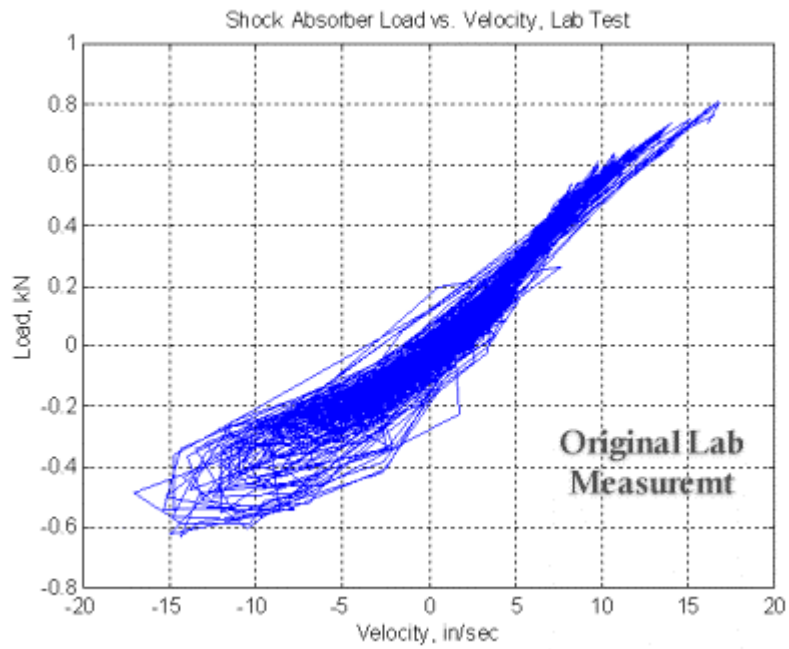
## Frequency Dependent Models

- linear systems
- with hysteresis
- many inputs



**Mathematical Complexity**

**CPU Power**



# Empirical Dynamics Modeling

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- **Blackbox**
- **Amplitude-dependent**
- **Frequency-dependent**
  
- **Random Waveform**
- **Multiple Input and Output**
- **Wide Class of Systems**

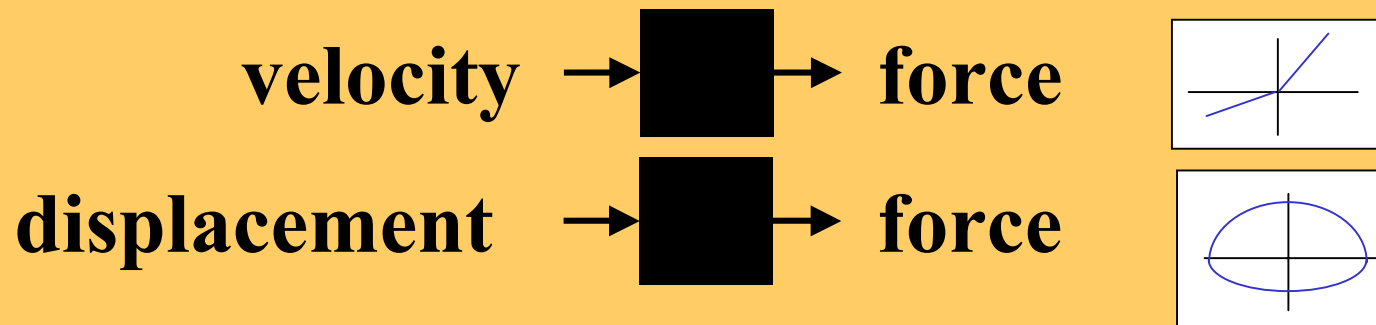
## Practical Considerations in Nonlinear Blackbox Modeling

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

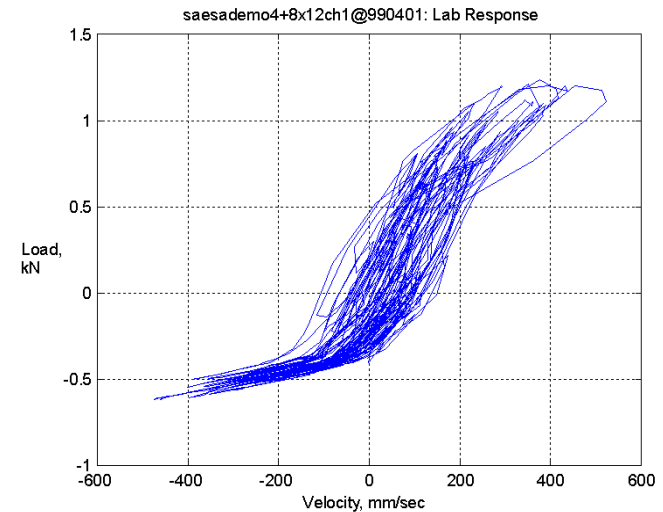
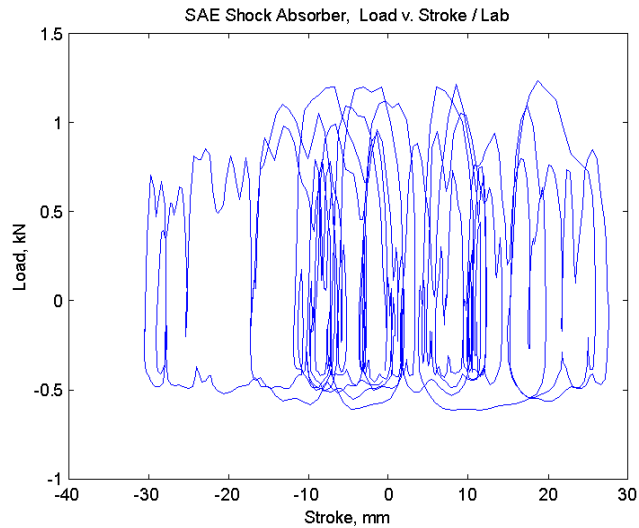
## Choice of Model Input

- 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

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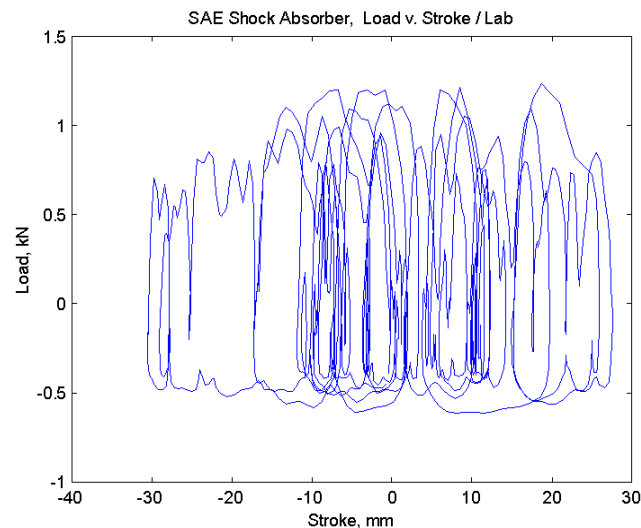
- Empirical Dynamics *damp*er models use displacement input, force output:

displacement → EDM → force

# Modeling Dampers with Displacement Input

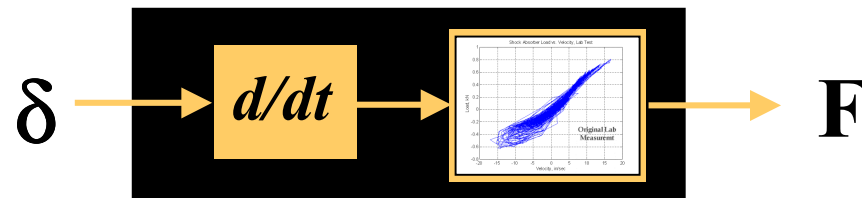
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Normally, it's not feasible to fit curves to random force-displacement data

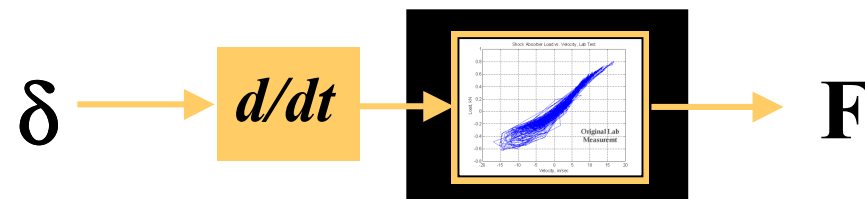


# Modeling Dampers with Displacement Input

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



## Empirical Dynamics damper model



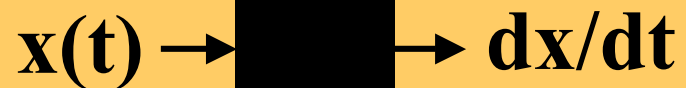
## conventional damper model

# EDM Differentiation

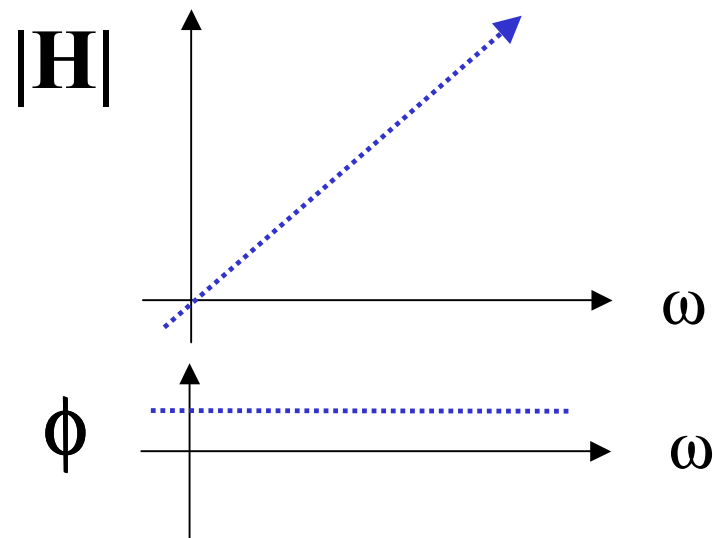
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- **Benefits**
  - Reduce differentiation errors
  - Noise immunity
  - Model different types of derivatives.

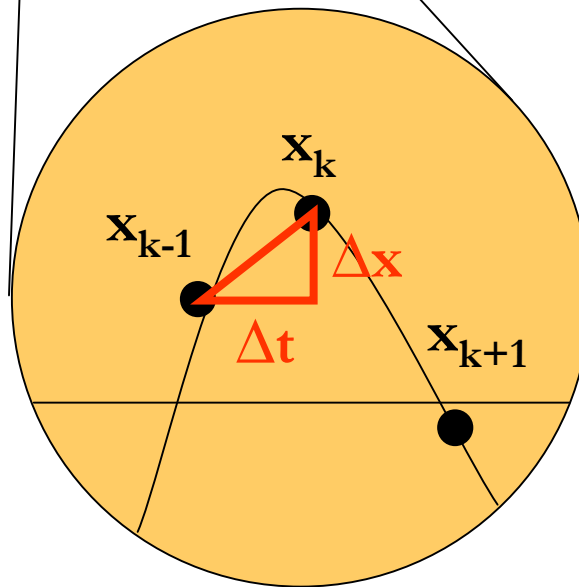
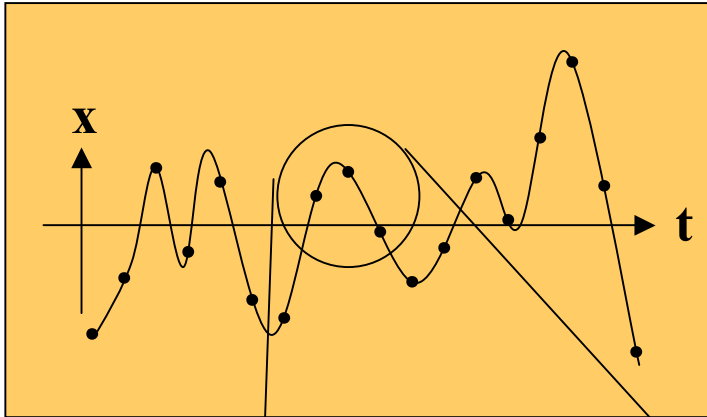
# Ideal Differentiator



- Frequency response:  $dx/dt \Leftrightarrow j\omega X = H$



# Finite Difference Differentiator

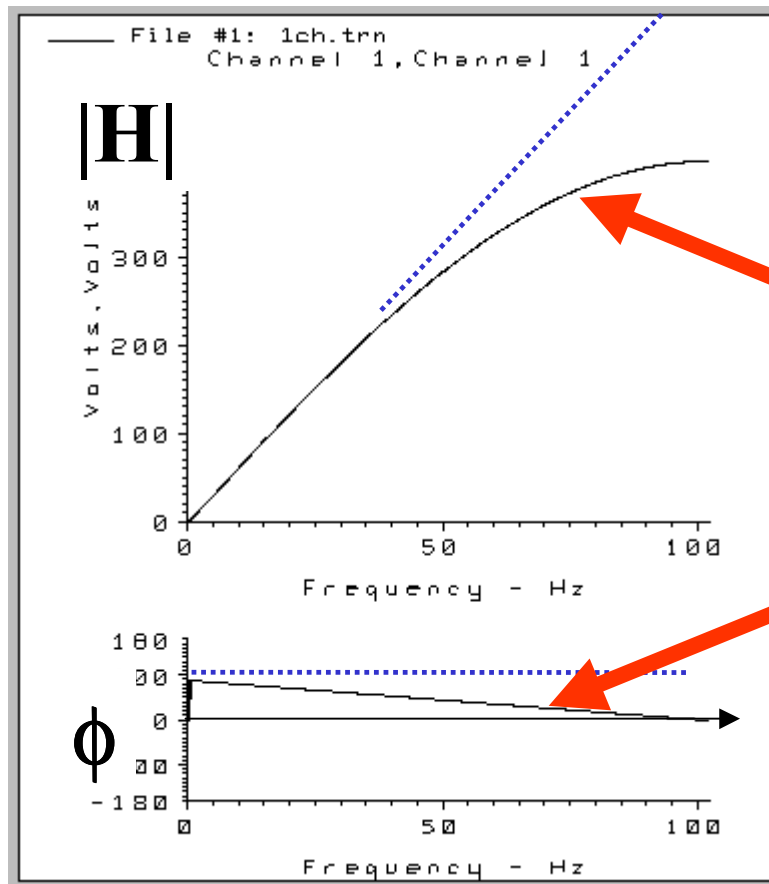


Backward Difference:

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

# Finite Difference Differentiator

## Frequency Response



..... Ideal

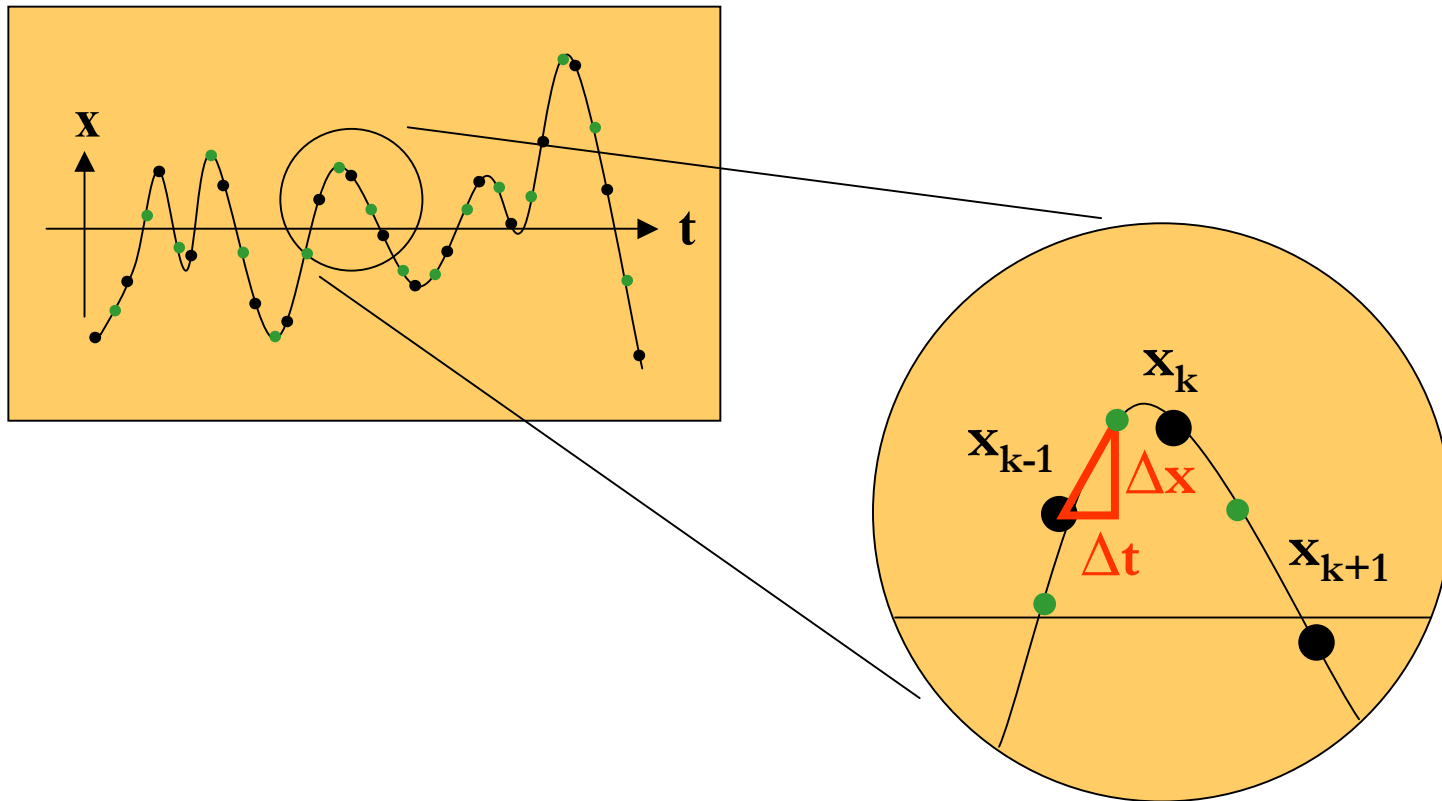
— Finite Diff.

High frequency  
attenuation

Large phase shift

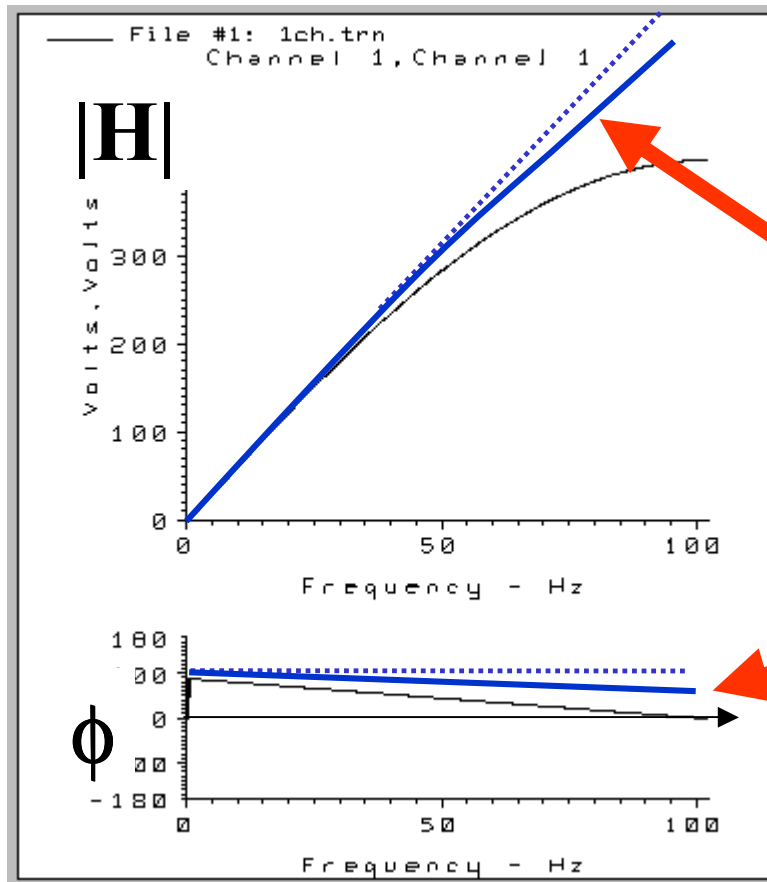
# Improved Differentiator

- Use higher sample rate



# 2x Upsampled Differentiator

## Frequency Response



- ..... Ideal
- Finite Diff.
- 2x Sampling

Better high frequencies

Less phase shift

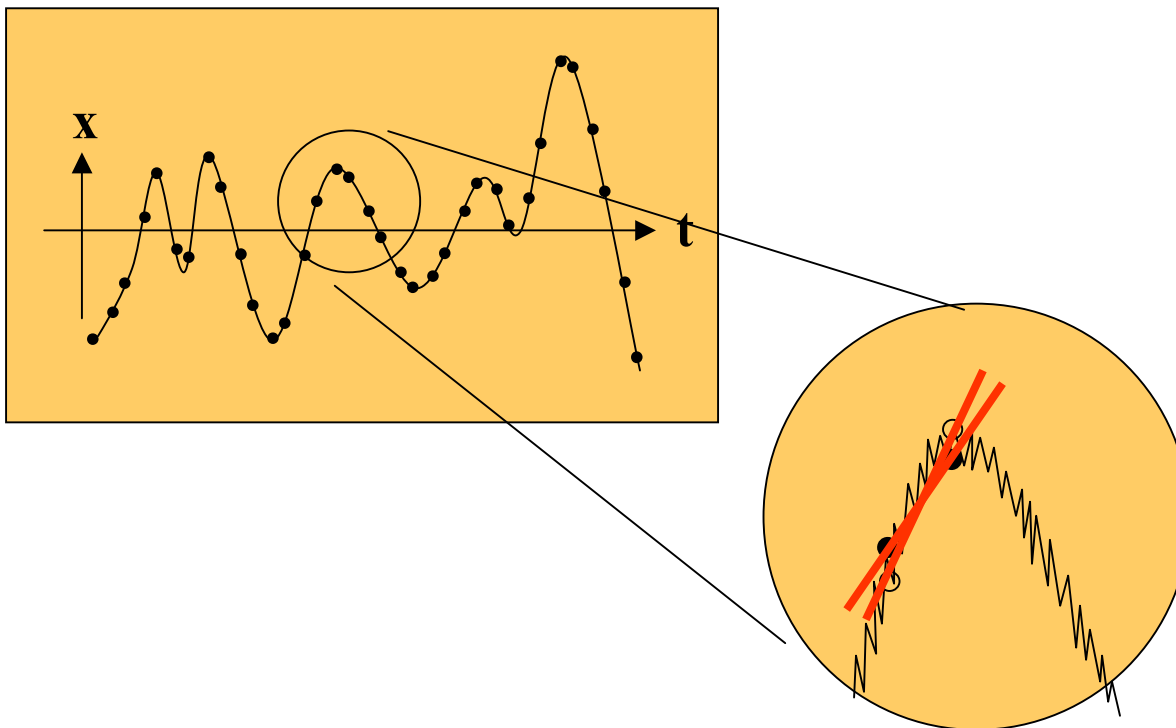
# Higher Sample Rate Differentiation

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

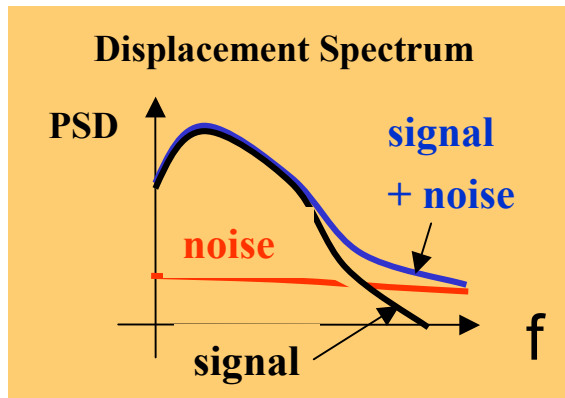
# Differentiators: Dealing with Noise

- typically, noise problems occur at higher frequencies

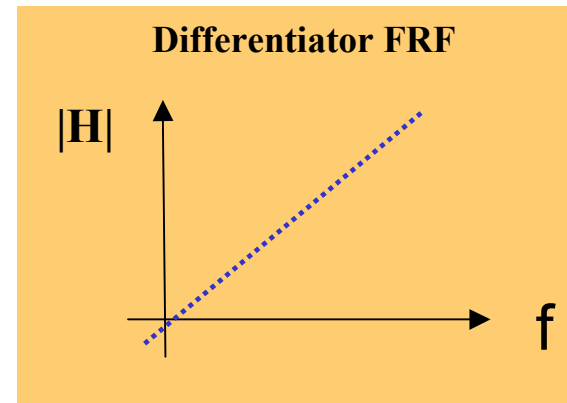


# Differentiators & Noise

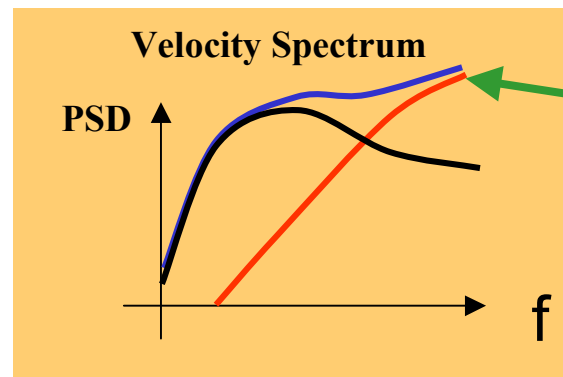
- Frequency Domain Effects



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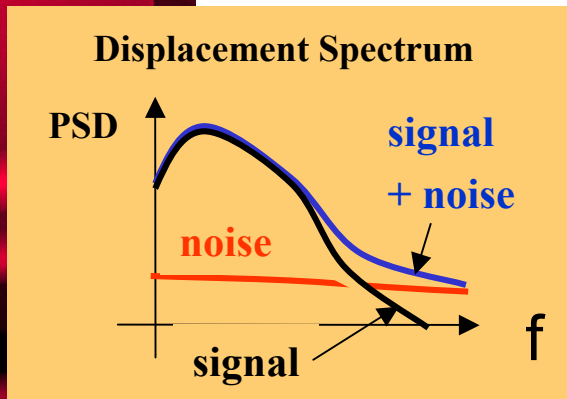
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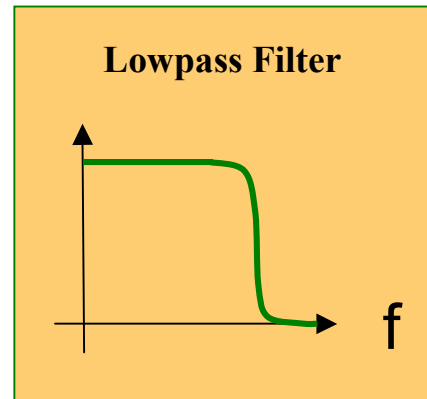
**High frequency noise dominates the differentiated signal**

# Differentiators & Noise

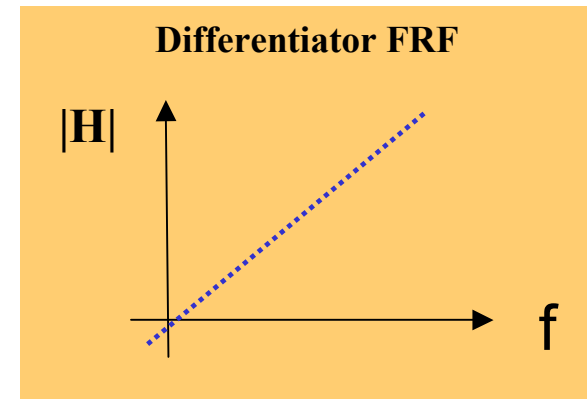
- Use of Lowpass Filter



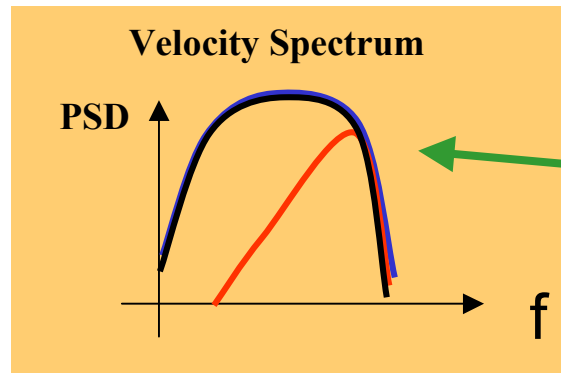
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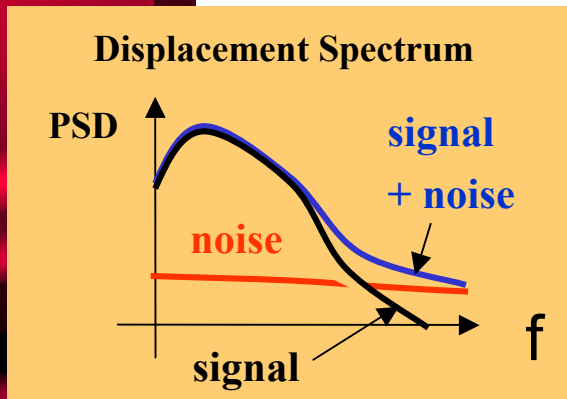
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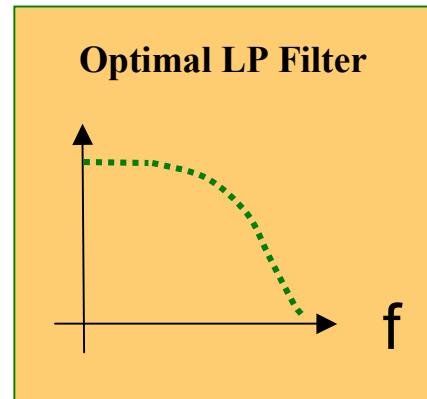
High frequency noise contribution is reduced

# Differentiators & Noise

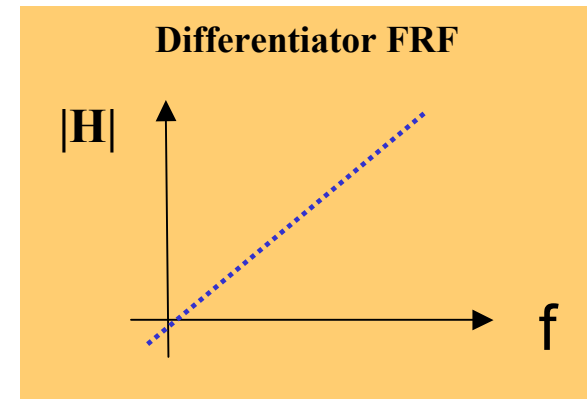
- Use of Optimal Lowpass Filter



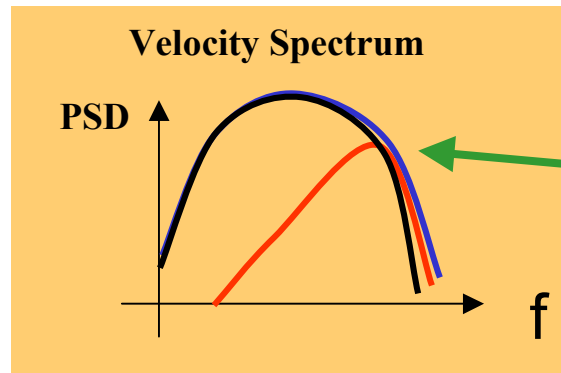
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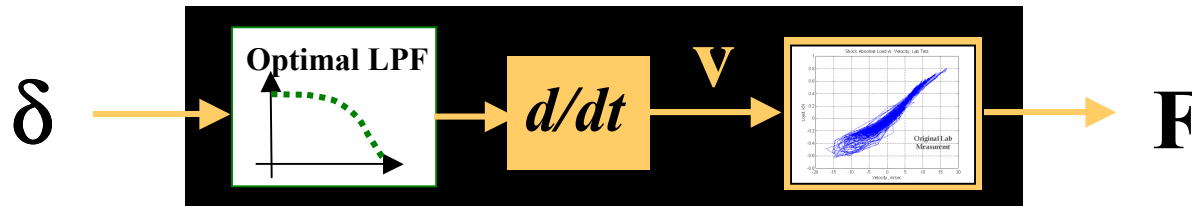


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**Improved  
high frequency  
signal response**

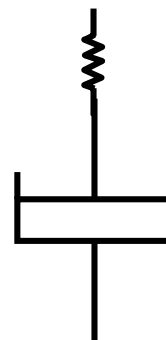
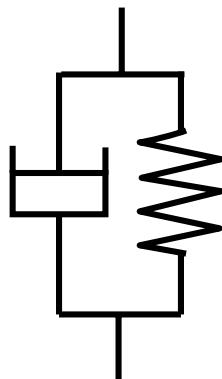
# Differentiation using EDM



- EDM differentiation effectively includes upsampled, optimal LPF

# Alternate Derivatives

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



## Choice of EDM Damper Input

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- 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 combination of displacement & velocity
-

## Practical Considerations in Nonlinear Blackbox Modeling

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

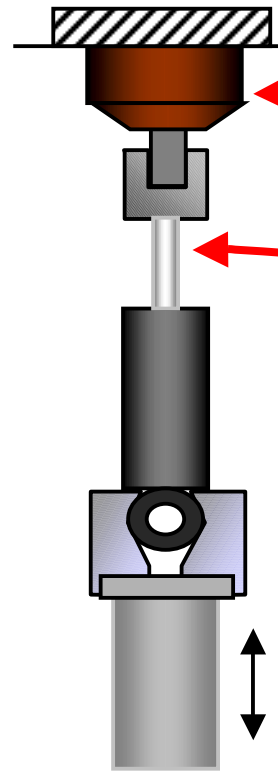
## Representation of Inertial Forces

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- A mechanical lab test may exclude important inertial force components
- These components may affect ED model accuracy at high frequencies

# Representation of Inertial Forces

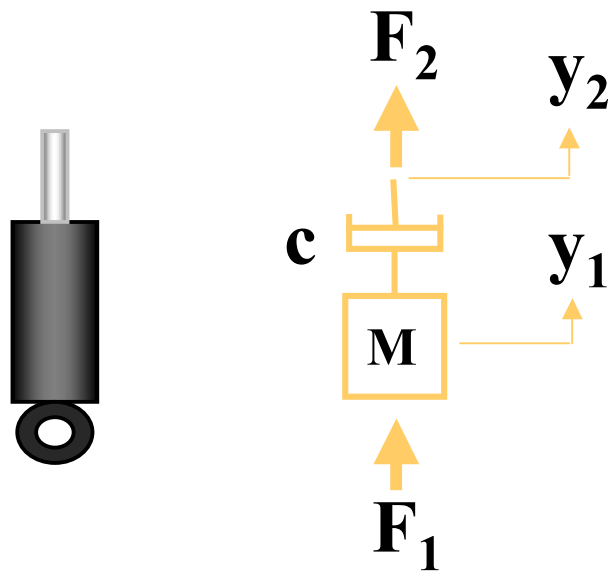
- Example: Std damper test rig



- 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



$$\Sigma \mathbf{F} = M\ddot{y}_1 = \mathbf{F}_1 + \mathbf{F}_2$$

$$\mathbf{F}_2 = c (y_1 - y_2)$$

# Representation of Inertial Forces

- Equations of Motion

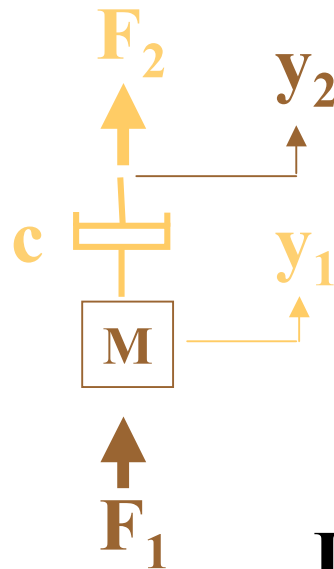
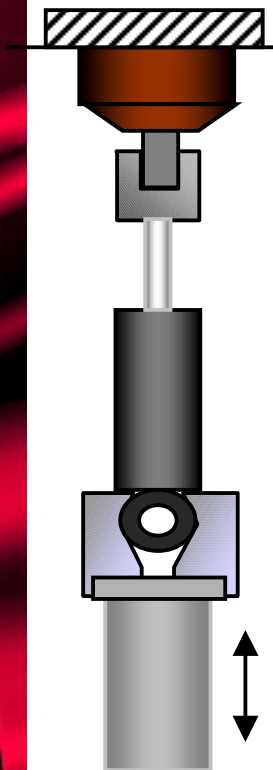
## Damper Test:

$$y_2 = 0$$

$F_1$  is not measured

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

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

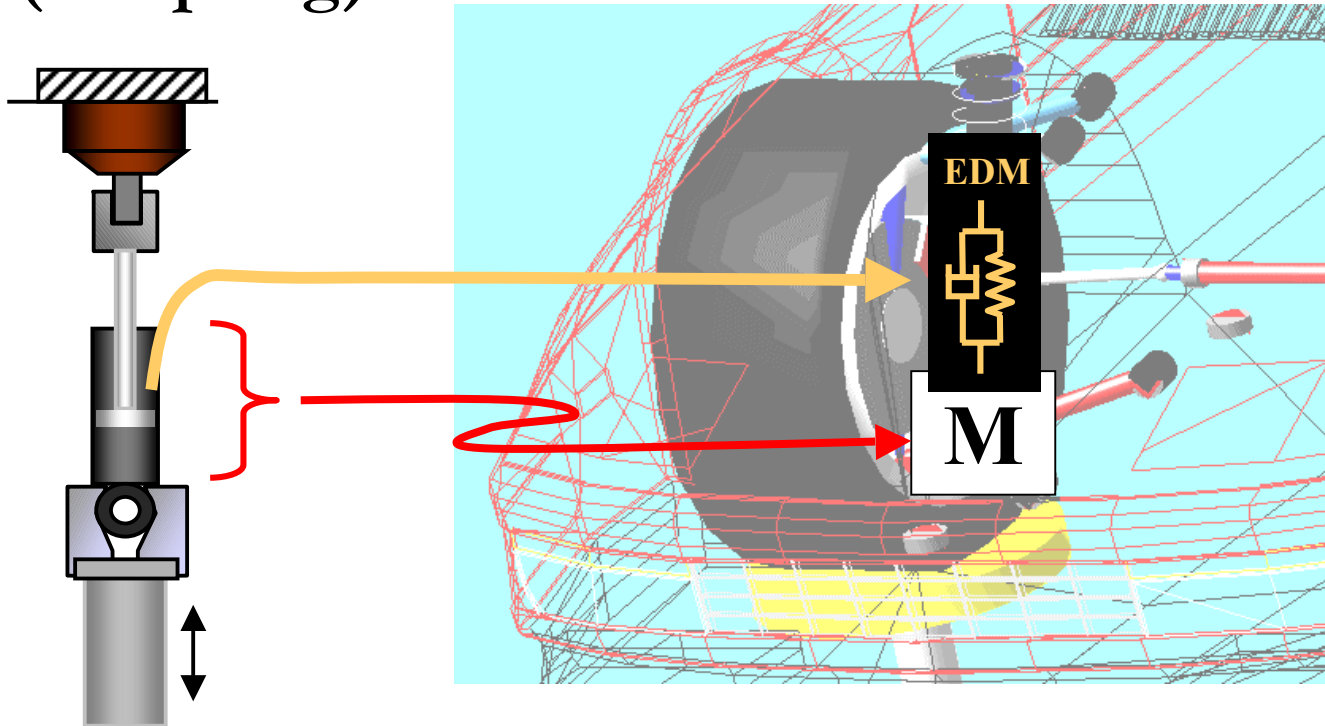


**Inertial force  $M\ddot{y}_1$  is ignored**  
**Only damping is modeled**

# Inertial Forces, Modeling Workarounds

Simple  
Damper  
(no spring)

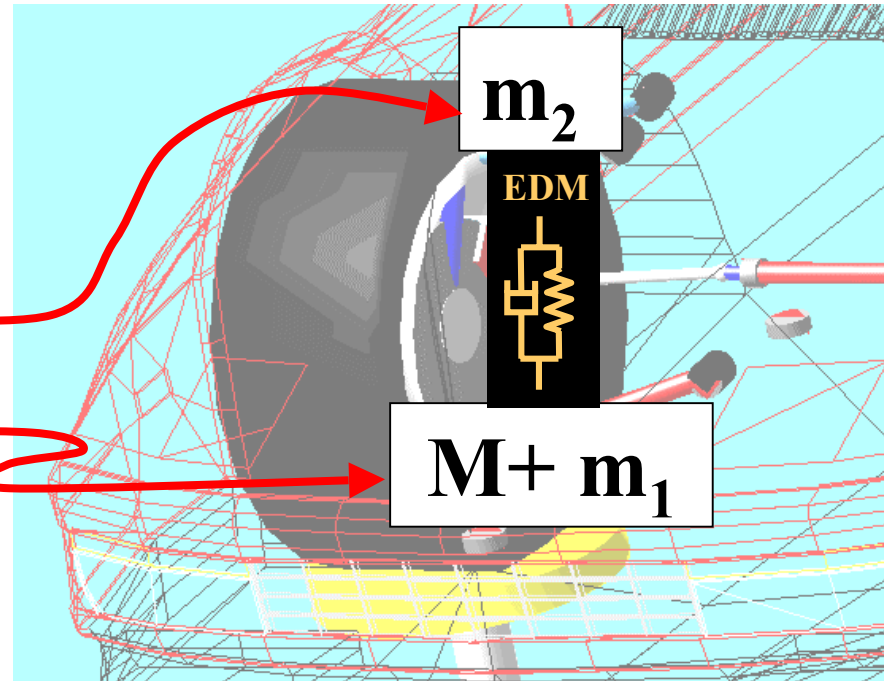
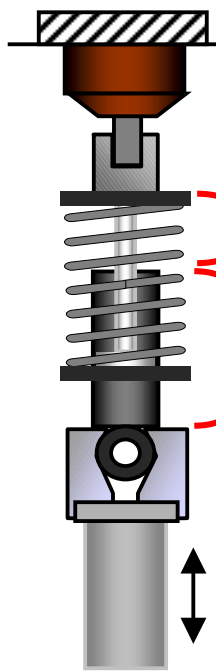
Add lumped mass of s/a body to  
one end



# Inertial Forces, Modeling Workarounds

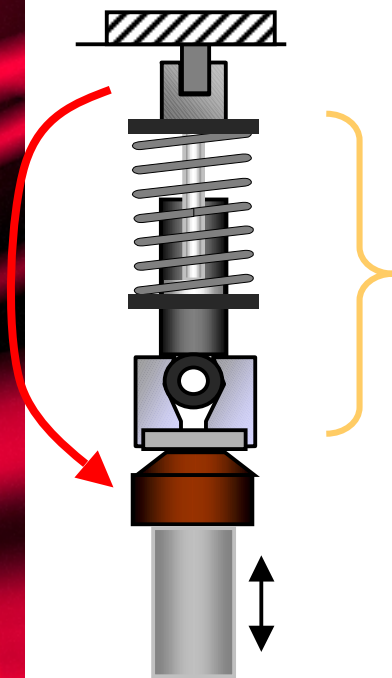
Strut  
(incl spring)

Assign a fraction of mass to each end

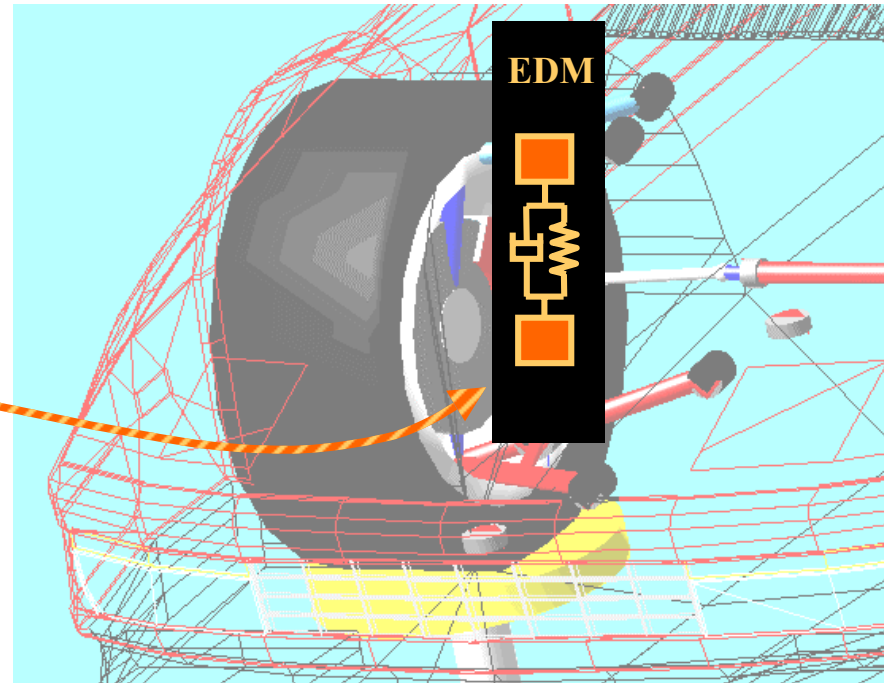


# Inertial Forces, Modeling Workarounds

**Damper or  
Strut**



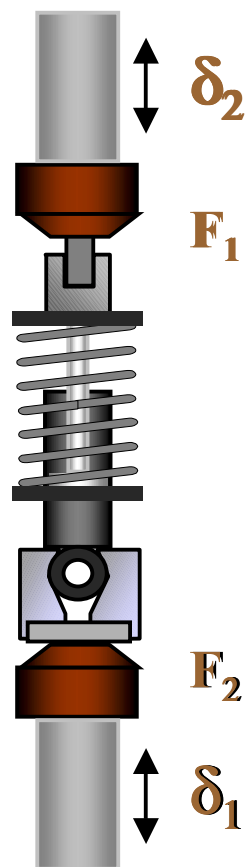
**Use load cell at the active end**



- (+) Some inertia forces are included in the blackbox
- (-) Difficult to measure - moving load cell

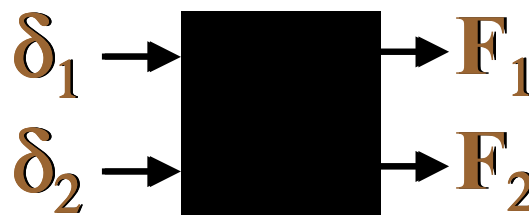
# Inertial Forces, Modeling Workarounds

## 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

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- Other specimens => similar issues
  
- Problem is inevitable at sufficiently high accelerations

# Inertial Forces and EDM

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## 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.

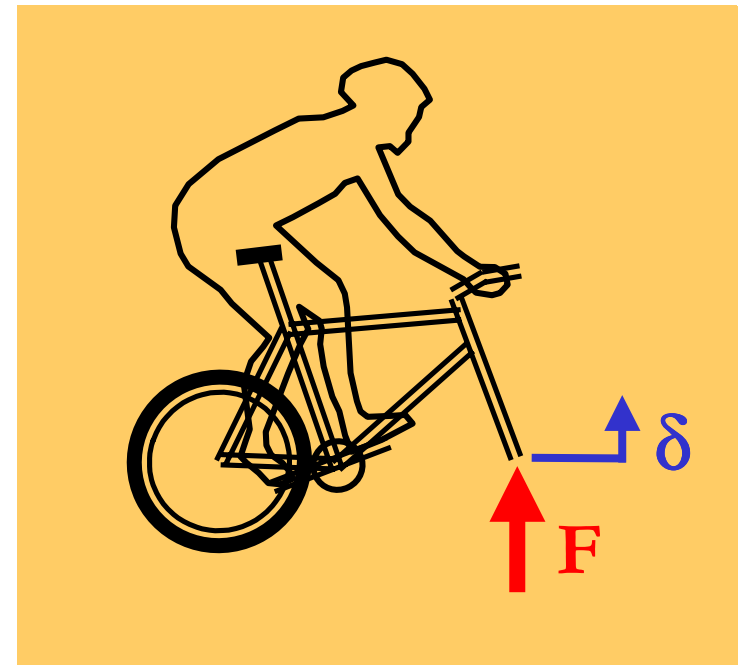
## Practical Considerations in Nonlinear Blackbox Modeling

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- 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

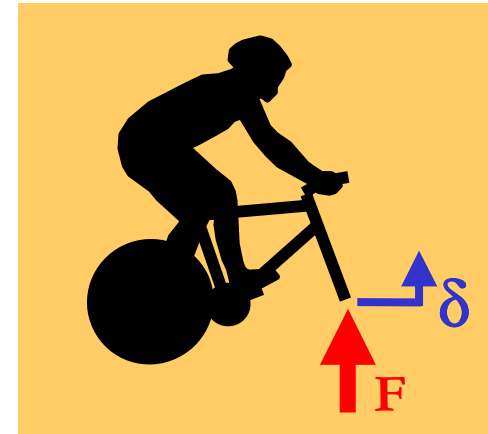


# Choice of Blackbox Boundaries

## Scenario 1

Blackbox =

Bike + Rider combination



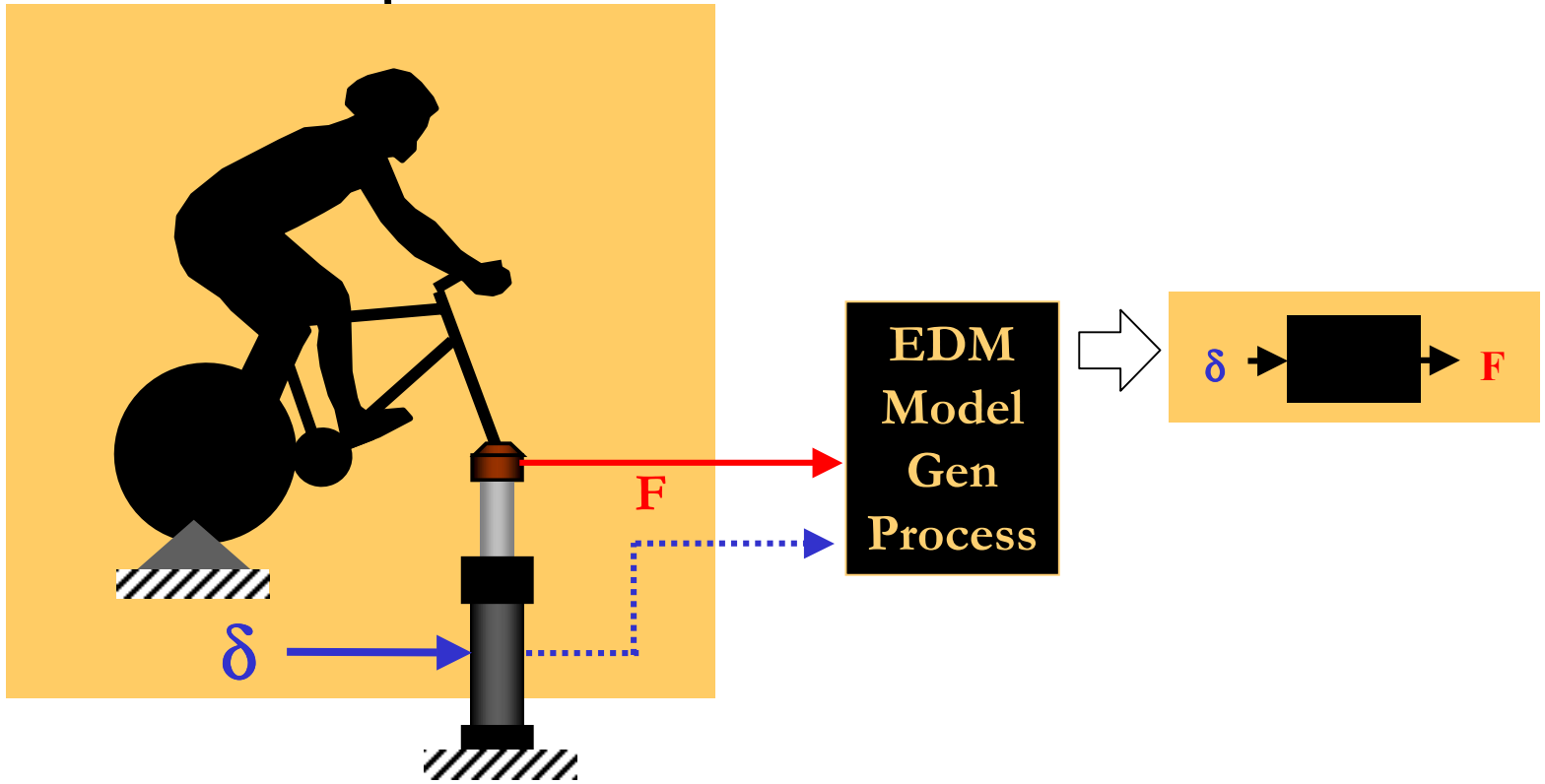
(+) can model displacement  
=> force directly  
(SISO model)



(-) model is valid only for  
one particular Rider

# Lab Test Proposal

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



# Choice of Blackbox Boundaries

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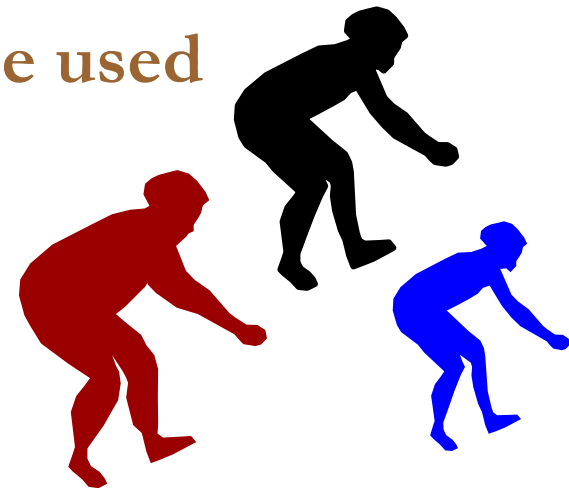
## Scenario 2

1 Blackbox = Bike

1 Other model = Rider

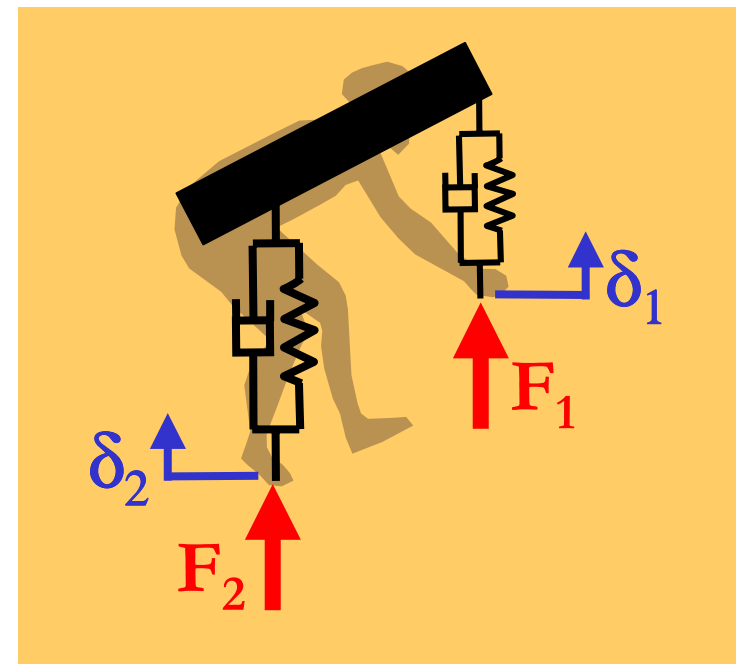


(+) Different Riders can be used



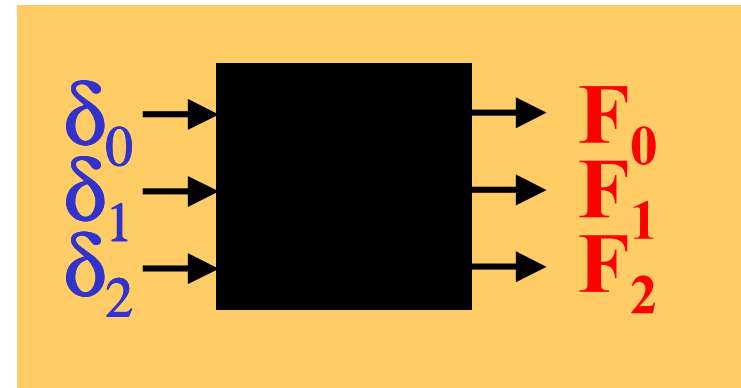
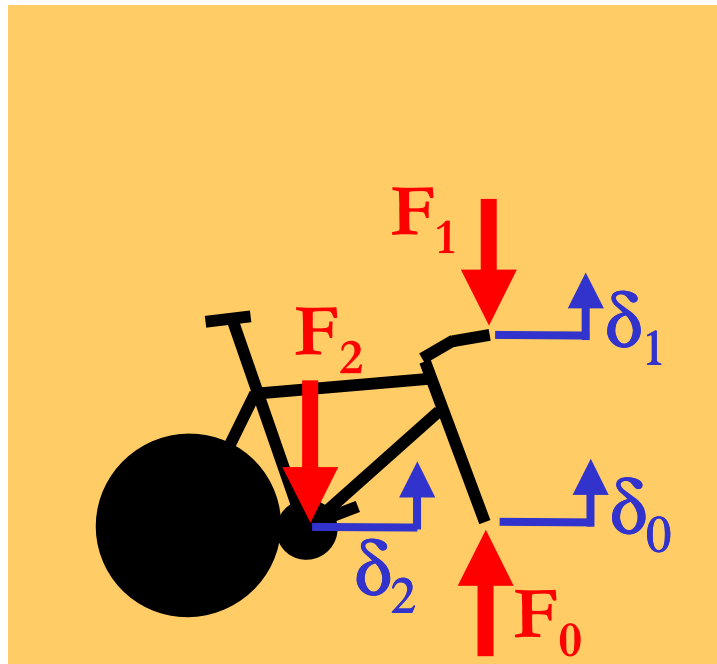
# Rider Model

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



# Choice of Blackbox Boundaries

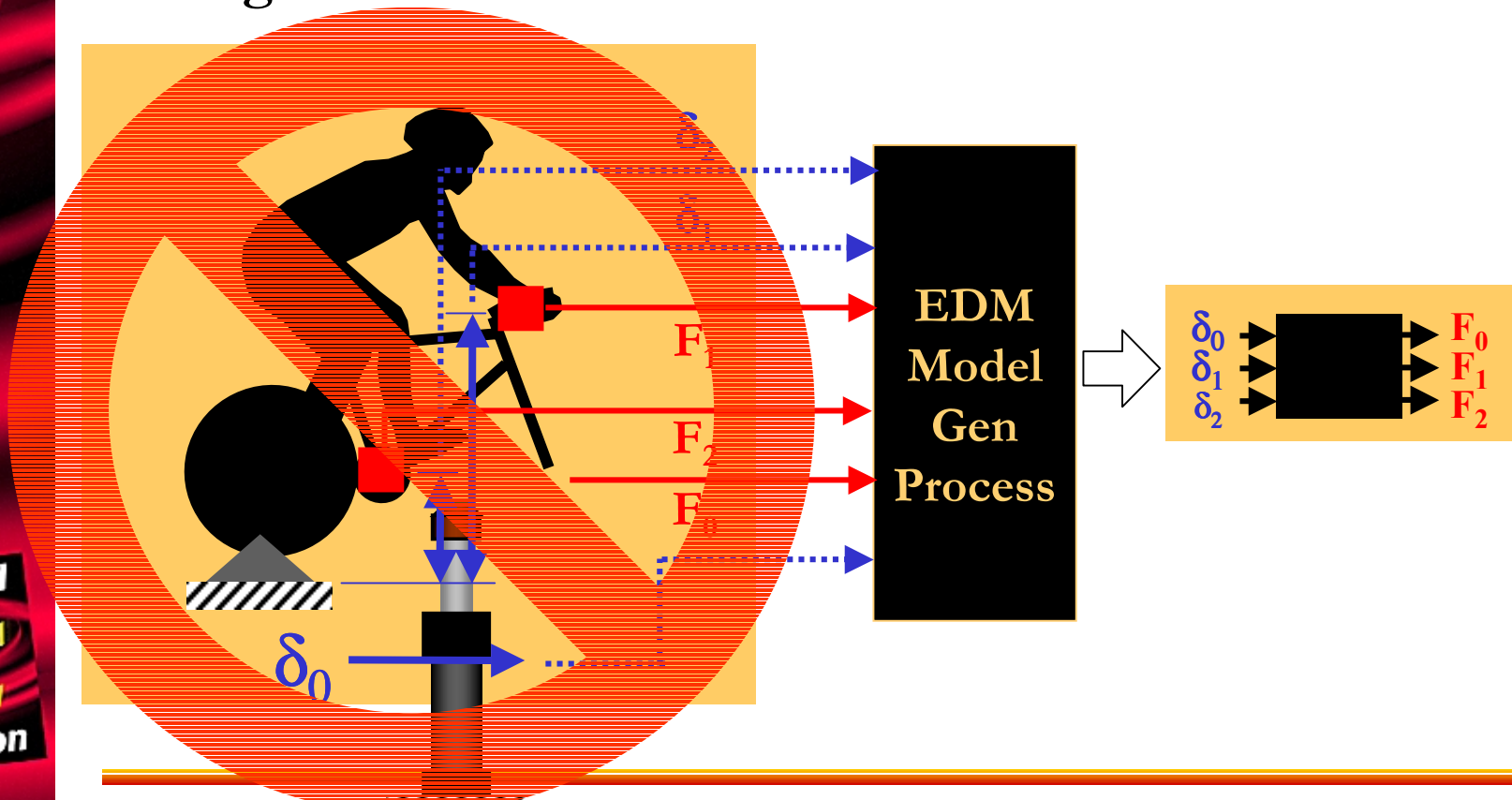
Blackbox = Bike



(-) Requires more  
blackbox inputs !

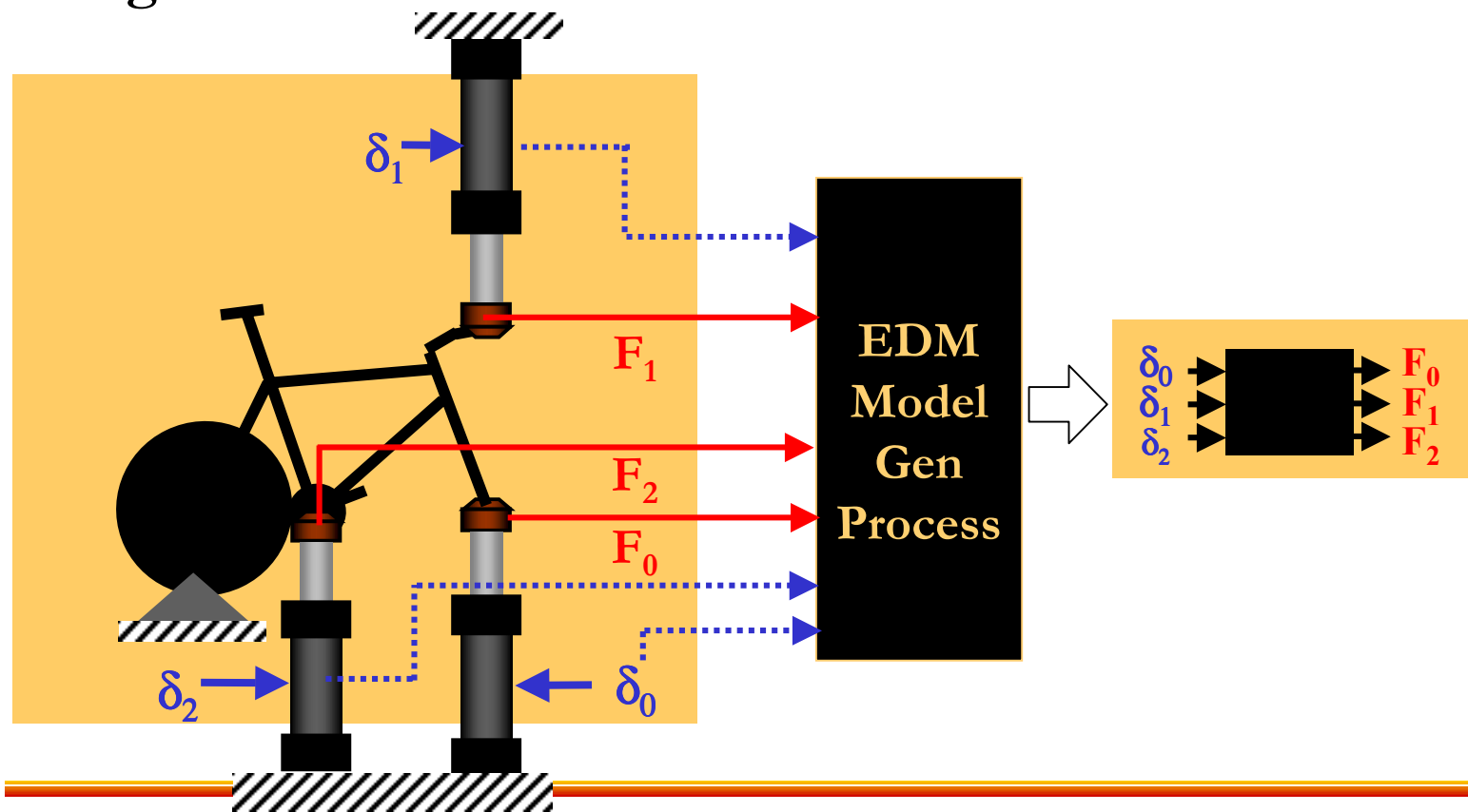
# Lab Test Proposal

- Single Actuator
- Rider
- 6 signal measurements



# Lab Test Proposal 2

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



# Lab Test Requirement

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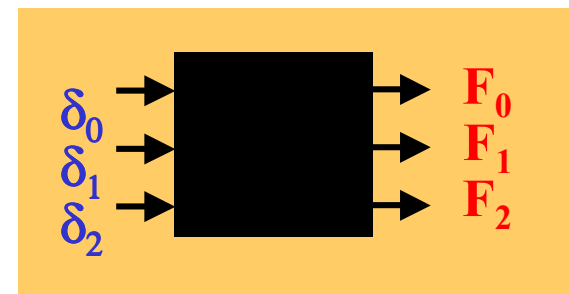
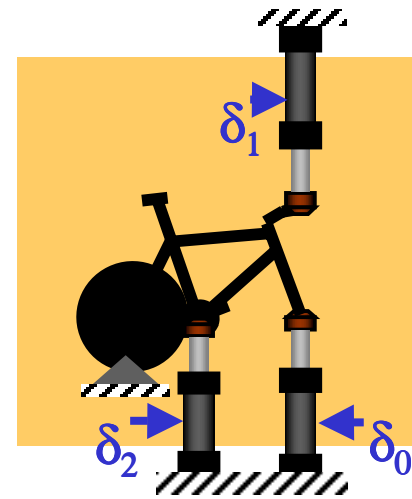
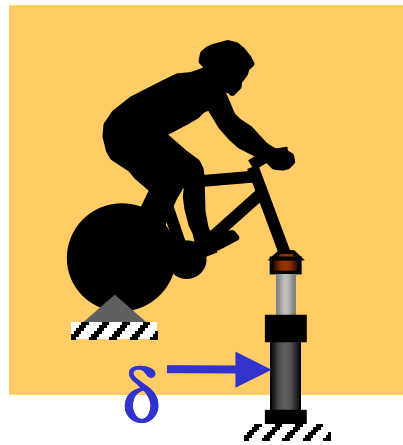
**Number of independently  
controlled actuators**

**=**

**Number of ED model inputs.**

# Choice of Blackbox

- **Simplicity vs. Adjustability**



# Choice of Blackbox Boundaries

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- Apply same thinking to more advanced systems

# Choice of Blackbox Boundaries

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## 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

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

# Reference

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**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>**