Practical Application of the Empirical Dynamics Method

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ABSTRACT

Recent studies have shown that the Empirical Dynamics™ Modeling (EDM™) method can be used to generate high accuracy blackbox models for vehicle suspension components, when both amplitude dependence and frequency dependence are present. Development is now underway to integrate EDM models into the suspension design and development process. Work in this area includes:

- Identifying factors that affect the practical application of the ED method.
- Testing the ADAMS-EDM interface methodology, in actual case studies.
- Development of software tools to enable widespread use of ED modeling.

This presentation will focus primarily on the first item above.

Experience with EDM has revealed several issues that affect its practical application, such as:

- Repeatability of specimen responses. When the same lab excitation is applied more than once to a specimen, the response will differ each time. These variations cannot be predicted within the EDM framework.
- The choice of displacement or velocity as the model input, for damper-like components. Model accuracy may be greater when the input is displacement, and EDM is allowed to identify the differentiator.
- The choice of force or displacement as the model input. Force (or moment) inputs may produce low accuracy models, for damper-like components.
- The choice of blackbox boundaries. Specimens that serve as 'terminal' system elements may require substantially fewer model inputs than those that serve as 'intermediate' elements.
- The lab test configuration. When ED models are generated using conventional test rigs, the model may represent some but not all of the inertial forces in the component.
- Documentation of the lab test configuration. Unambiguous communication of specimen orientation and signal polarities, from the lab test to the analyst workstation, is essential.

Descriptions of these factors, and some workarounds, will be presented.

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Practical Issues in Using EDM

- Repeatability of Measured Response
- Choice of Model Input
  - Displacement
  - Velocity
  - Force
- Choice of Blackbox Boundaries
- Incomplete Representation of Inertial Forces
- Lab Test Configuration

Issue 1: Repeatability of Measured Response

Repeatability: Definition

- **Characteristic of laboratory-measured signals**
- **Result of multiple tests, using identical input each time**
- **Repeatability = similarity of responses**

Repeatability: Issue

- **No two measurements are the same**
  - **unmeasured or uncontrolled conditions**
  - **external disturbances**

- **Accuracy of EDM is limited by (non)repeatability**

Repeatability Measurement

- Run test 2x
- Calculate difference in responses
- Express in terms of RMS

Alternative Repeatability Measures

- More than 2 tests
  - Calculate ensemble average, deviations
- Short term
  - Play a small segment of excitation
  - Repeat it again immediately
- Frequency domain
  - Calculate PSD of repeatability error

Dealing with Repeatability Issues

- **Bandwidth Limitations**
- **Amplitude Considerations**
- **Consider more inputs to model**

Issue 2: Choice of ED Model Input

Choice of ED Model Input

- **Focus on EDM *damper* models**
- **EDM damper input choices**
  - **Displacement**
  - **Velocity**
  - **Force**

Model Input: Displacement or Velocity?

Objective — Determine which is best, for EDM

Procedure — Consider limitations of conventional discrete differentiators

- Bandwidth
- Phase
- Noise Sensitivity

Conventional Differentiators

- **First Backward Difference**
  - **Amplitude roll-off at high frequency**
  - **Phase shift**

Improved Differentiators

- Up/downsample with finite differences
- High order differentiator

Conventional Differentiators

- **Dealing with Noise**
  - Low pass filter
  - Optimal filter
    - requires estimate of noise spectrum

Differentiation via EDM

- **EDM identifies differentiator as needed**
  - **No assumptions required**
  - **Handles derivatives of any order**

- **Similar to optimal filter**
  - **no need for noise spectrum estimate**

Model Input: Displacement or Velocity?

- **Conclusion**
  - **Let EDM handle the differentiation**

Model Input: Displacement or Force?

- **For damper-like elements, prefer <u>displacement</u> as input, rather than force**

Model Input: Displacement or Force?

- **Same damping force at different displacement**
- **Force doesn't uniquely determine displacement**
- **Force-velocity integration constant is not defined**

Model Input: Displacement or Force?

- **Contrast w/ elastomer:**
  Force defines unique displacement

- **Spring-like behavior => no integration constant needed.**

Model Input: Displacement or Force?

Complication

- MacPherson strut (spring + damper)
  - Q: can displacement input be used?
  - A: depends on connection of spring & damper

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Model Input: Displacement or Force?

serial connection

- **displacement still not unique**
- **can't use force input**

parallel connection

- **spring helps define displacement uniquely**
- **can use force input**

Model Input: Displacement or Force?

More Complication

- Spring + (spring & damper) (etc)
  - Q: can displacement input be used?
  - A1: depends on connection of spring & damper
  - A2: need a general purpose criterion
  - tentative: consider FRF of specimen, in terms of force/displacement and vv.
  - Rule = Avoid ‘integrator’ behavior at low frequencies

Model Input: Displacement or Force?

General Criterion for Force Input

- Consider frequency response functions (FRFs)
  - Force =>displacement
  - Any input => any output

- Rule: Avoid ‘integrator’ behavior at low frequencies

Issue 3: 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

- **Input force depends on rider dynamic properties:**
  - **mass**
  - **bio-suspension (arm & knee stiffness)**

Choice of Blackbox Boundaries

- Several choices for blackbox boundaries
  - Bike + Rider
  - Bike alone

Choice of Blackbox Boundaries

Blackbox = Bike + Rider

(-) does not allow any modification for rider characteristics

(+) can model displacement => force directly

Choice of Blackbox Boundaries

Blackbox = Bike alone

(+) Can be used with any type of rider – assess effects of variable mass & stiffness

(-) Requires accurate rider model.

- **Mass spring damper is simplest**
- **ED rider may be more precise, but difficult to measure**

(-) Requires more blackbox inputs !

Choice of Blackbox Boundaries

- **More blackbox inputs: displacement at front hub is insufficient information to define force output**

- **To include effect of “variable” rider, use additional inputs to cover effect of rider**

- **Additional inputs could be displacements at handlebars, bottom bracket, …**

Choice of Blackbox Boundaries

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

Choice of Blackbox Boundaries

Summary

- Number of ED model inputs depends on where/how define black box

Issue 4: Inertial Forces in EDM

EDM Representation of Inertial Forces

- **Focus = lab test configuration**
- **Example: Std damper test rig**

  - **load cell between s/a and ground; typically, rod attaches to load cell end**
  - **measures damping force, but not inertia force of actuator body**

Inertial Forces, Modeling Workarounds

Simple Damper (no spring)	**Add lumped mass of s / a body to one end**
Strut (incl spring)	**Assign a fraction of mass to each end**
	Can't simulate higher frequency dynamics (spring surge , ~ 40Hz)

Inertial Forces, Modeling Workarounds

Strut

(incl spring)

Use alternative test rig

- two actuators
- two load cells

=> 2 input, 2 output blackbox

Potential limitations from moving load cell

EDM Representation of Inertial Forces

- Other specimens => similar issues
- Inevitable at sufficiently high frequencies

Summary

- For accurate EDM characterization at high frequencies, use special test rig

Issue 5: Lab Test Configuration

Lab Test Configuration

- Coordinate systems, signs
  - Test rig cdts ≠ ADAMS cdts
  - ED model defined wrt Lab cdts
  - Potentially erroneous dynamics
  - Especially easy to confuse left hand vs. right hand models
  - Cdt transformation may be necessary

Lab Test Configuration

- **Lab dimensions required**
  - **For EDM**
    - **Moment arms**
  - **For ADAMS**
    - **Damper length**

Lab Test Configuration

- **Workarounds**
  - Define axis & sign conventions
  - Record lab test conditions
    - Axis orientation diagram
    - Lengths
  - Coordinate transformations tools

Summary

- **For successful Empirical Dynamics Modeling, understand the limitations:**
  - Lab test repeatability
  - Choice of input
  - Blackbox boundaries
  - Inertial force measurement
  - Coordinate systems