Détection, caractérisation et identification de non-linéarités en dynamique des structures

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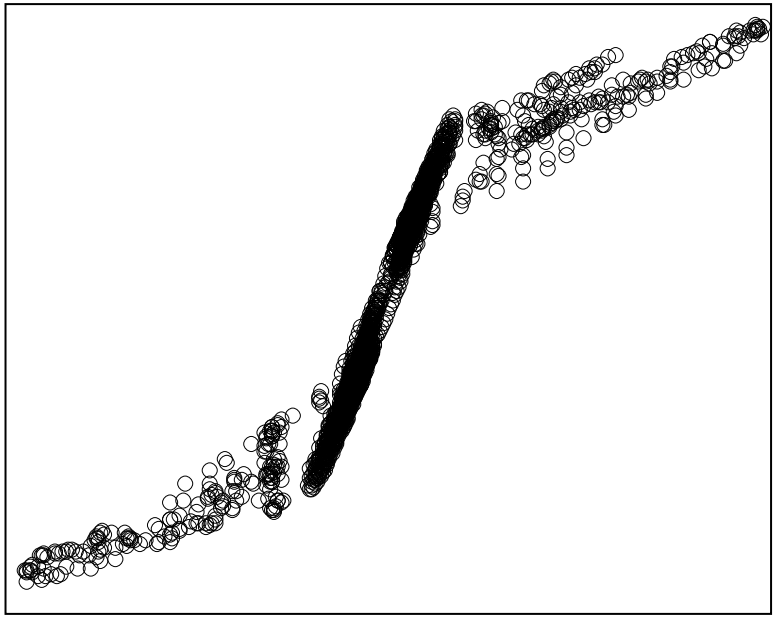


Mots-Clefs

- Acoustique
- Vibrations
- Expérimentations
- Basses Fréquences (autour de 200Hz et inférieures)

Applications

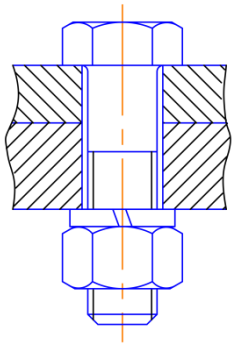
- Transports
- Bâtiments
- Environnement
- Surveillance
- Contrôle et synthèse
- Musique
- Audio…

Thèmes

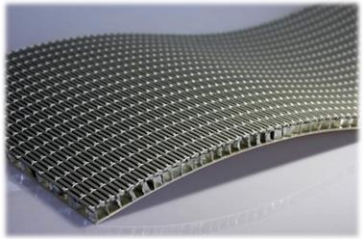
- Conception d'Expériences
- Outils et Méthodes en Basses Fréquences
- Perception
- Systèmes dynamiques non linéaires
- Traitement du Signal
- Capteurs
- Propagation…

Is Your Application Nonlinear ?

Bolts, joints and gaps



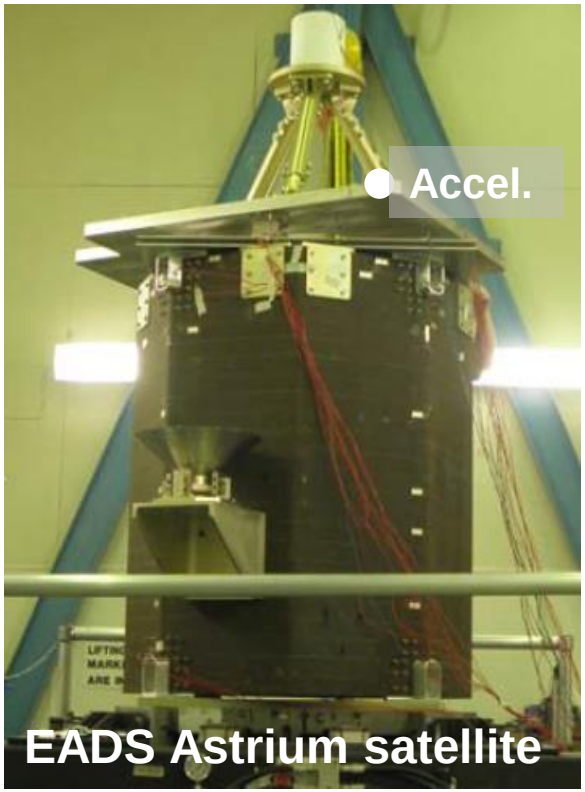
Elastomers and composites

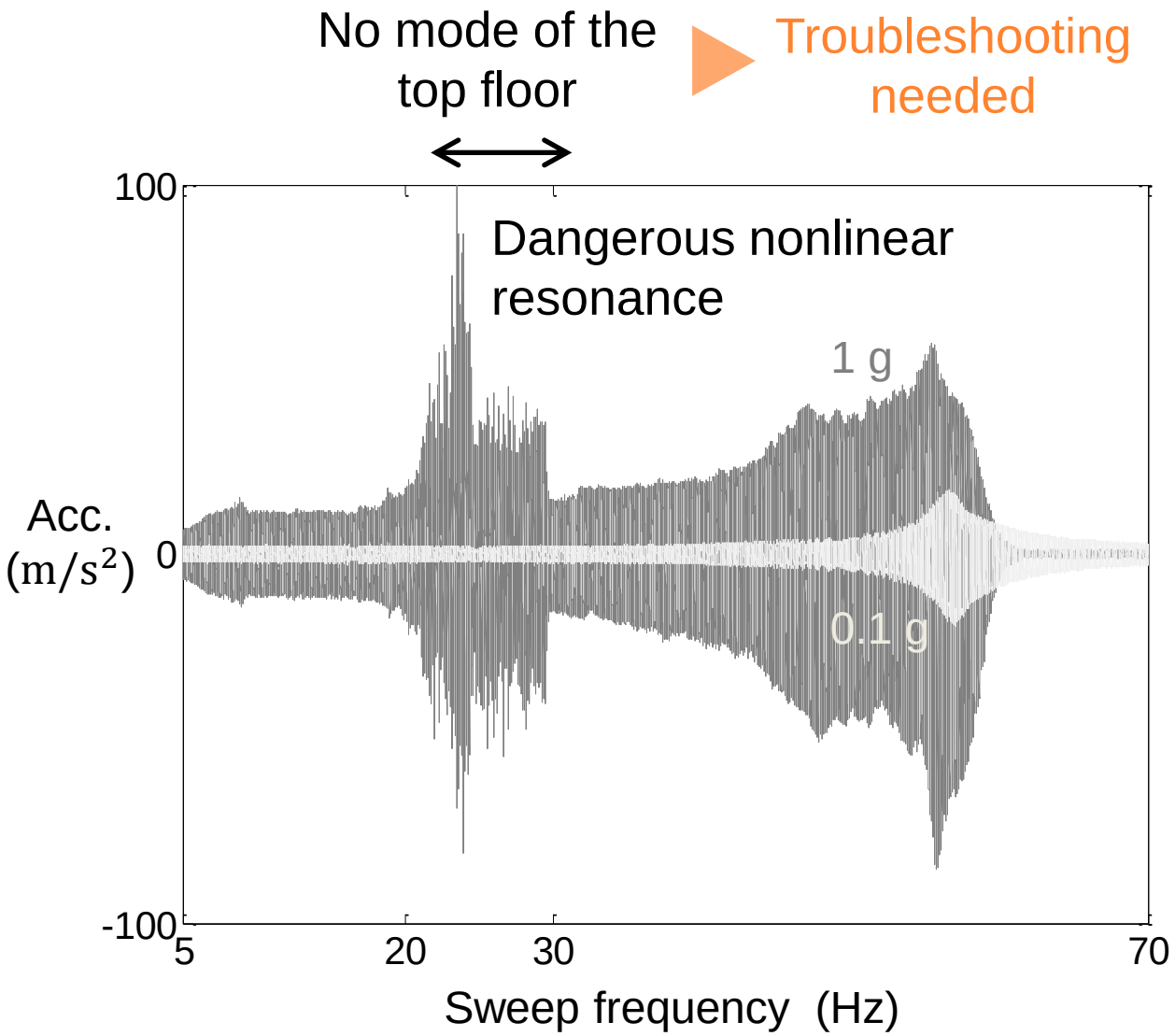


Friction and contact

Large amplitudes

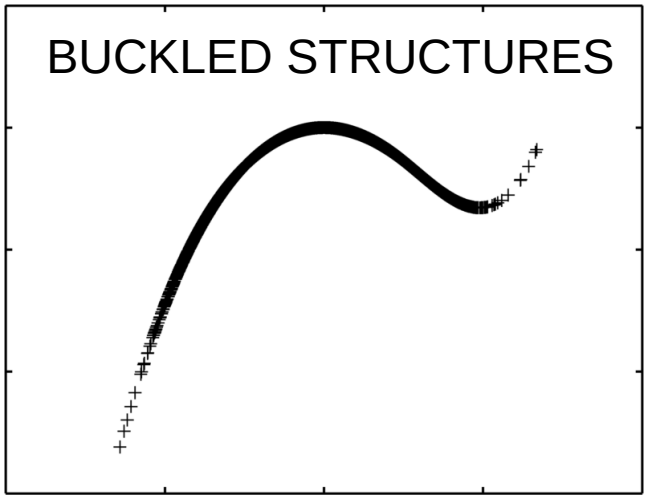
Why Should You Care About Nonlinearity ?

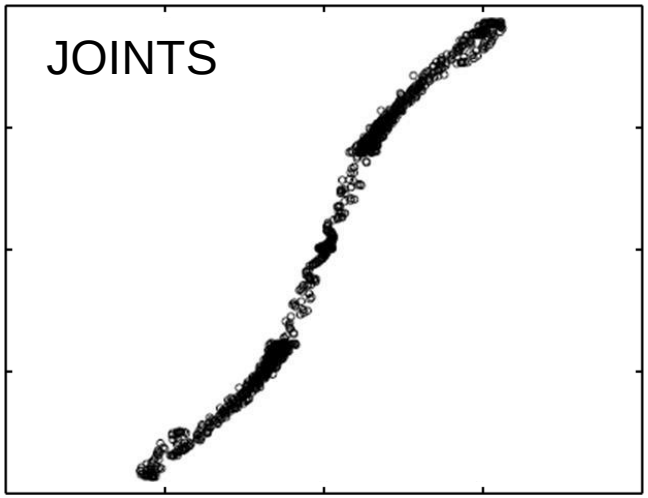


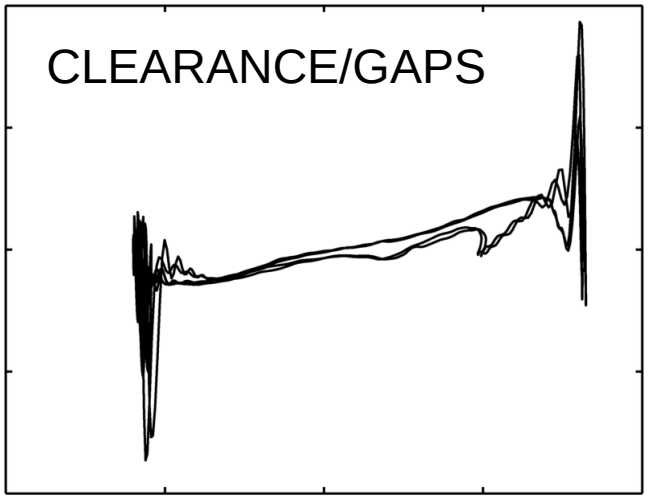


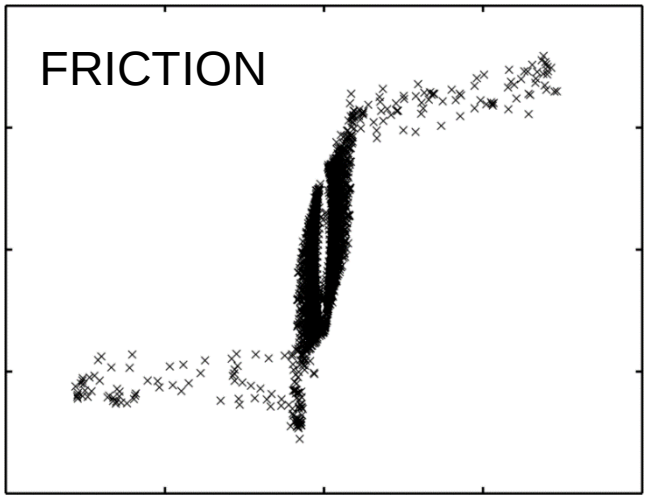
Why Is Nonlinear System Identification Difficult ?

Individualistic nature of structural nonlinearities.





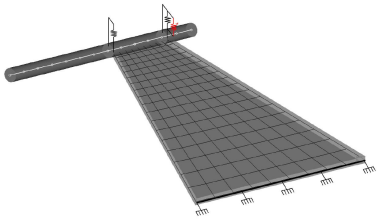




The Big Picture

VIBRATION MEASUREMENTS

LINEAR FINITE ELEMENT MODEL

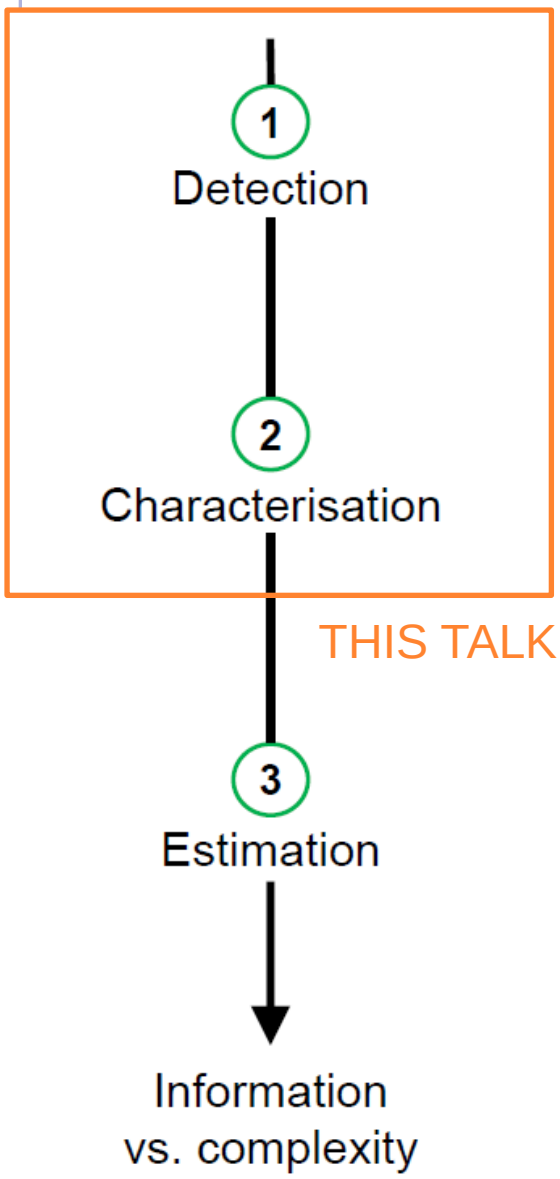


MEASURE → **IDENTIFY** → HYBRID MODELING → UNDERSTAND → DESIGN

Identify nonlinear connections early on

Compute nonlinear features and responses

The Nonlinear System Identification Process



Do I observe nonlinear effects?

Should I build a nonlinear model?

Where is the nonlinearity located ?

What is the underlying physics?

What mathematical model?

Model parameters?

How uncertain are they?

NSI of a Full-Scale Aerospace Structure

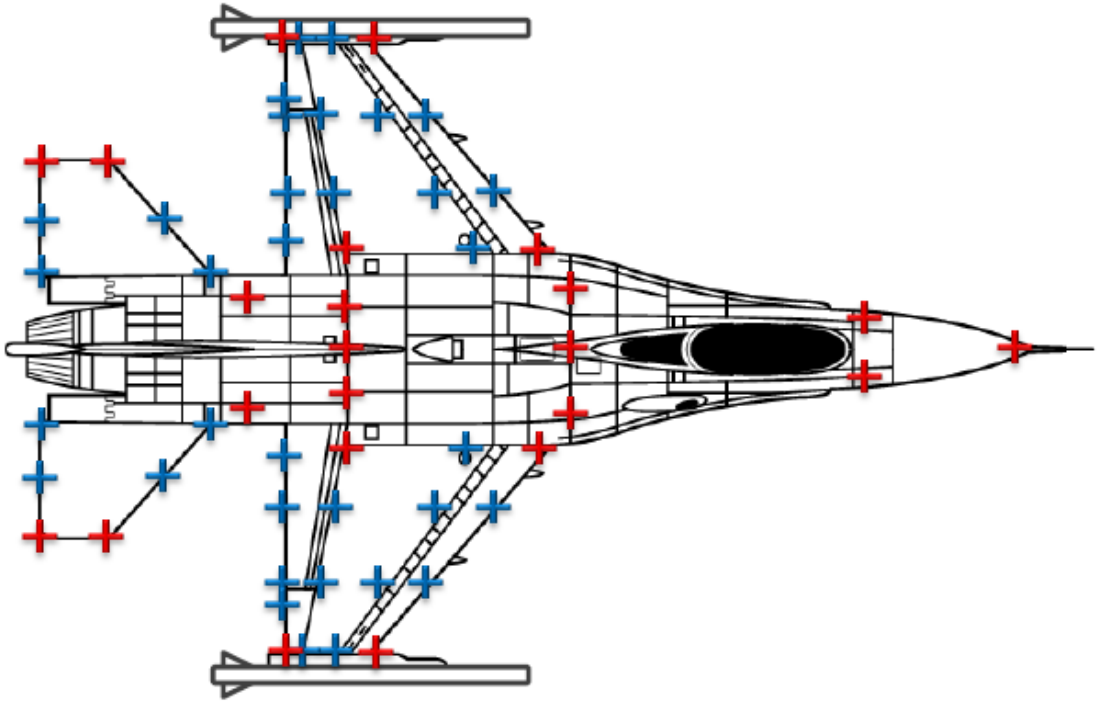
Decommissioned F-16 aircraft, Belgian Airforce Base.
Collaboration with Siemens LMS.

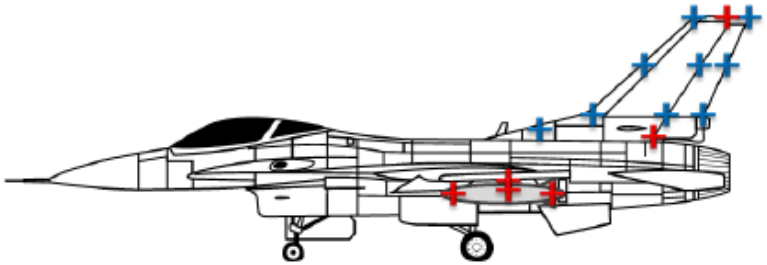
Testing Campaign, September 2014

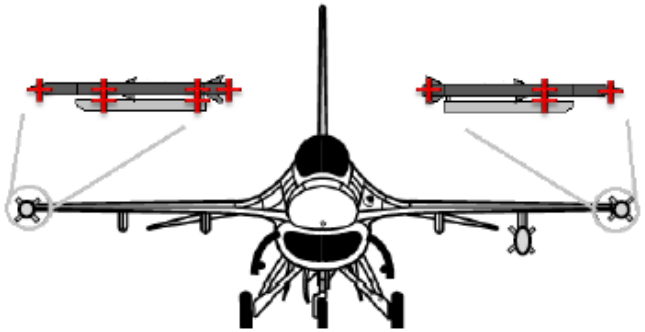
Resting on the landing gears with flat tires; control surfaces held fixed.

Two shakers underneath the wings (sine sweep, random, multisine force signals).

Sensor Set-Up (>160 Accelerometers)







A Specific Testing Campaign

3 different excitation signals: random, sine sweep, multisine

Consider multiple levels of excitations/types of excitations.

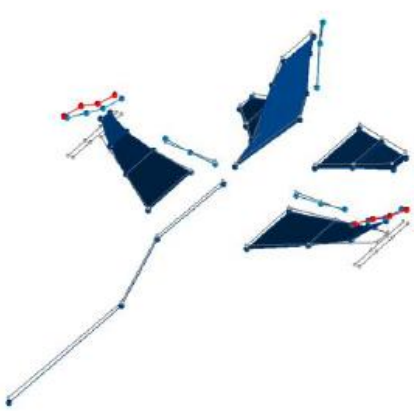
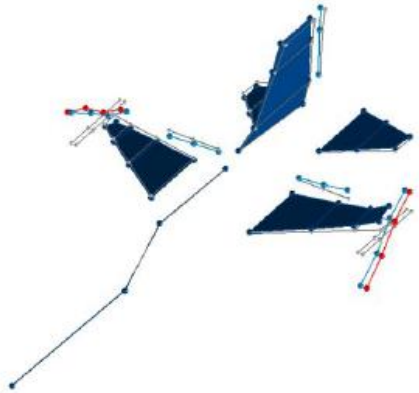
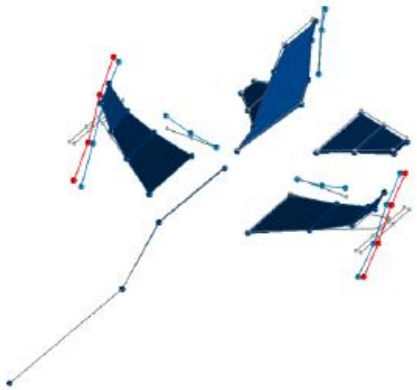
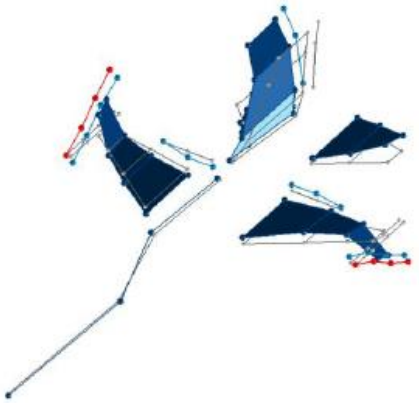
Record throughput time histories.

Measure the force signal.

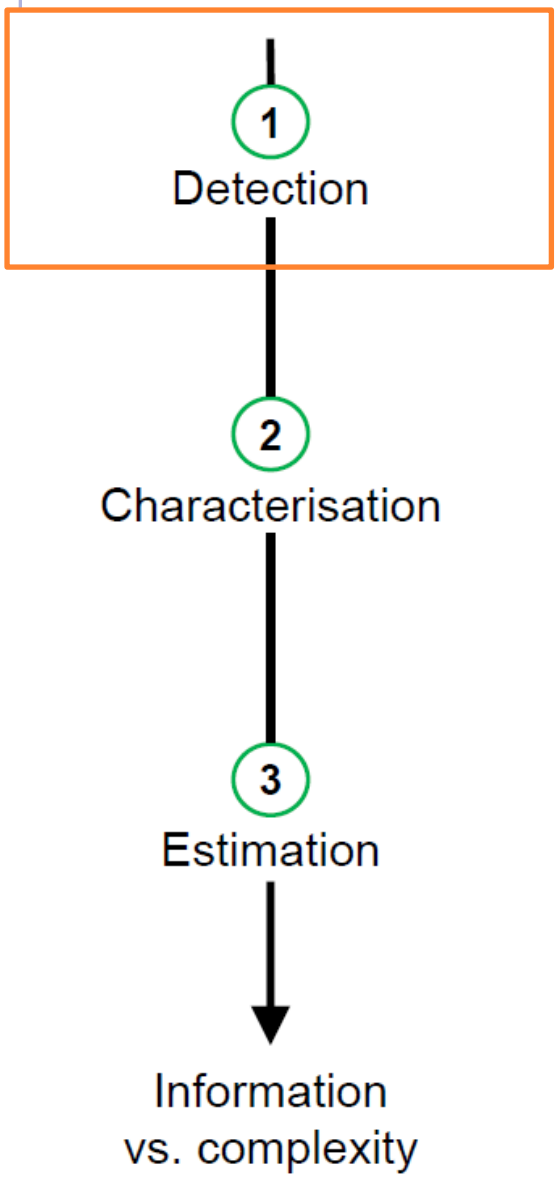
Instrument potential nonlinearities with sensors on both sides.

Linear Modal Analysis at Low Level

Modes	Natural Frequency	Damping Ratio
RBM (roll motion)	3.5 Hz	1.68 %
RBM (vertical motion)	3.9 Hz	2.31 %
Sym Wing bending	5.2 Hz	0.84 %
ASym Missile rotation	6.6 Hz	0.77 %
Sym Wing torsion	7.3 Hz	0.43 %
ASym Wing bending	9.1 Hz	0.74 %

The Nonlinear System Identification Process



Do I observe nonlinear effects?

Should I build a nonlinear model?

Where is the nonlinearity located ?

What is the underlying physics?

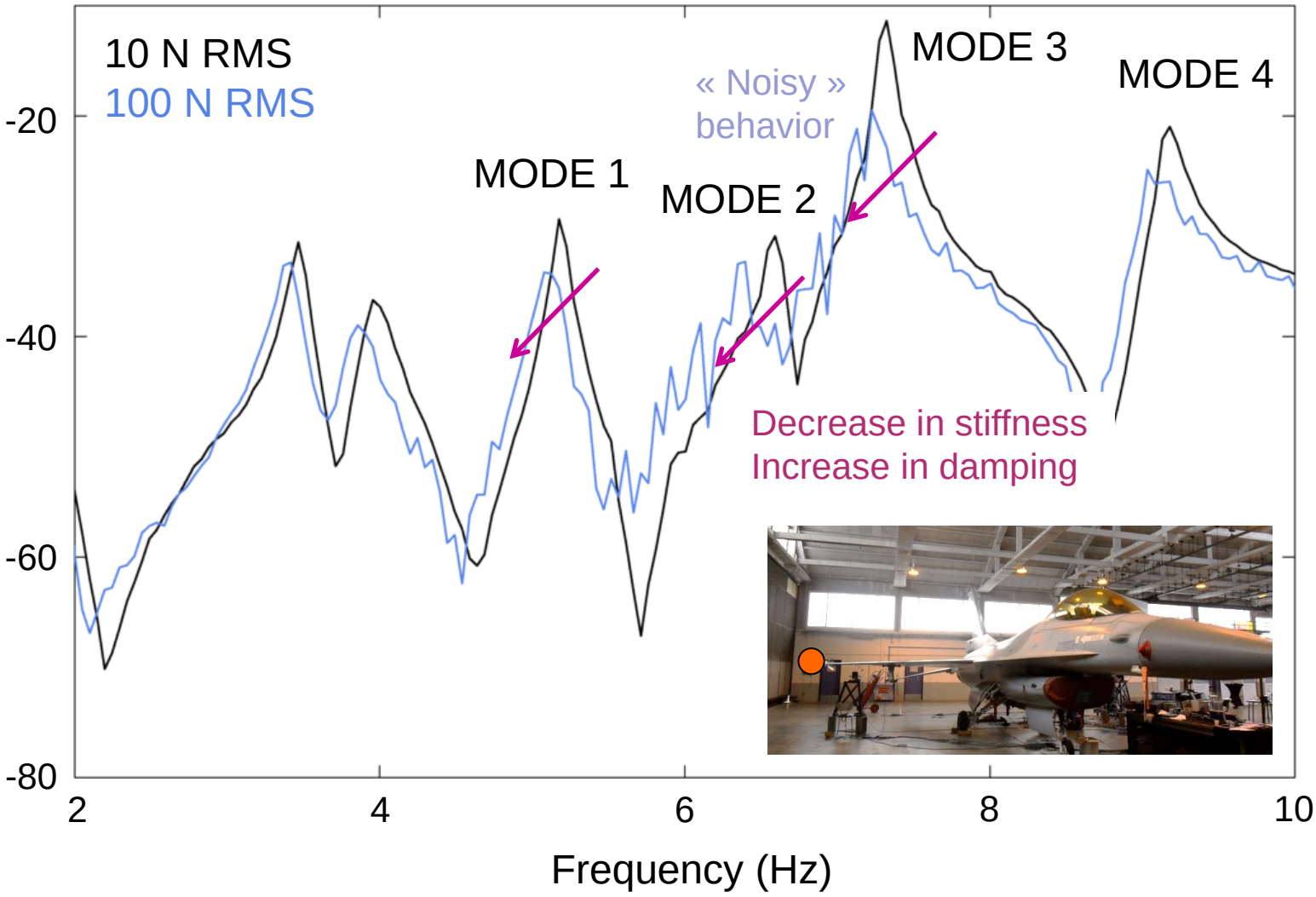
What mathematical model?

Model parameters?

How uncertain are they?

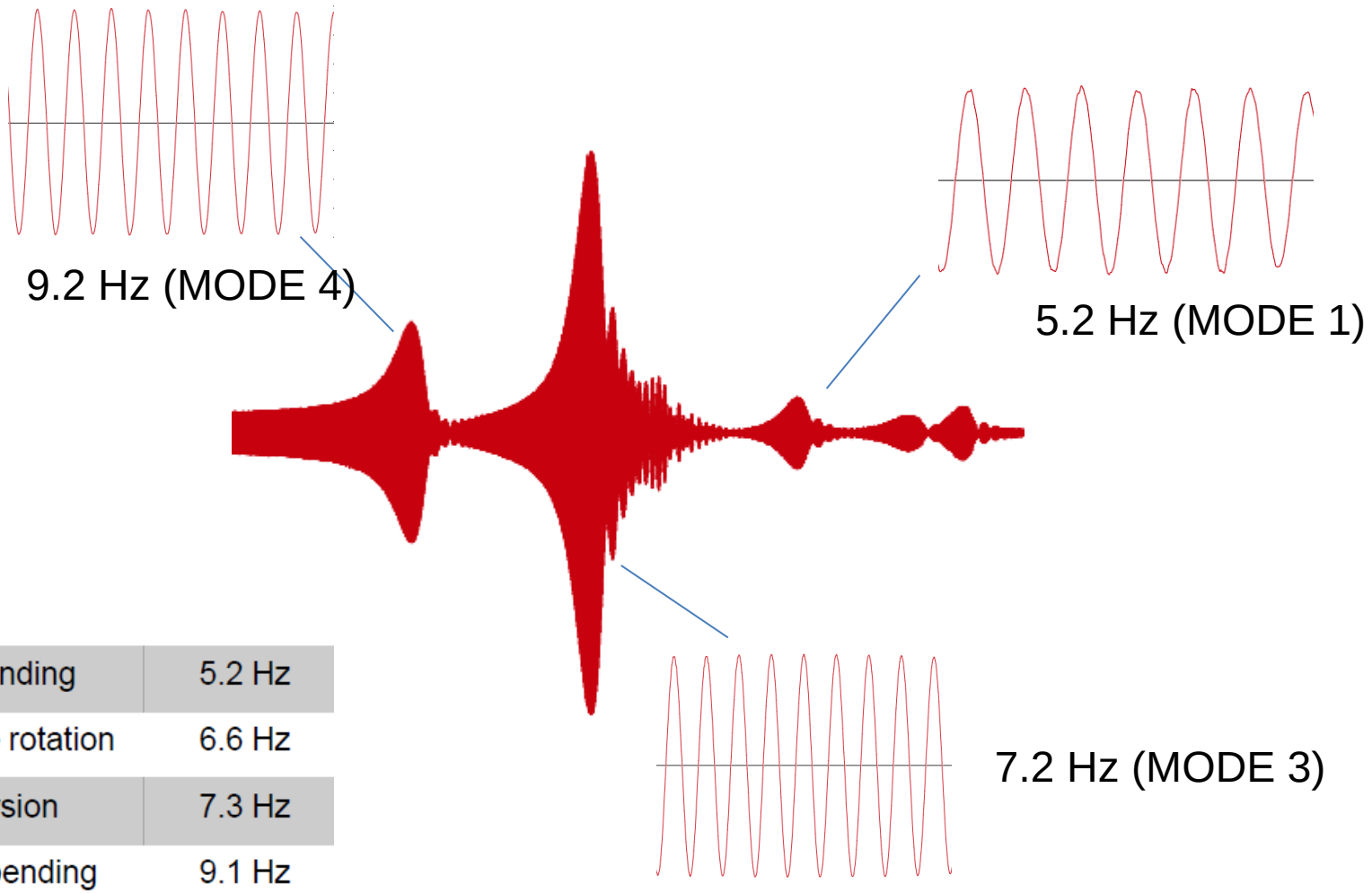
Homogeneity Test (FRFs at Several Levels)

Excitation: random



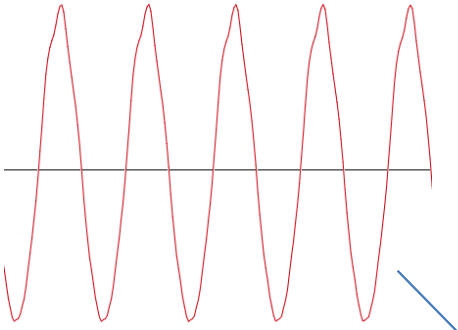
Time Series at Low Level (Right Missile)

Excitation: sine sweep down

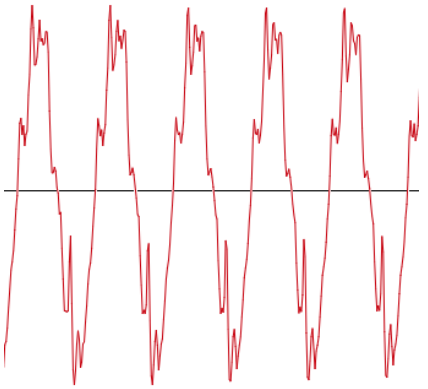


Sym Wing bending	5.2 Hz
ASym Missile rotation	6.6 Hz
Sym Wing torsion	7.3 Hz
ASym Wing bending	9.1 Hz

Time Series at High Level (Right Missile)

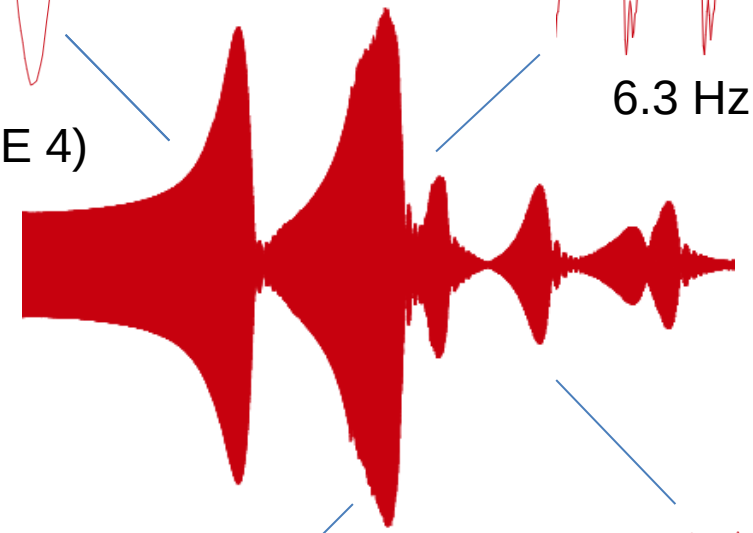


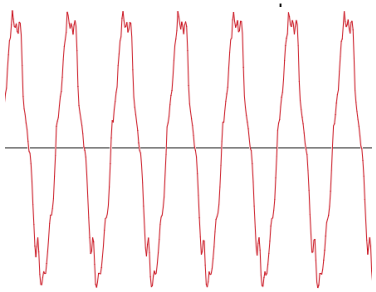
9.1 Hz (MODE 4)



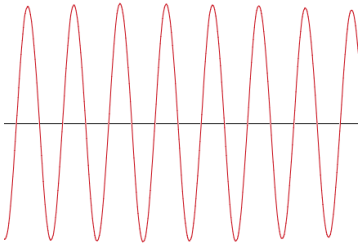
6.3 Hz (MODE 2)

Sym Wing bending	5.2 Hz
ASym Missile rotation	6.6 Hz
Sym Wing torsion	7.3 Hz
ASym Wing bending	9.1 Hz



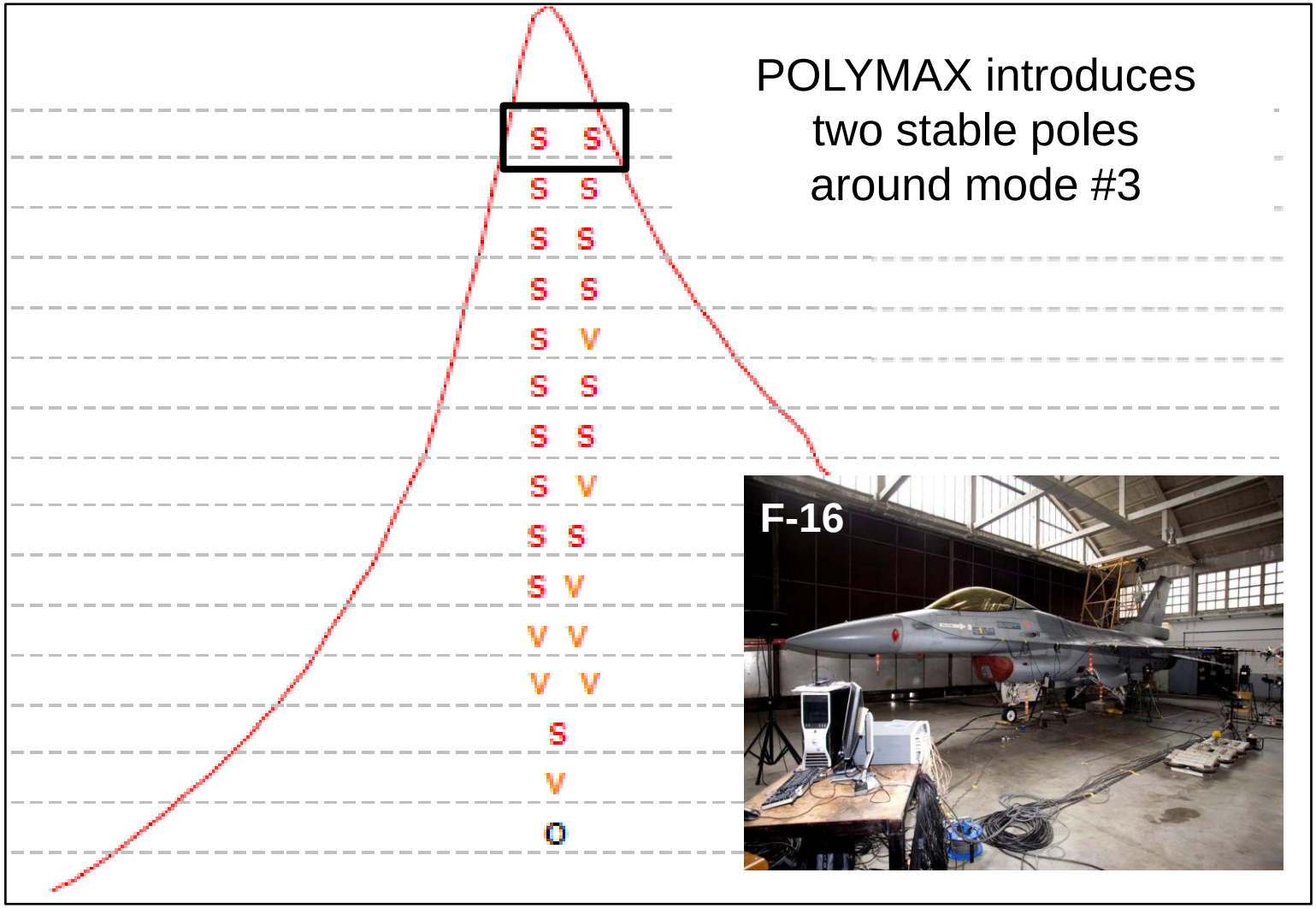


7 Hz (MODE 3)

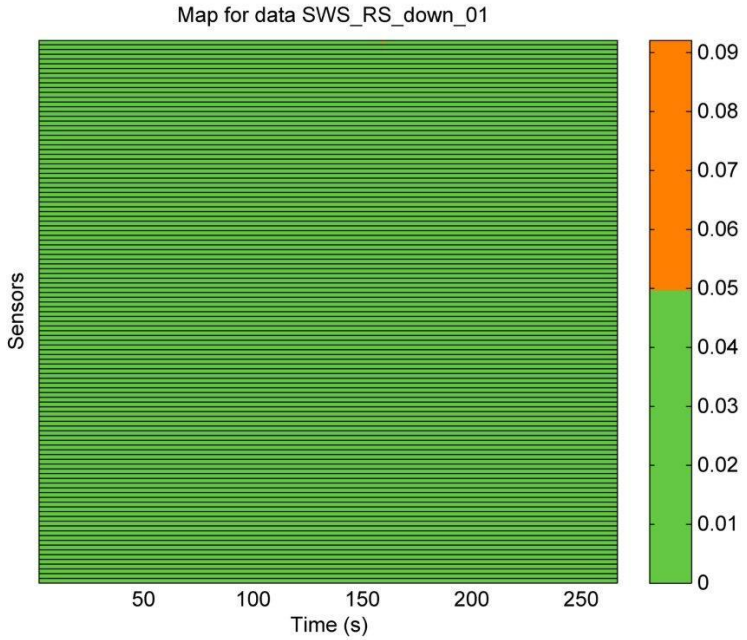


5 Hz (MODE 1)

Failure of Linear Modal Analysis at High Level

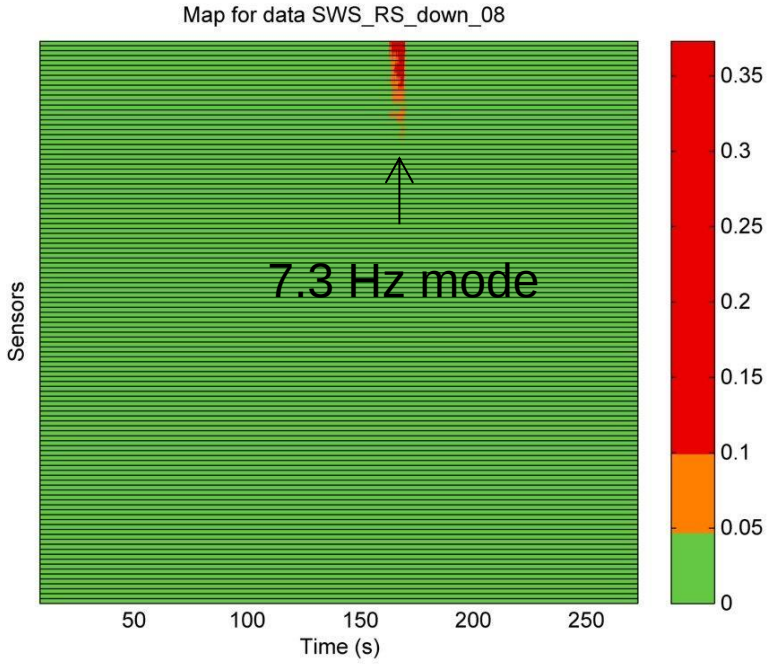


Map for Nonlinearity Detection



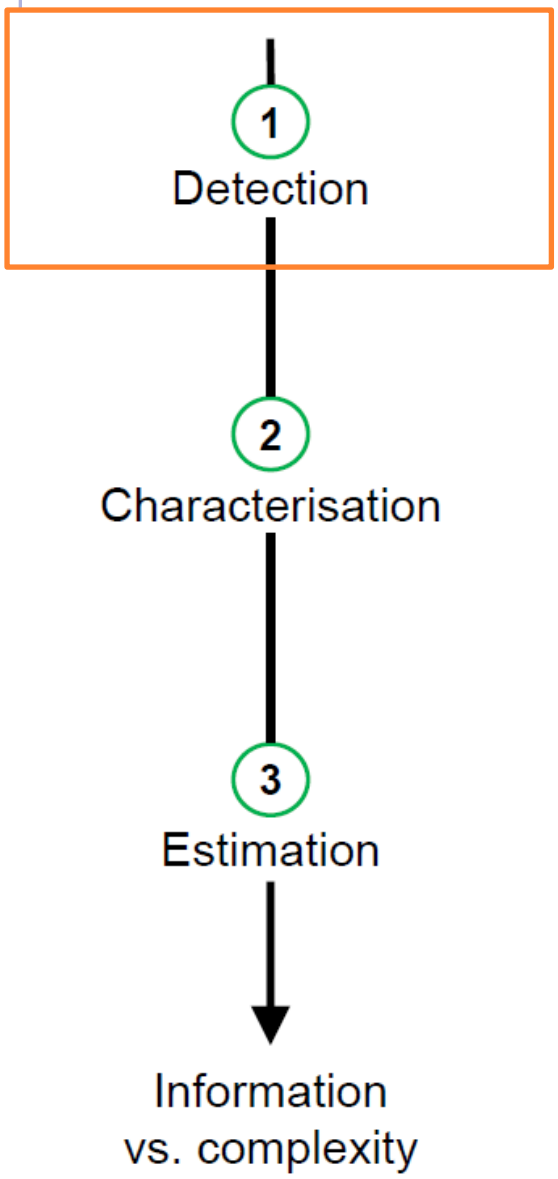
10N

Highlight a departure from planar motion in phase space



100N

The Nonlinear System Identification Process



Do I observe nonlinear effects? **YES**

Should I build a nonlinear model?

Where is the nonlinearity located ?

What is the underlying physics?

What mathematical model?

Model parameters?

How uncertain are they?

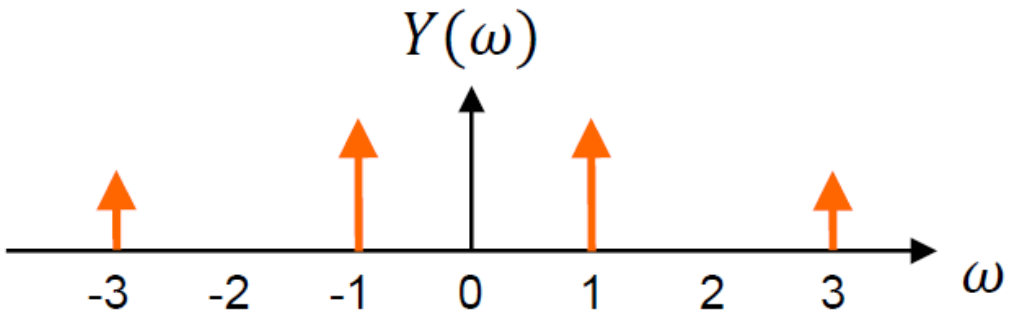
Nonlinearity Distortions

Output of a cubic nonlinearity:

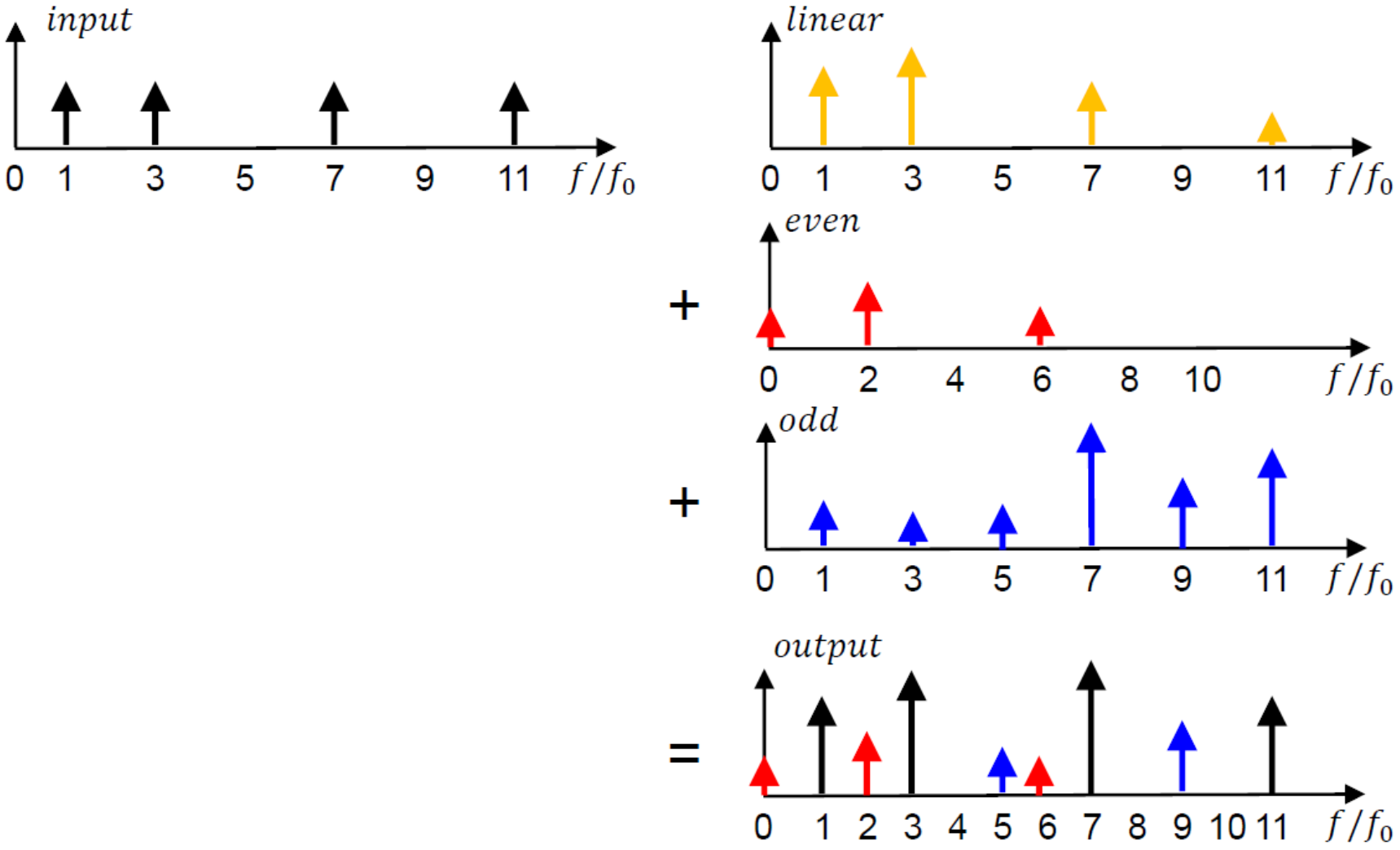
$$y(t) = u^3(t)$$
$$= (e^{j\omega t} - e^{-j\omega t})(e^{j\omega t} - e^{-j\omega t})\ (e^{j\omega t} - e^{-j\omega t})$$

All possible combinations, 3 by 3, of the frequencies -1 and 1.

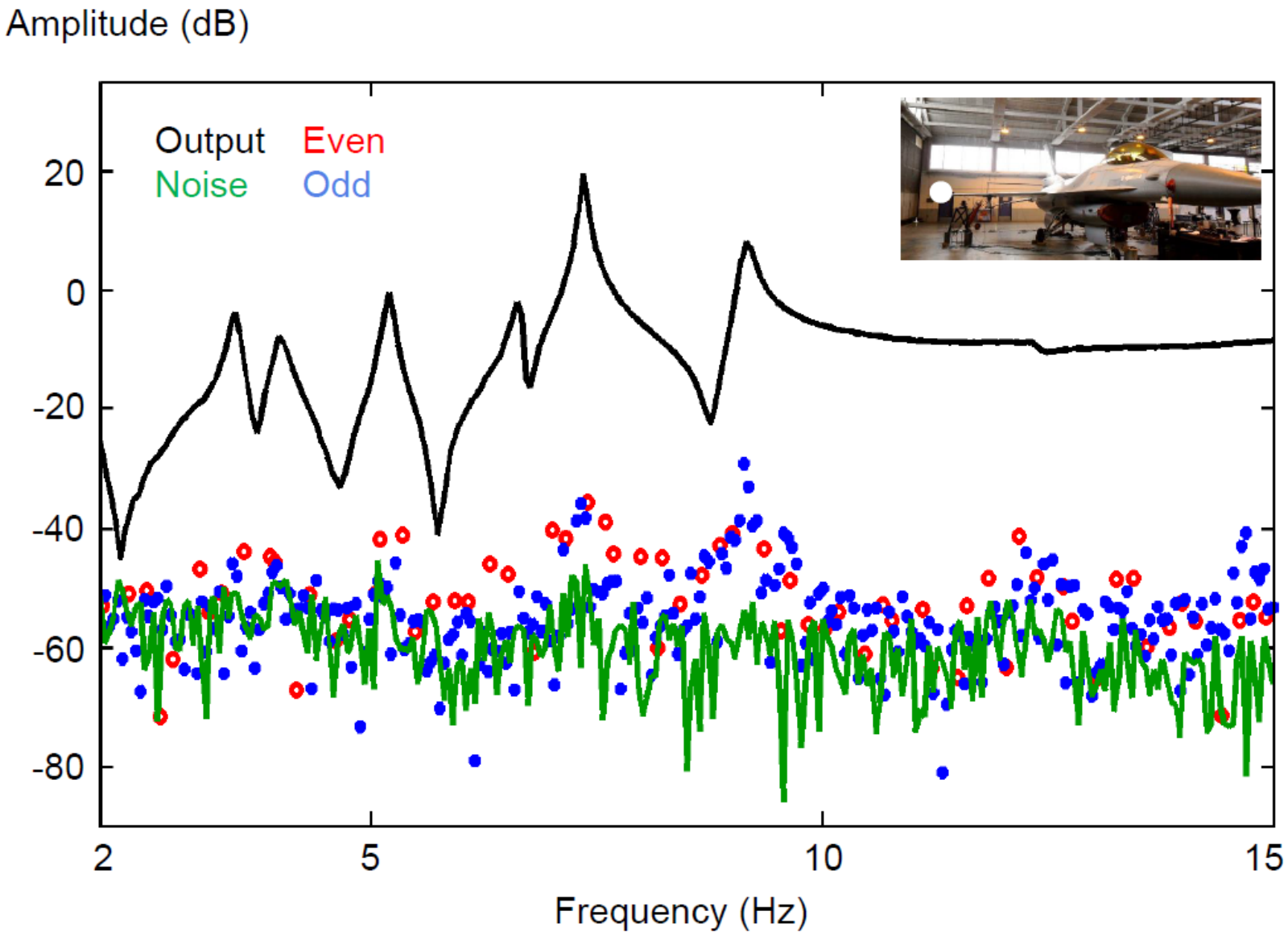
1 1 1	3
1 1 -1	1
1 -1 1	1
1 -1 -1	-1
-1 1 1	1
-1 1 -1	-1
-1 -1 1	-1
-1 -1 -1	-3



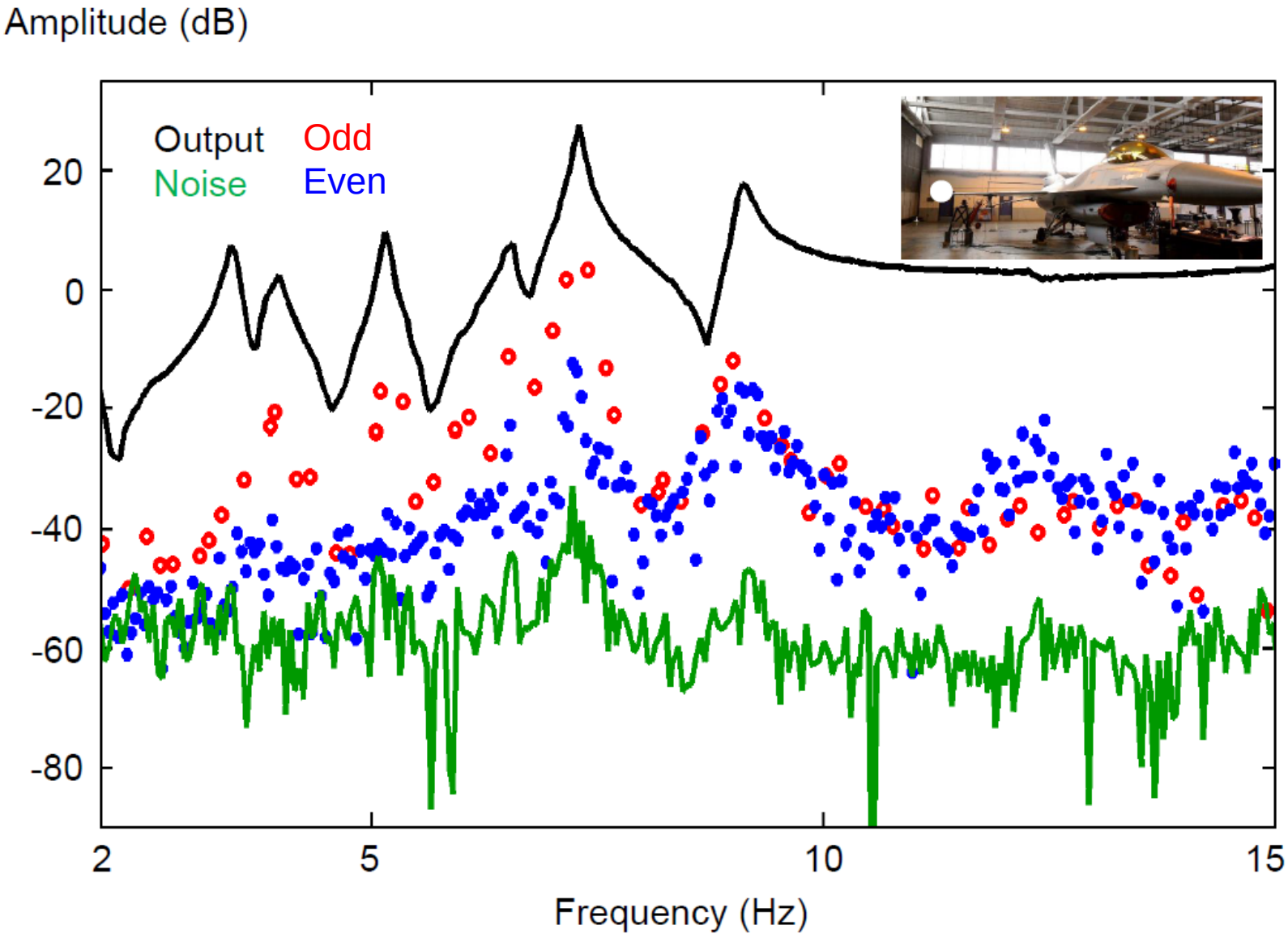
A Carefully Selected Input Spectrum



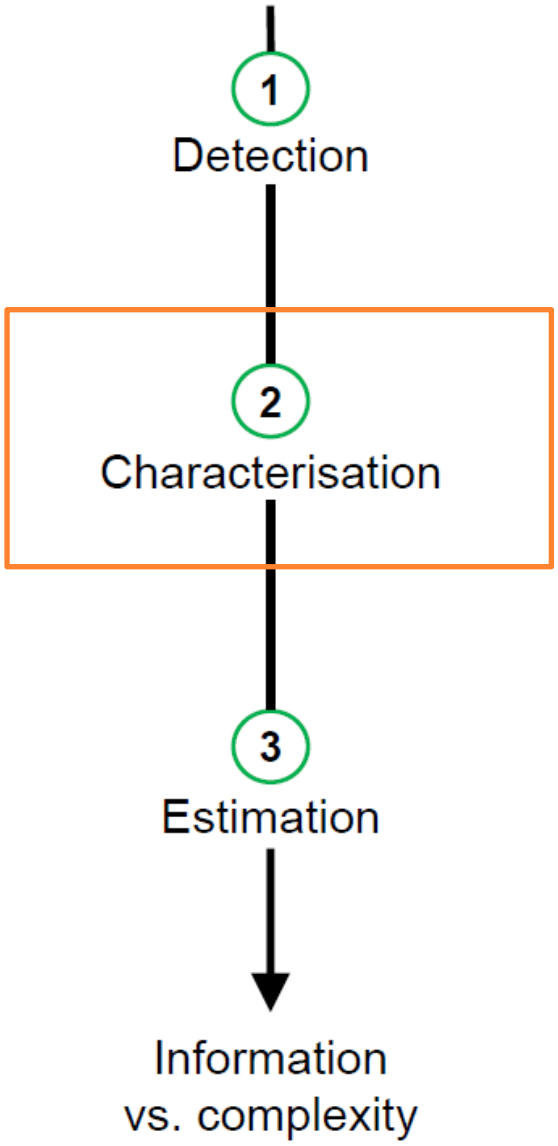
Negligible Distortions at Low Level



Important Distortions at High Level



The Nonlinear System Identification Process



Do I observe nonlinear effects? **YES**

Should I build a nonlinear model? **YES**

Where is the nonlinearity located ?

What is the underlying physics?

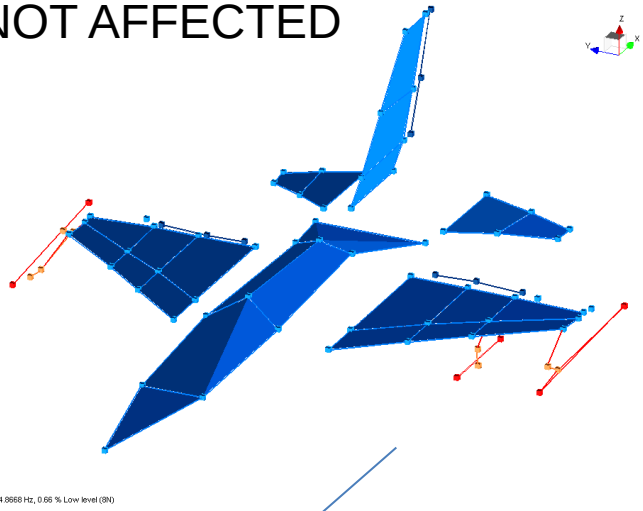
What mathematical model?

Model parameters?

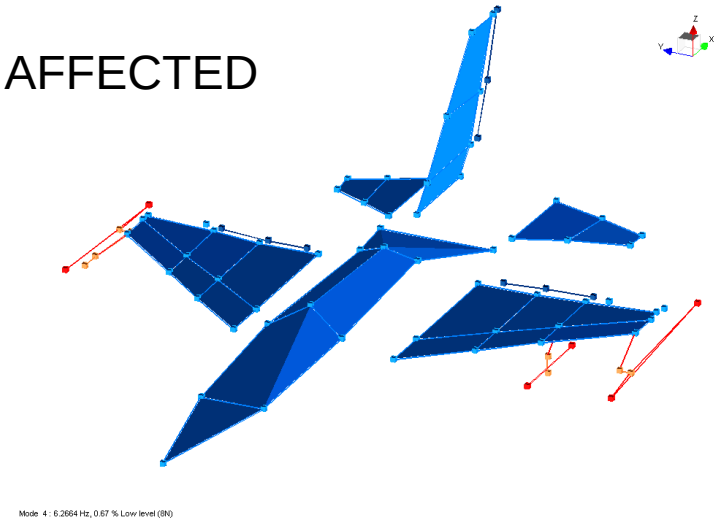
How uncertain are they?

Modal Shapes Give Useful Information

NOT AFFECTED

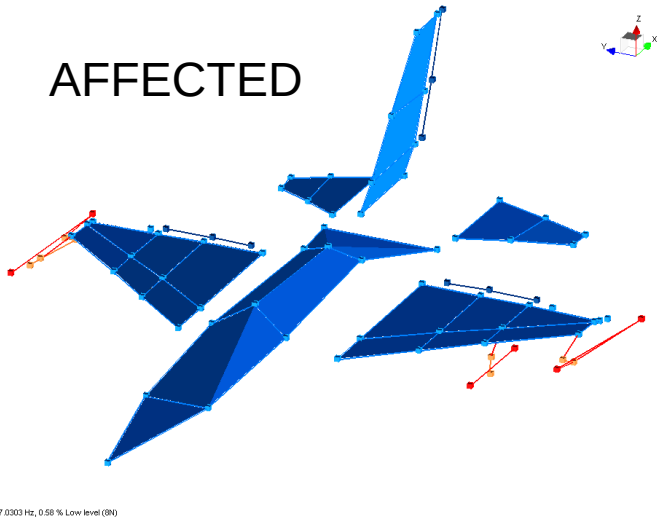


AFFECTED

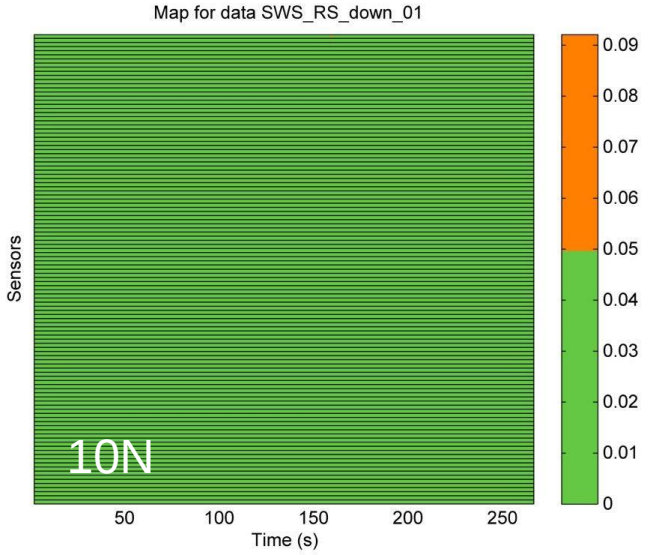


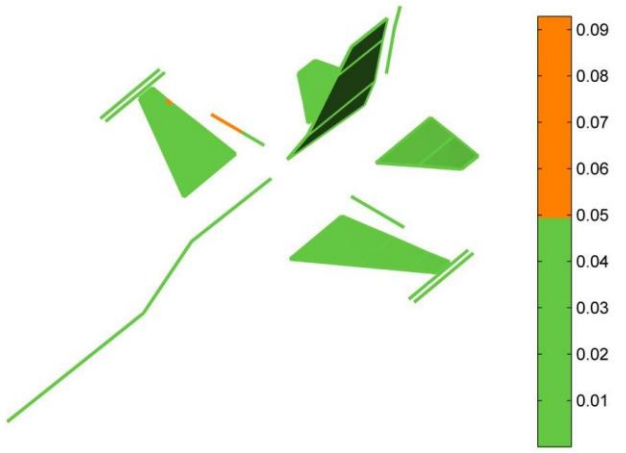
Sym Wing bending	5.2 Hz
ASym Missile rotation	6.6 Hz
Sym Wing torsion	7.3 Hz

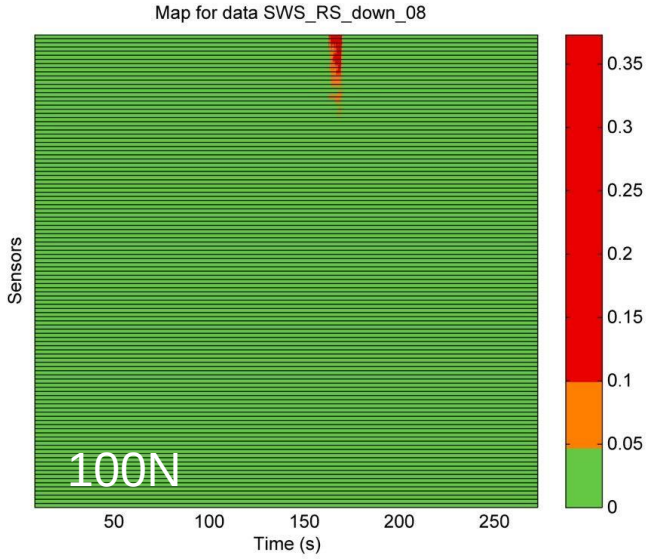
AFFECTED

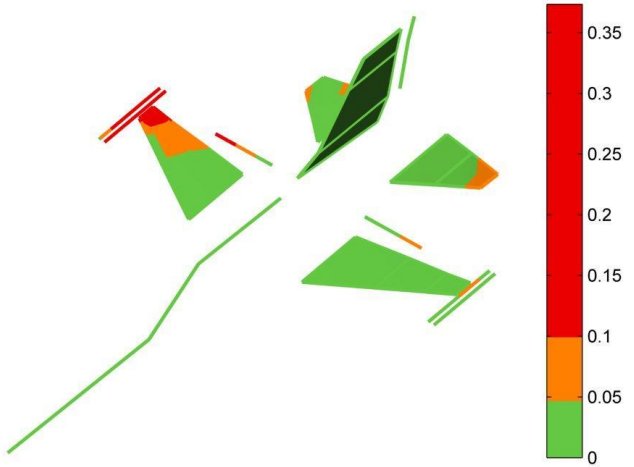


Nonlinearity at Wing Tip Is Clearly Revealed



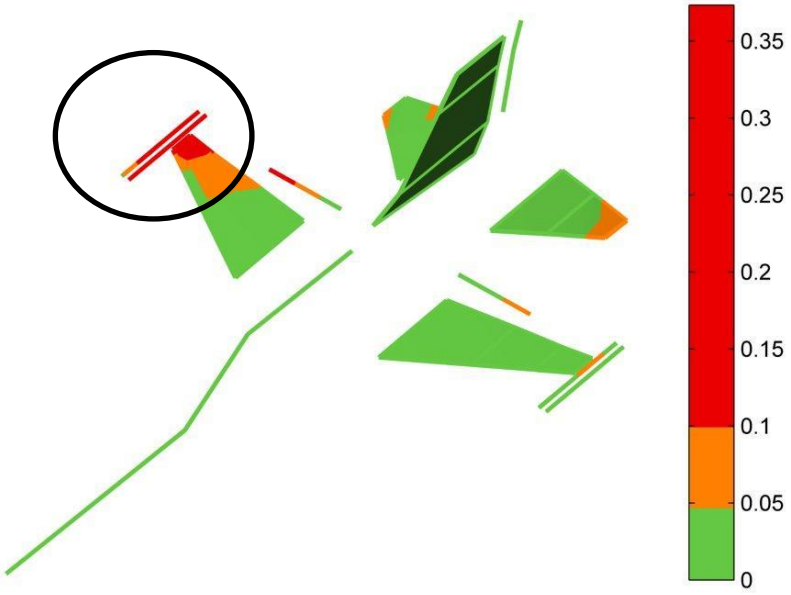




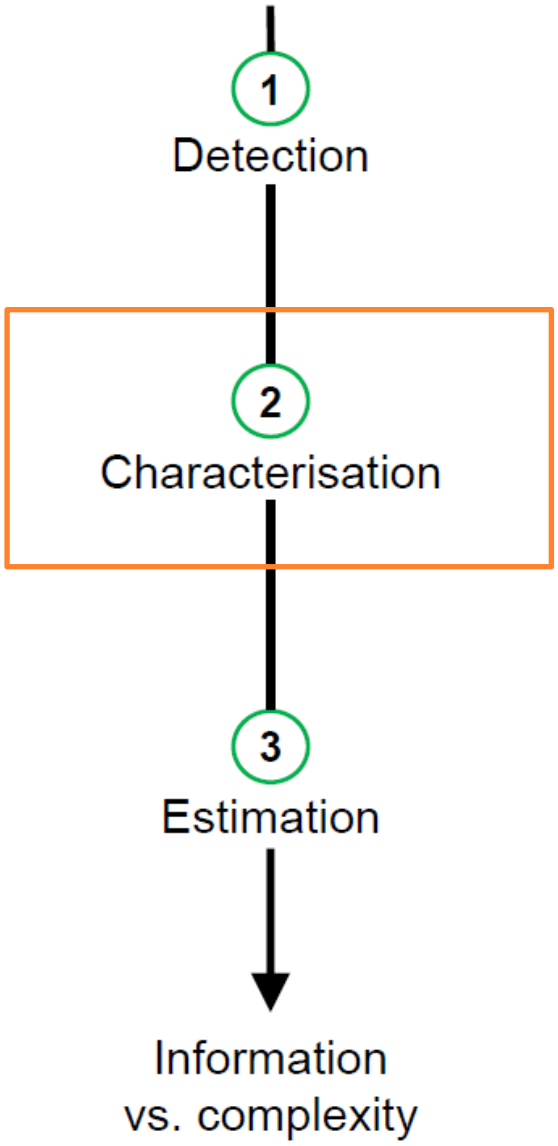


Let’s Have a Closer Look at Right Wing Tip

How would you model this connection ?



The Nonlinear System Identification Process



Do I observe nonlinear effects? **YES**

Should I build a nonlinear model? **YES**

Where is the nonlinearity located ? **WING TIP**

What is the underlying physics?

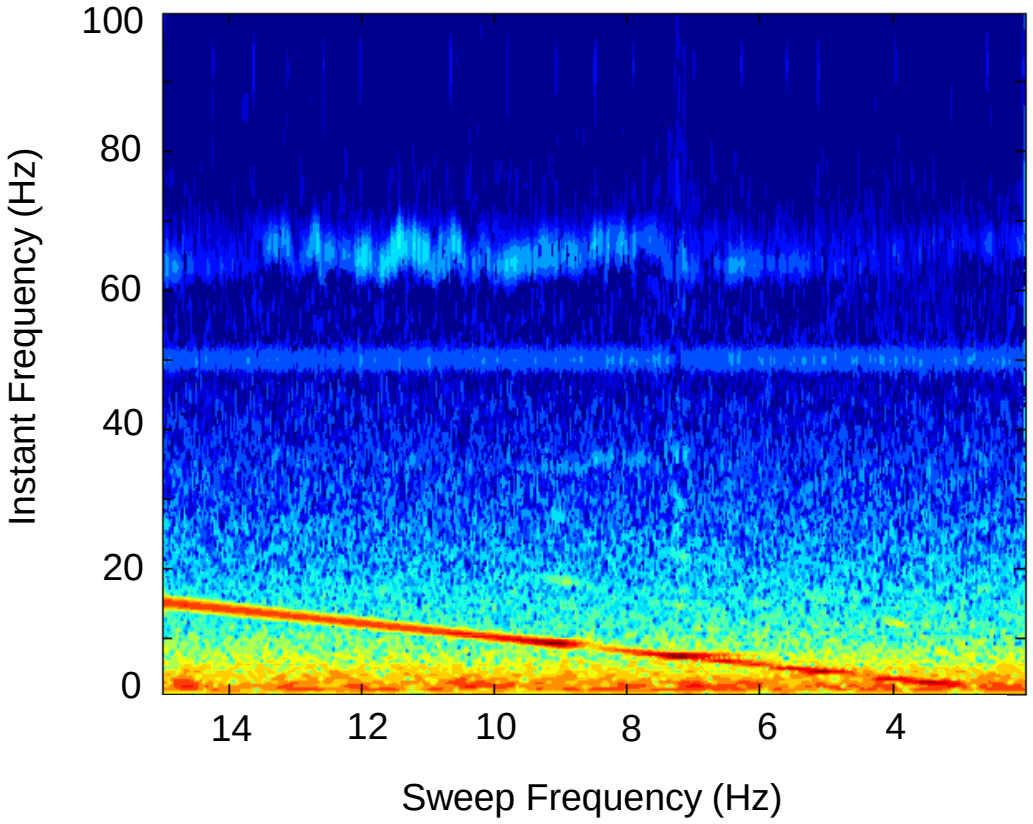
What mathematical model?

Model parameters?

How uncertain are they?

F-16: Sine Sweep Down (5N)

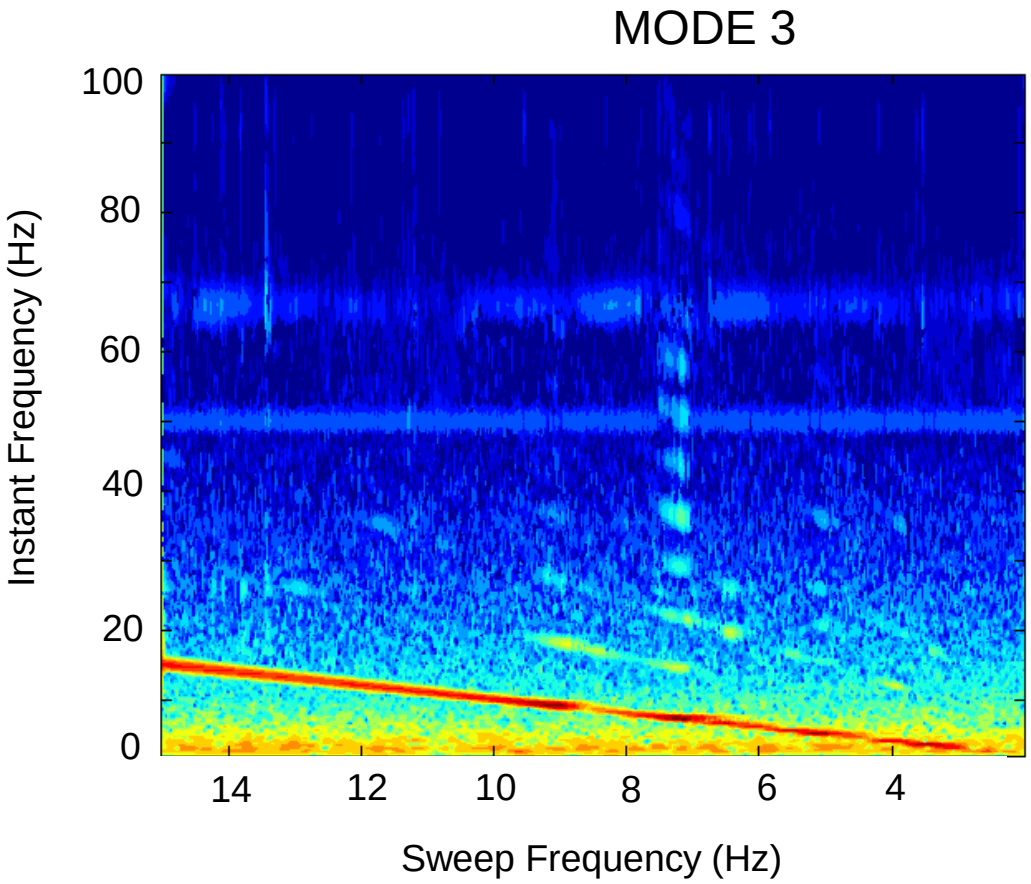
The excitation line is visible (sine sweep down)



Europe !

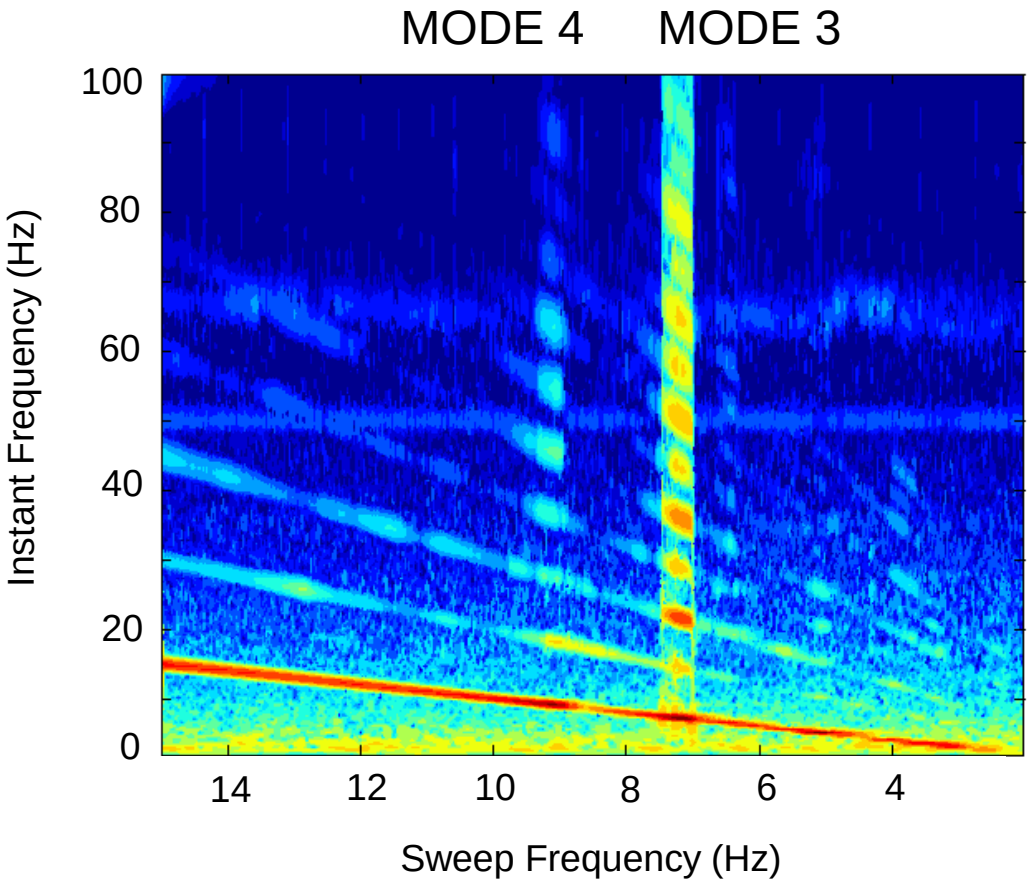
F-16: Sine Sweep Down (14N)

Harmonics and nonsmooth phenomena for mode 3



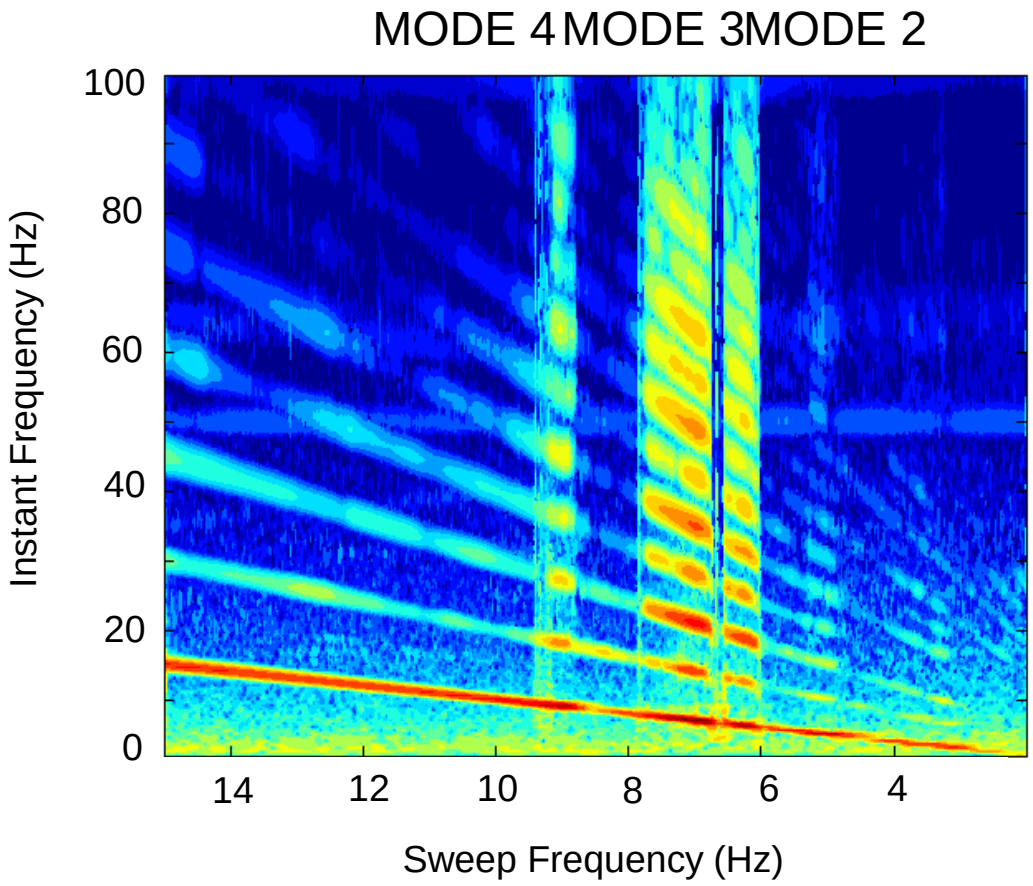
F-16: Sine Sweep Down (48N)

Some harmonics stronger than others (modal interactions ?)

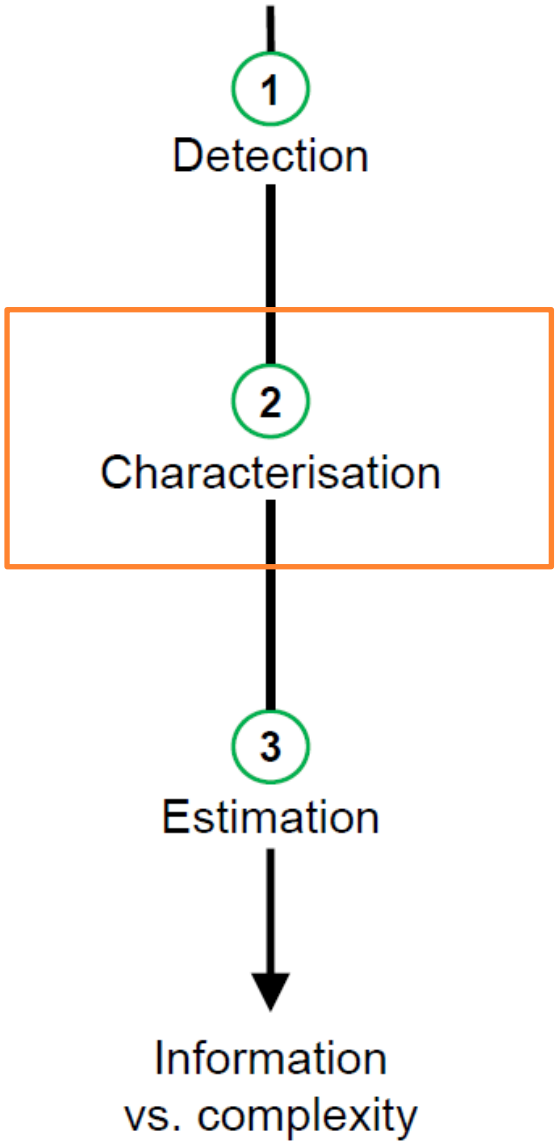


F-16: Sine Sweep Down (96N)

Several modes affected by nonlinearity



The Nonlinear System Identification Process



Do I observe nonlinear effects? **YES**

Should I build a nonlinear model? **YES**

Where is the nonlinearity located ? **WING TIP**

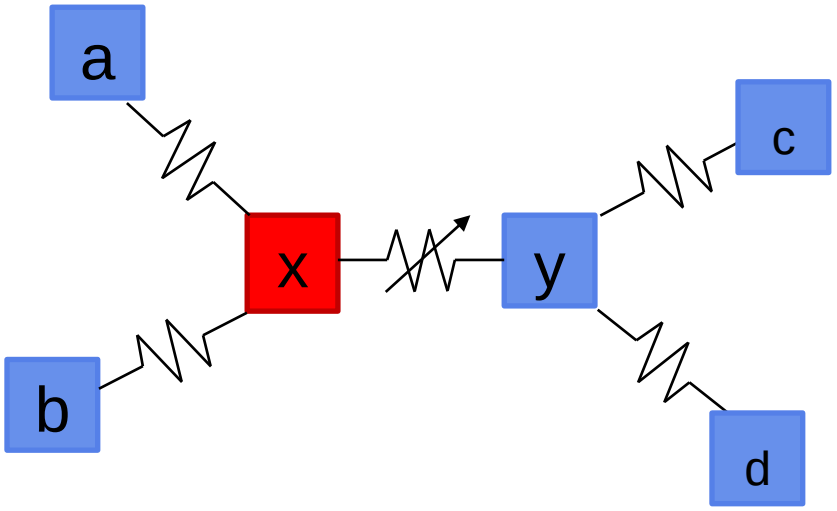
What is the underlying physics? **IMPACTS**

What mathematical model?

Model parameters?

How uncertain are they?

Can We *Visualize* the Nonlinearity ?



$$m\ddot{x} + k_1(x-a) + k_2(x-b) + f_{nl}(x-y, \dot{x}-\dot{y}) = 0$$

$$f_{nl}(x-y, \dot{x}-\dot{y}) \propto -m\ddot{x}$$

$$f_{nl}(x-y, \dot{x}-\dot{y}) \propto -\ddot{x}$$

Build a surface in a 3D plot

The Four Steps of the Acceleration Surface Method

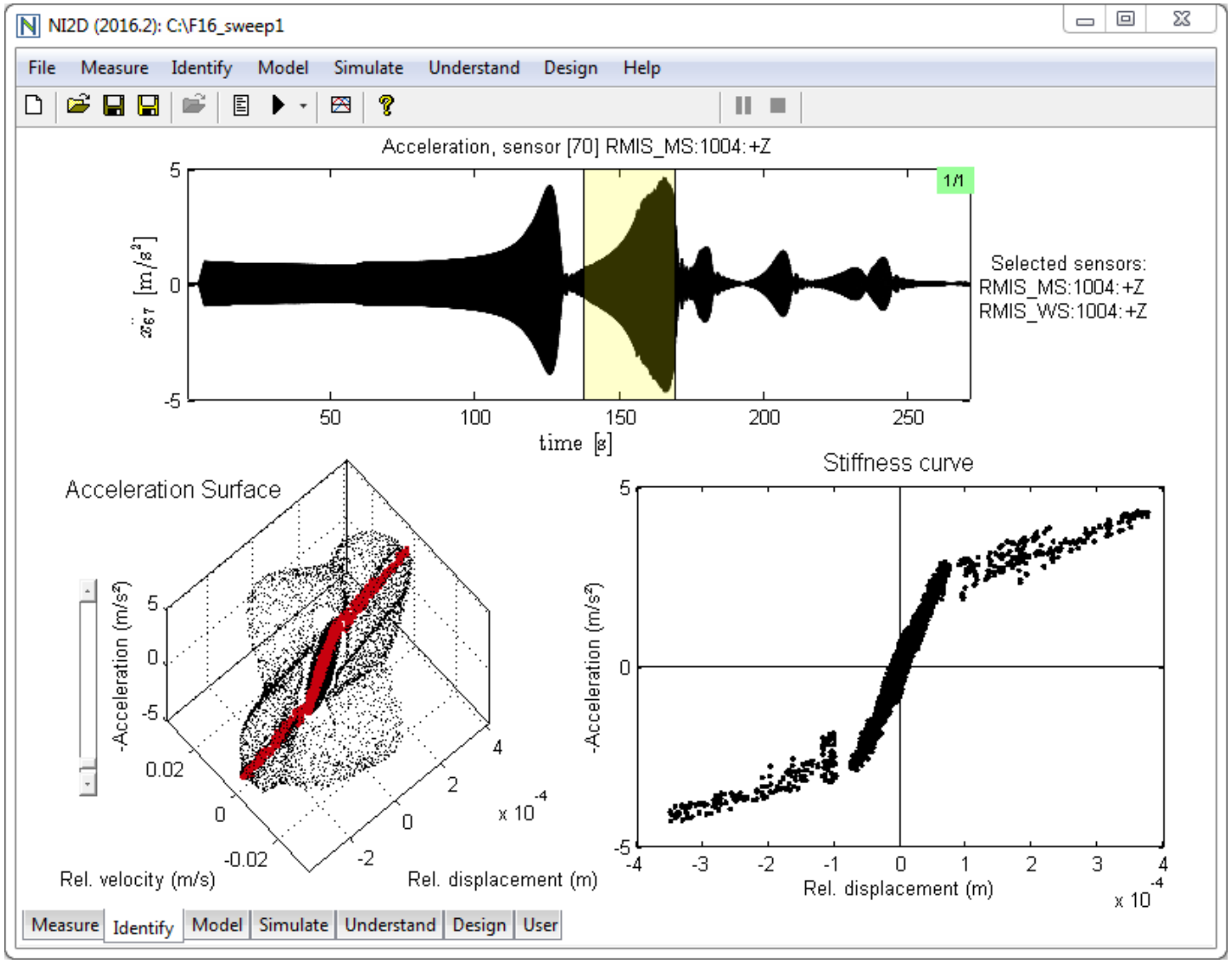
1. Instrument the nonlinear connection with 2 accelerometers.

2. Integrate and filter to get displacements and velocities (Worden, MSSP, 1990).

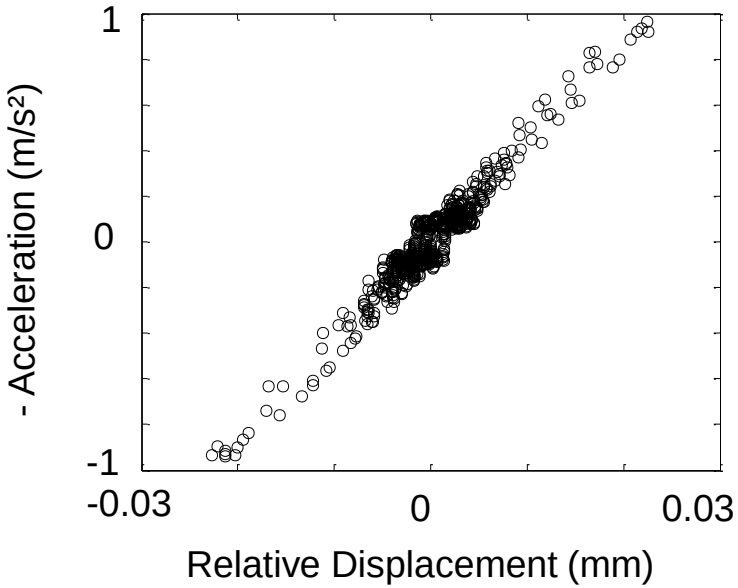
3. Calculate the 3D acceleration surface over a single mode.

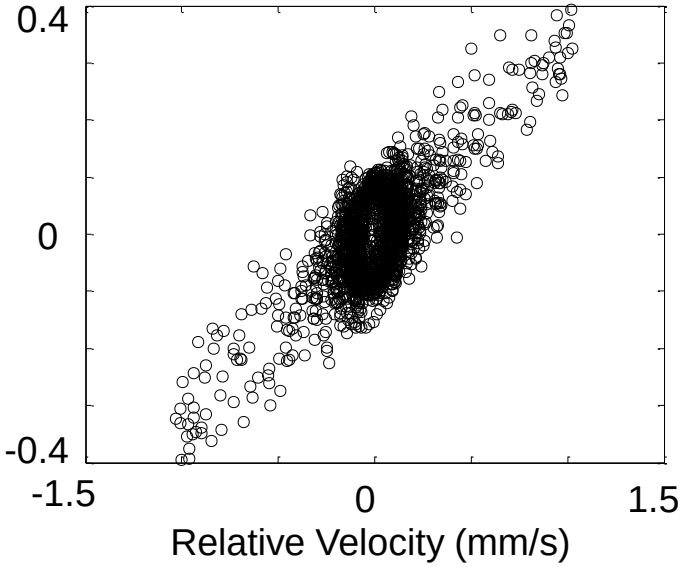
4. Consider surface slices to obtain stiffness/damping curves.

The Acceleration Surface Method

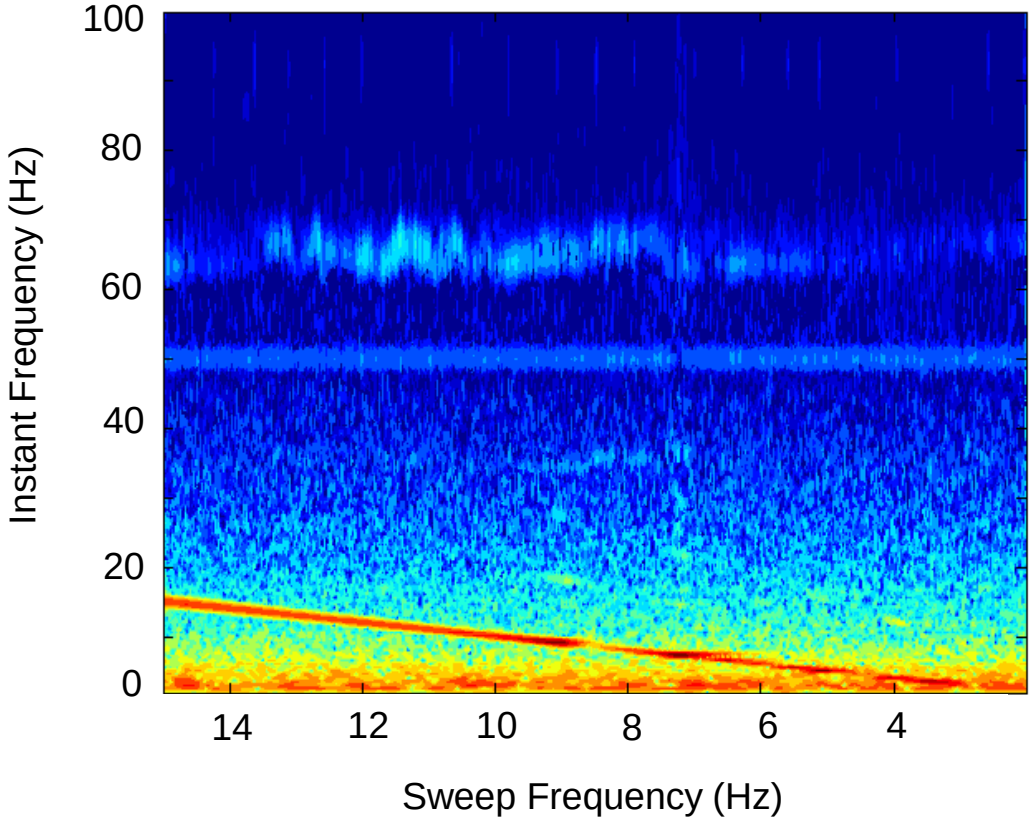


Linear Behavior at Low Level

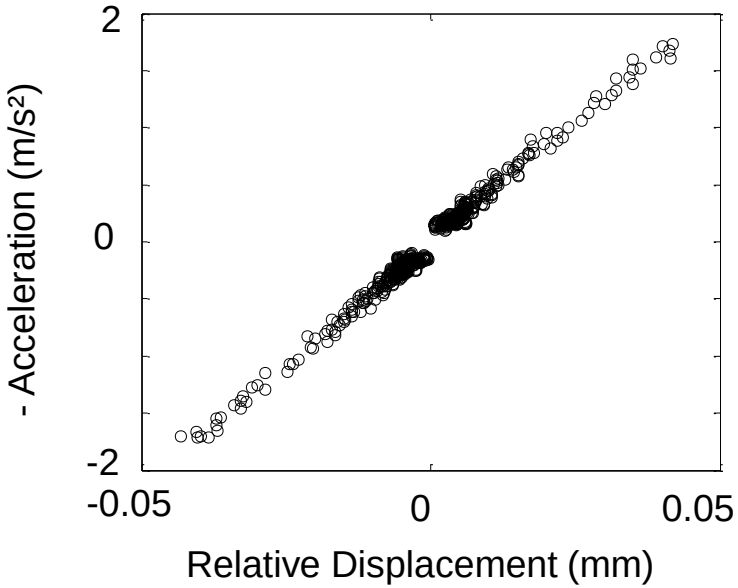


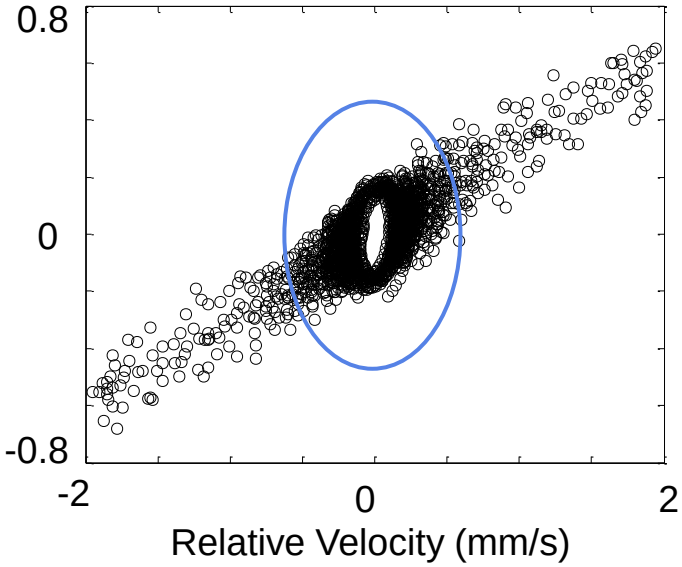


Sine sweep down of 4.8N

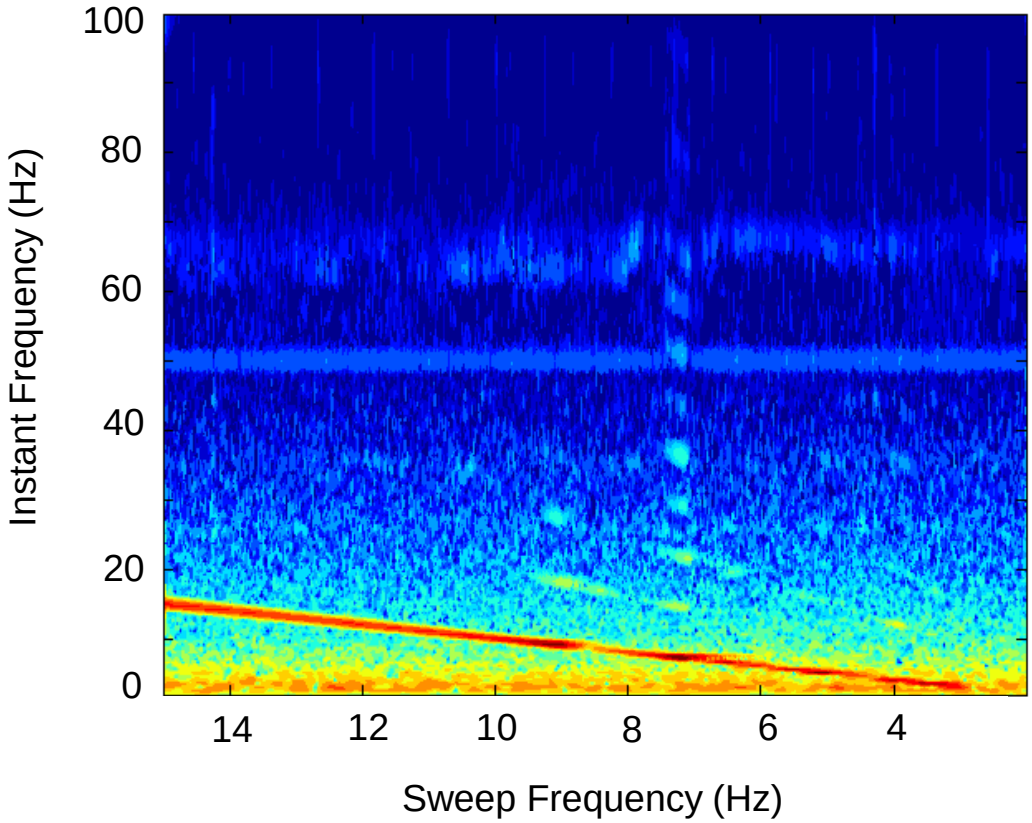


Hysteresis Visible in the Damping Curve

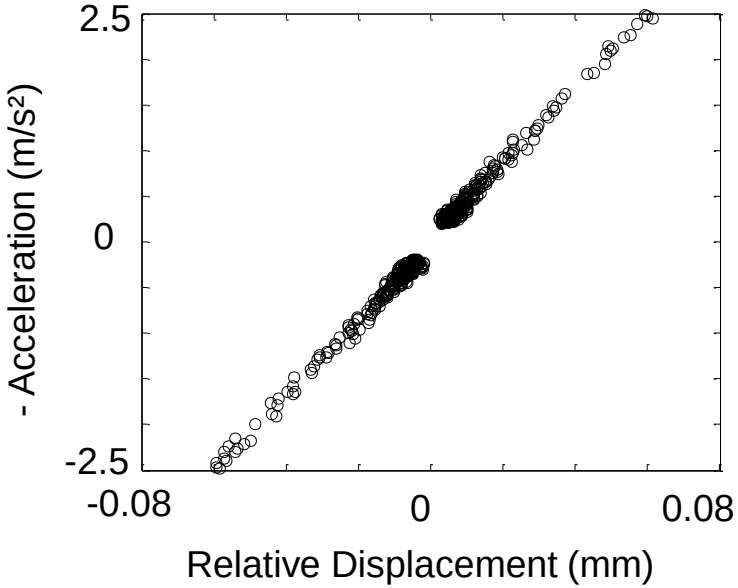


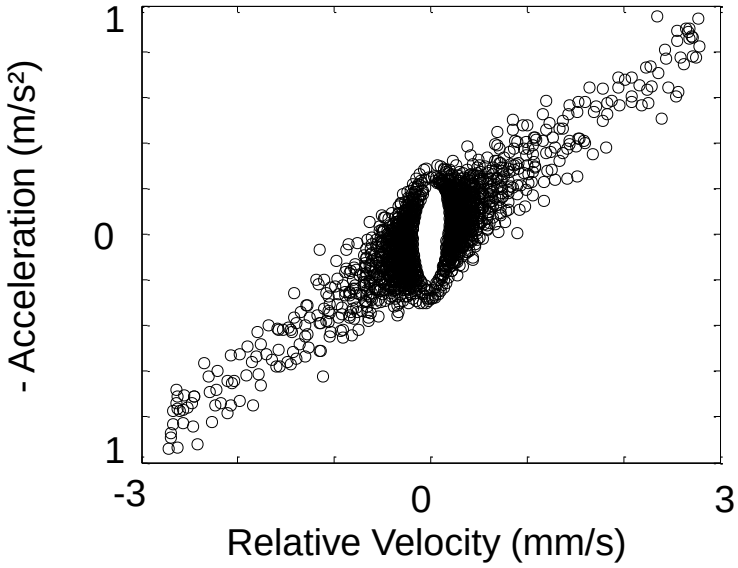


Sine sweep down of 9.6N

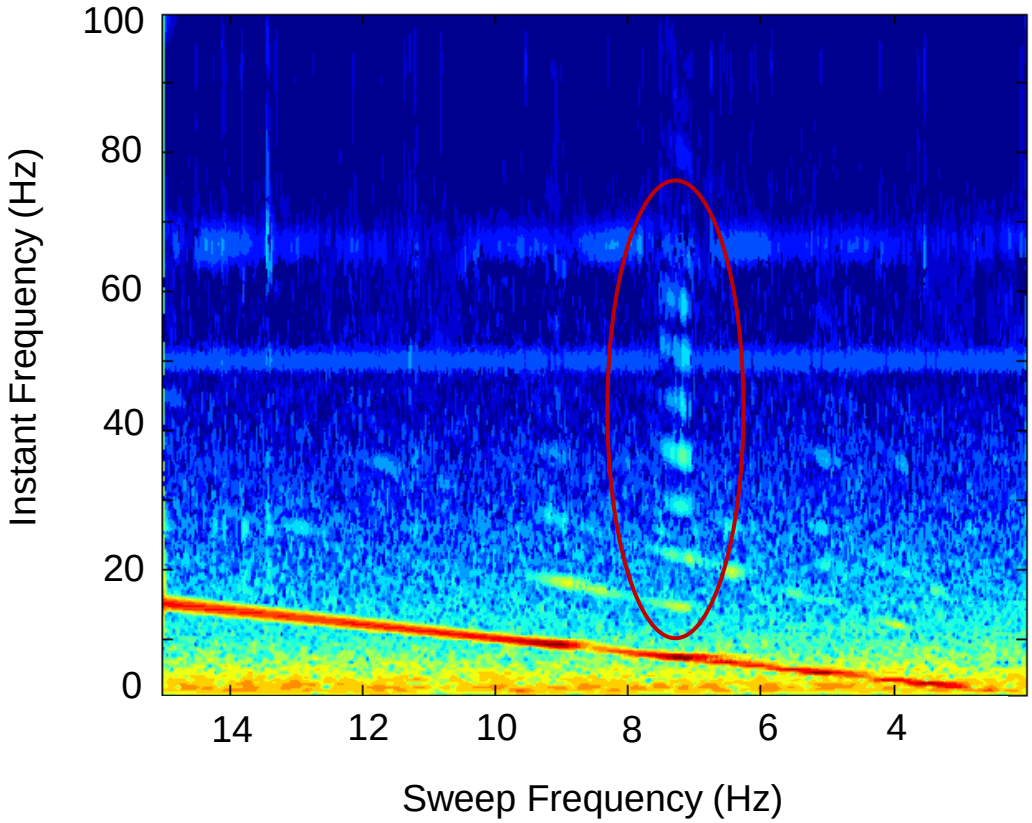


Harmonics Appear Around the Third Mode

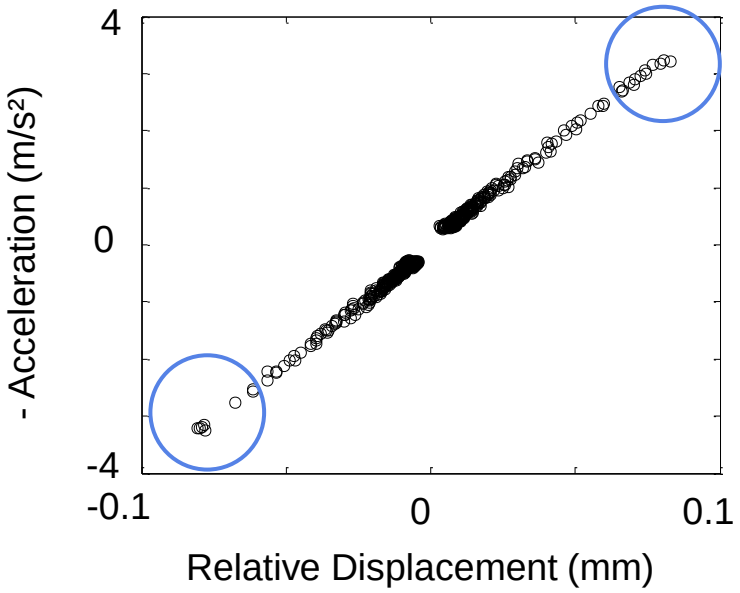


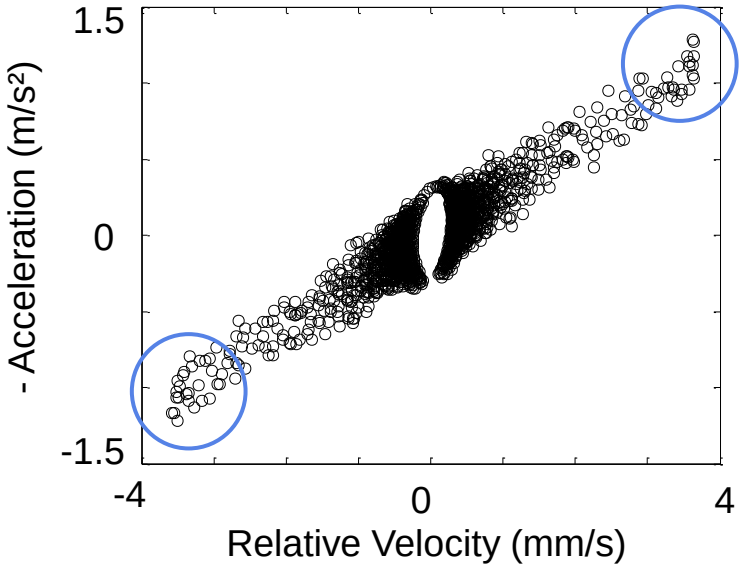


Sine sweep down of 14.4N

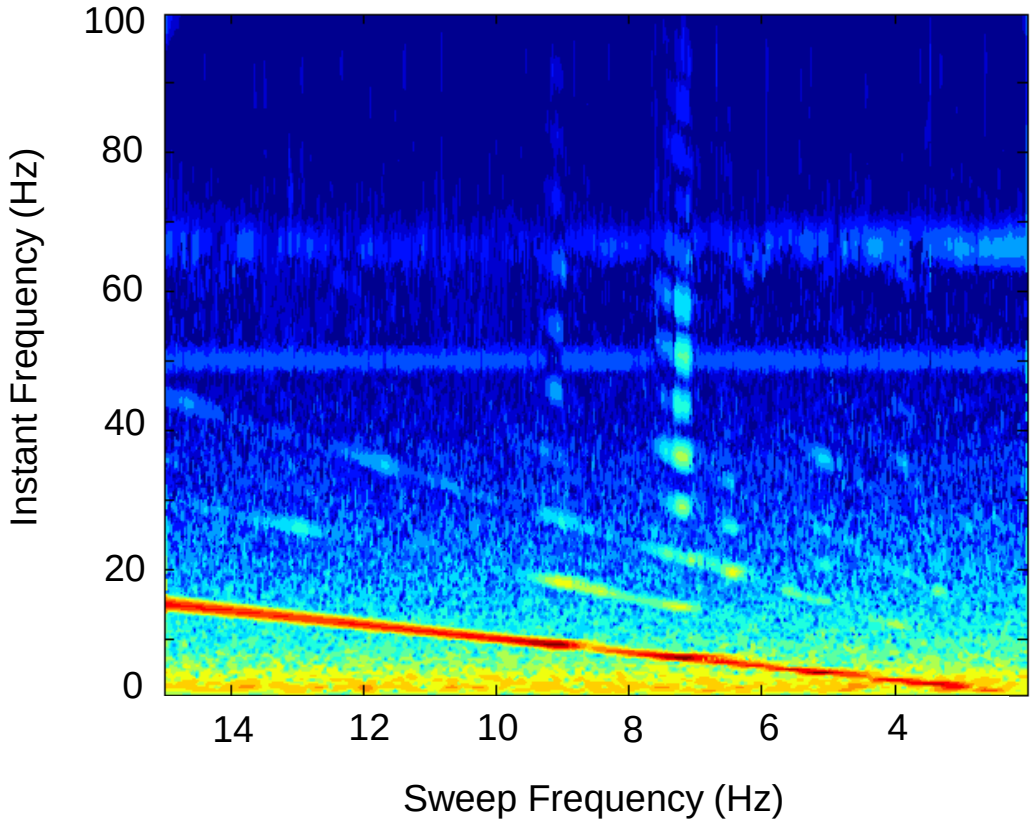


Extremities of Curves Indicate New Regime

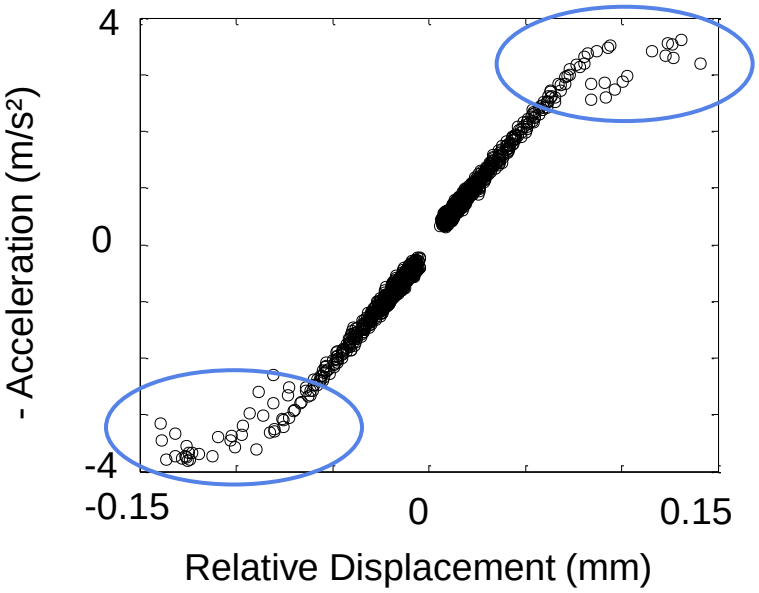


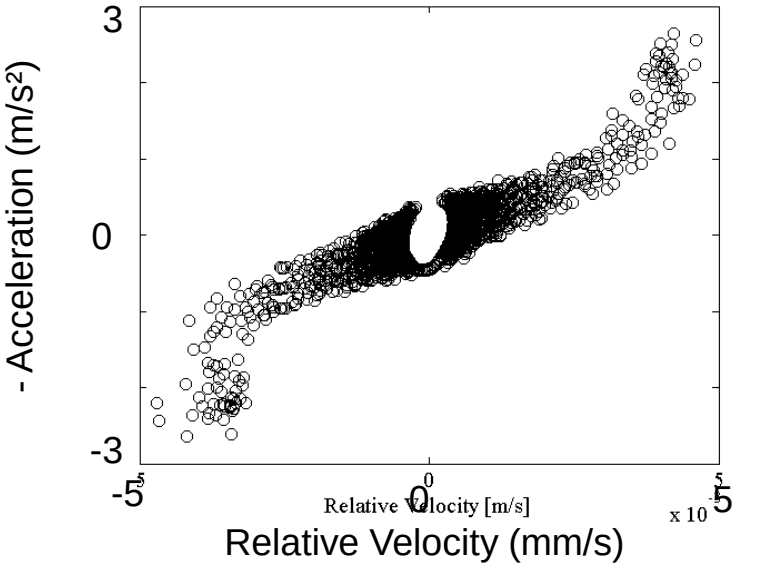


Sine sweep down of 19.2N

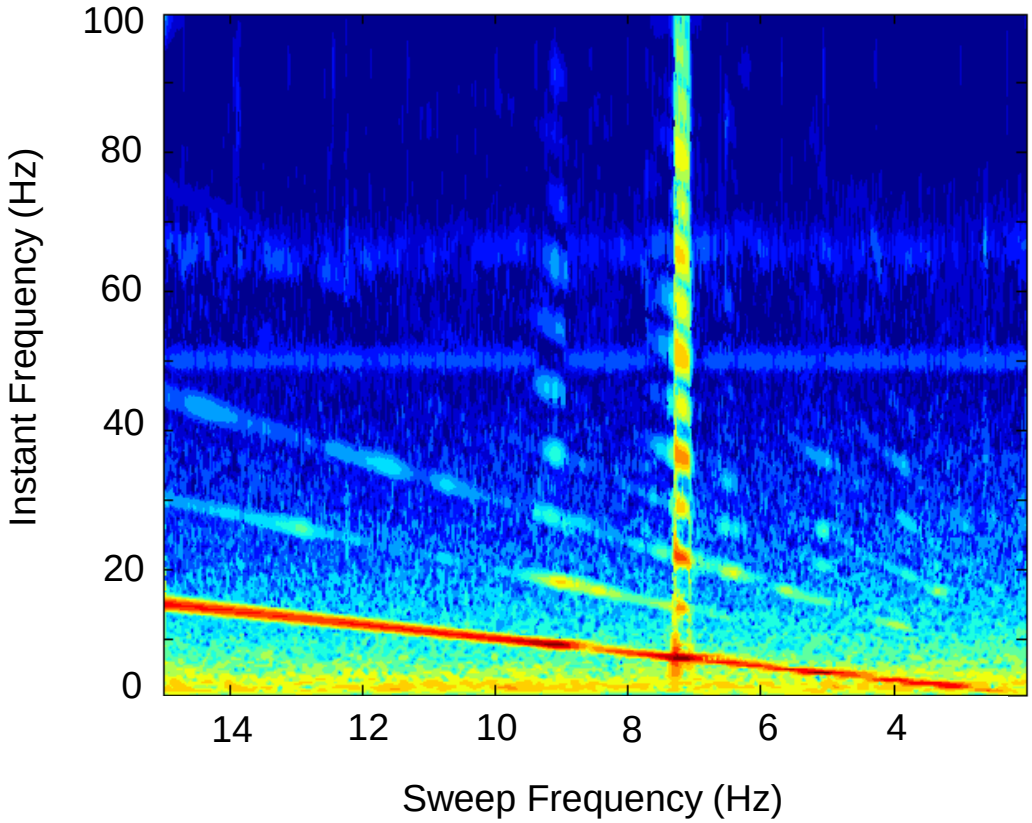


Joint Opening Causes Softening

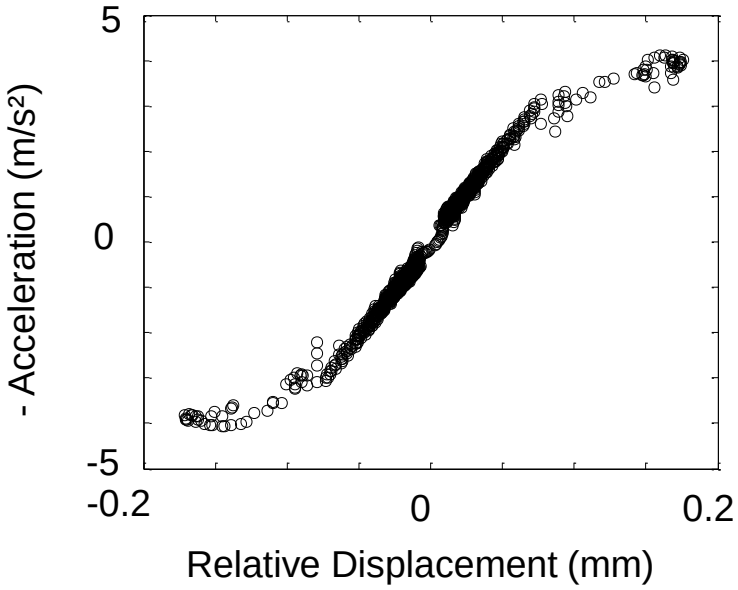


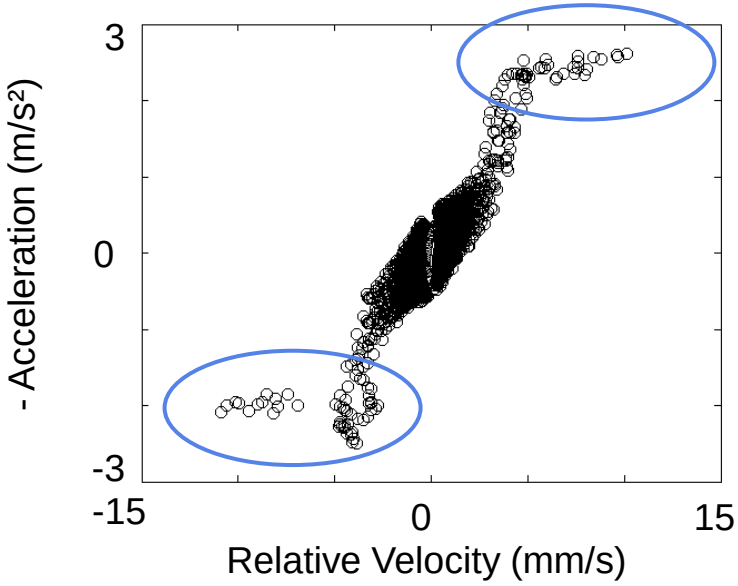


Sine sweep down of 28.8N

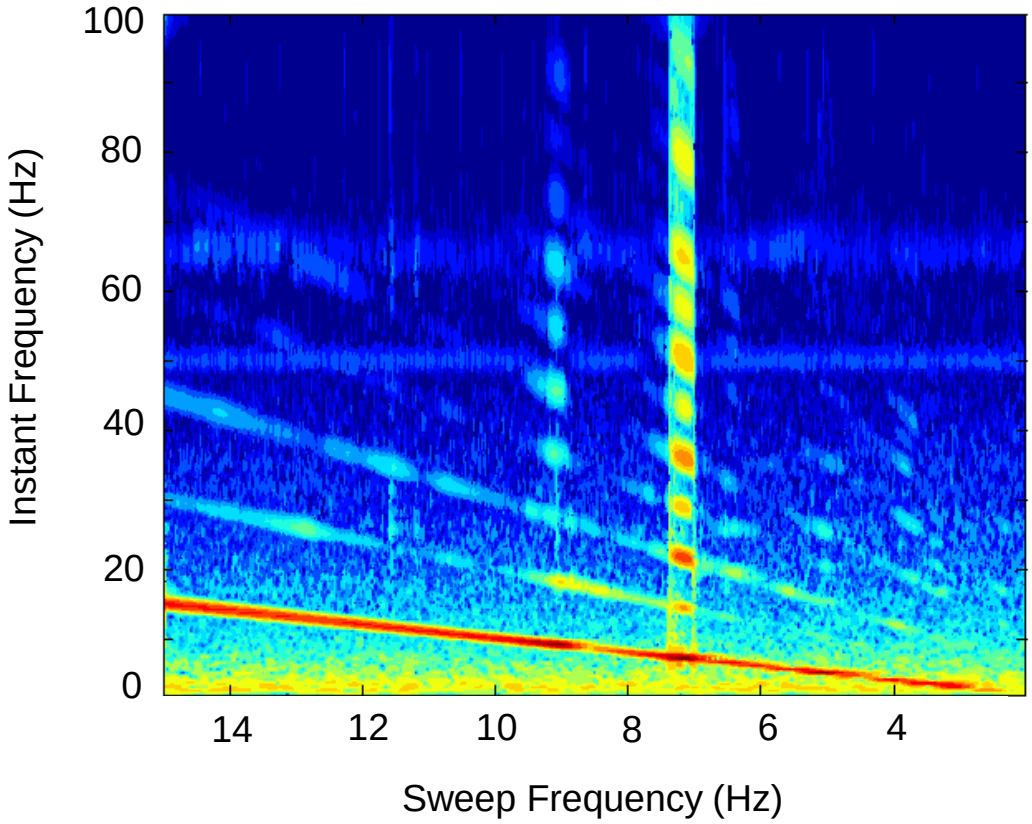


Coulomb Friction Identified

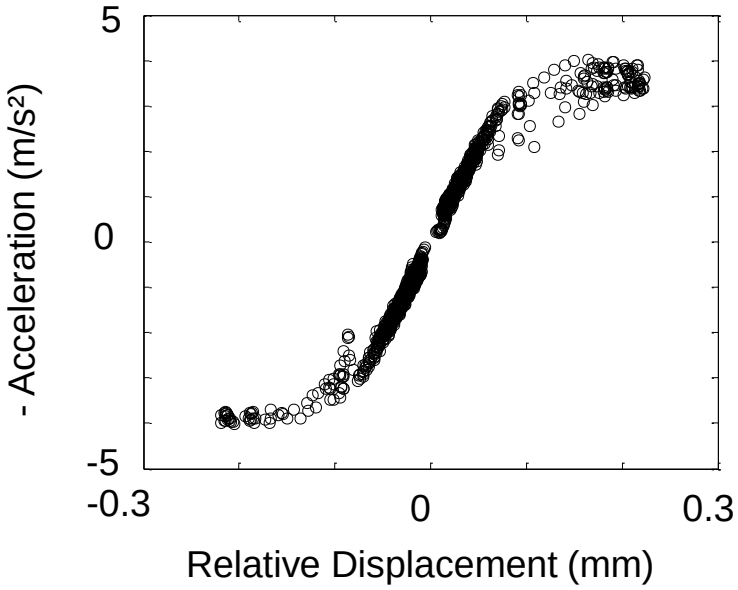


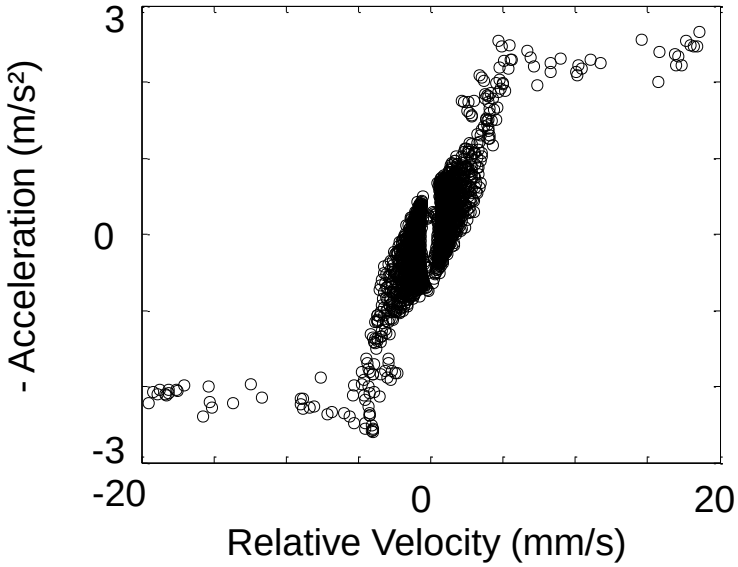


Sine sweep down of 38.4N

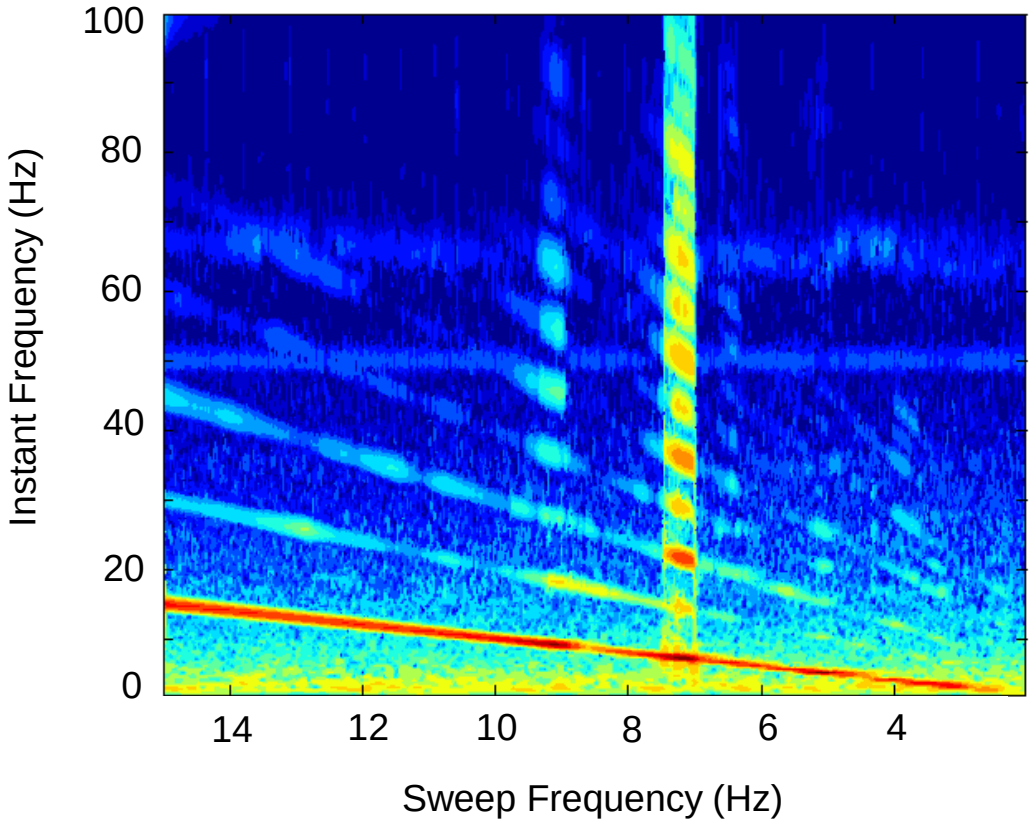


Softening and Coulomb Friction Remain at Higher Levels

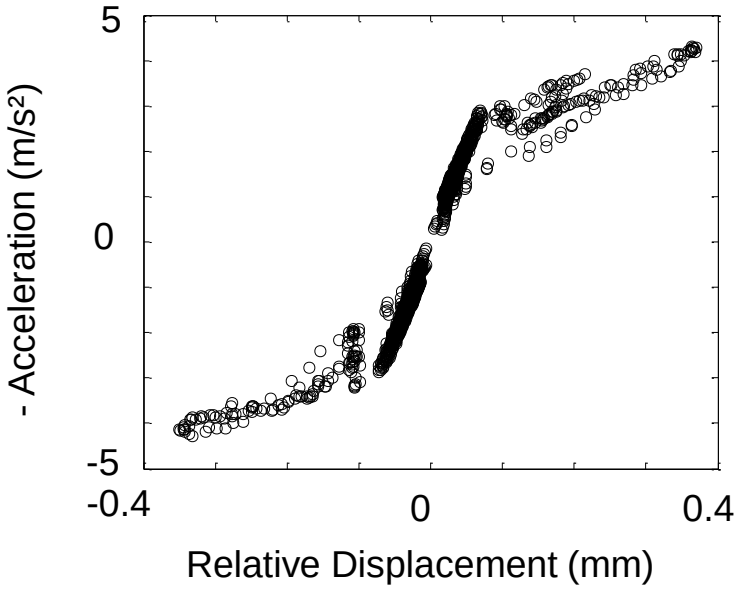


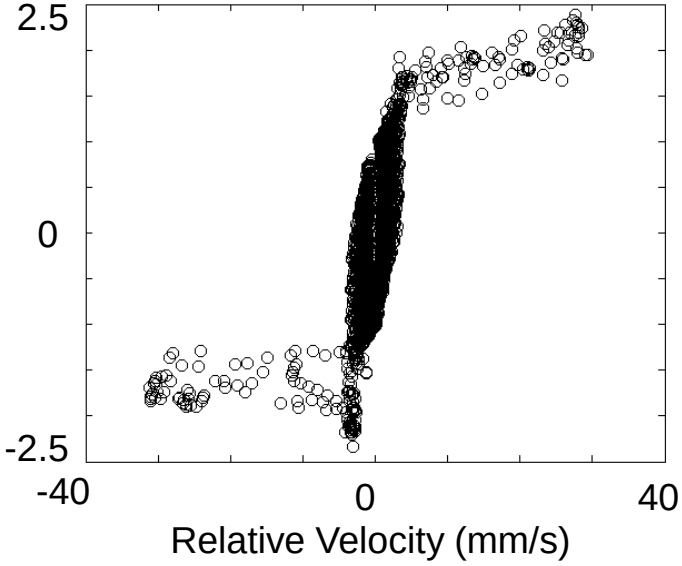


Sine sweep down of 48N

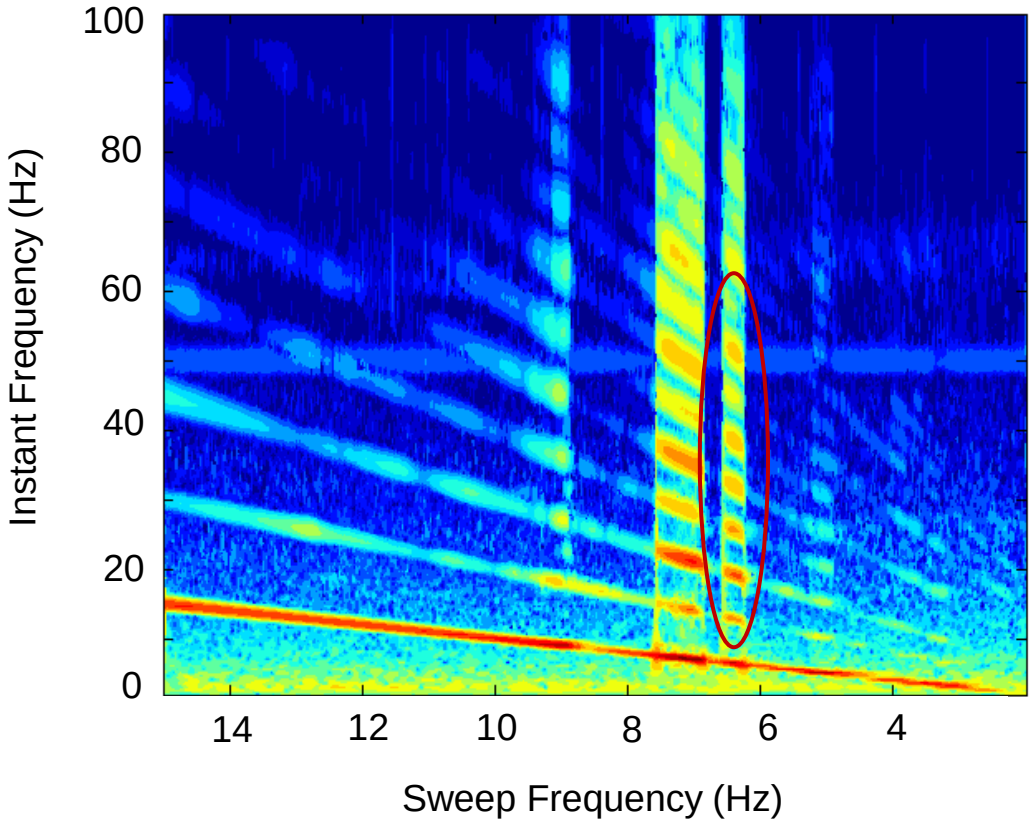


The Second Mode Becomes Highly Nonlinear Too

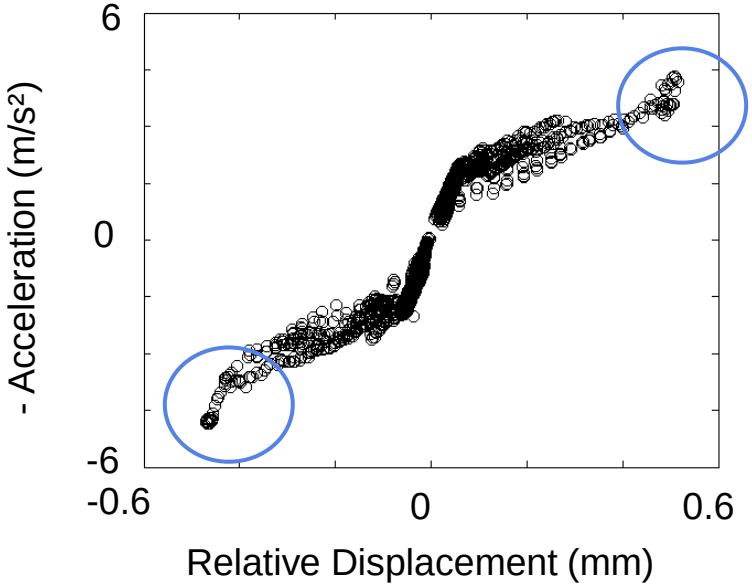


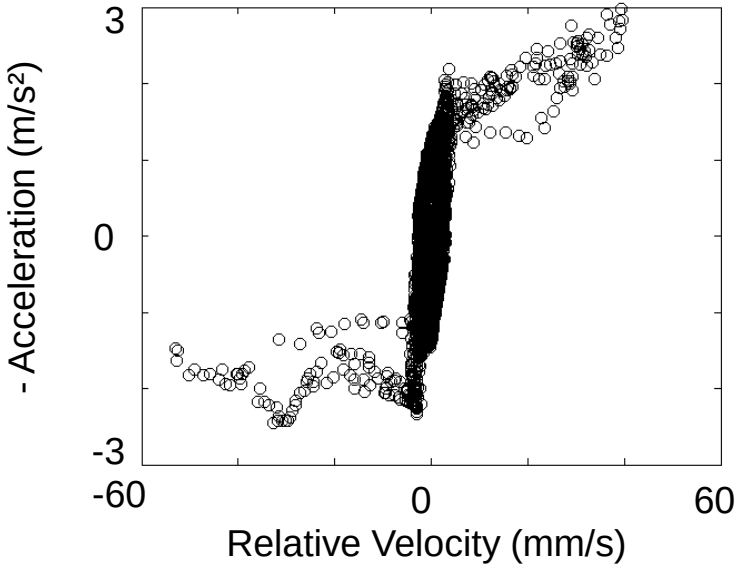


Sine sweep down of 67N

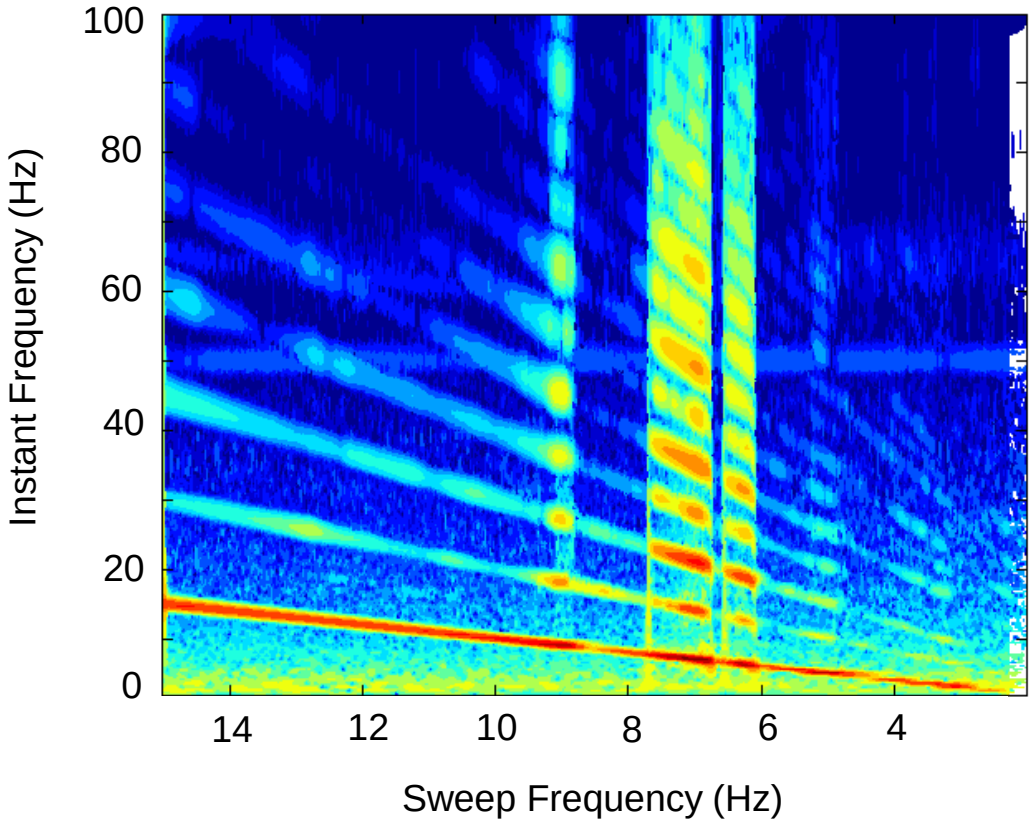


Impacts Occur for High Relative Displacements

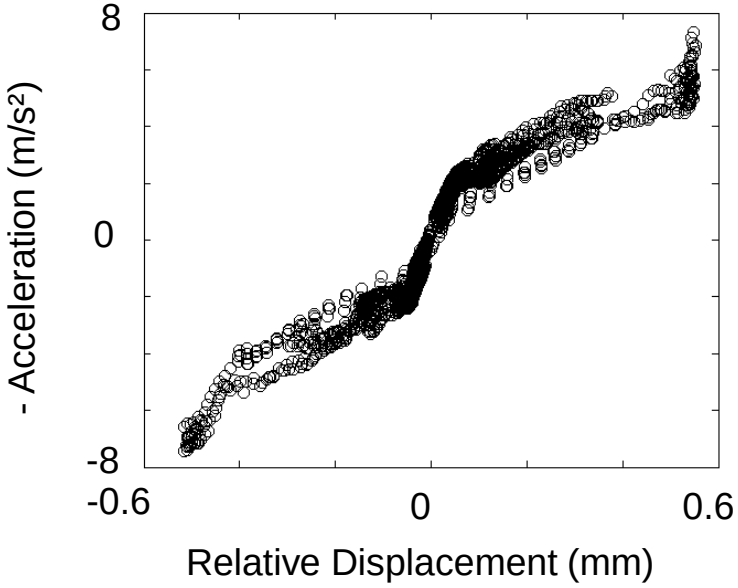


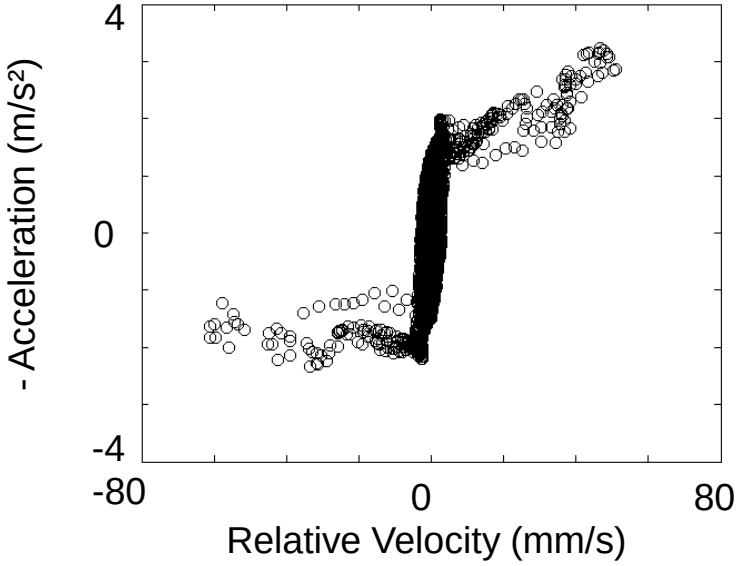


Sine sweep down of 86N



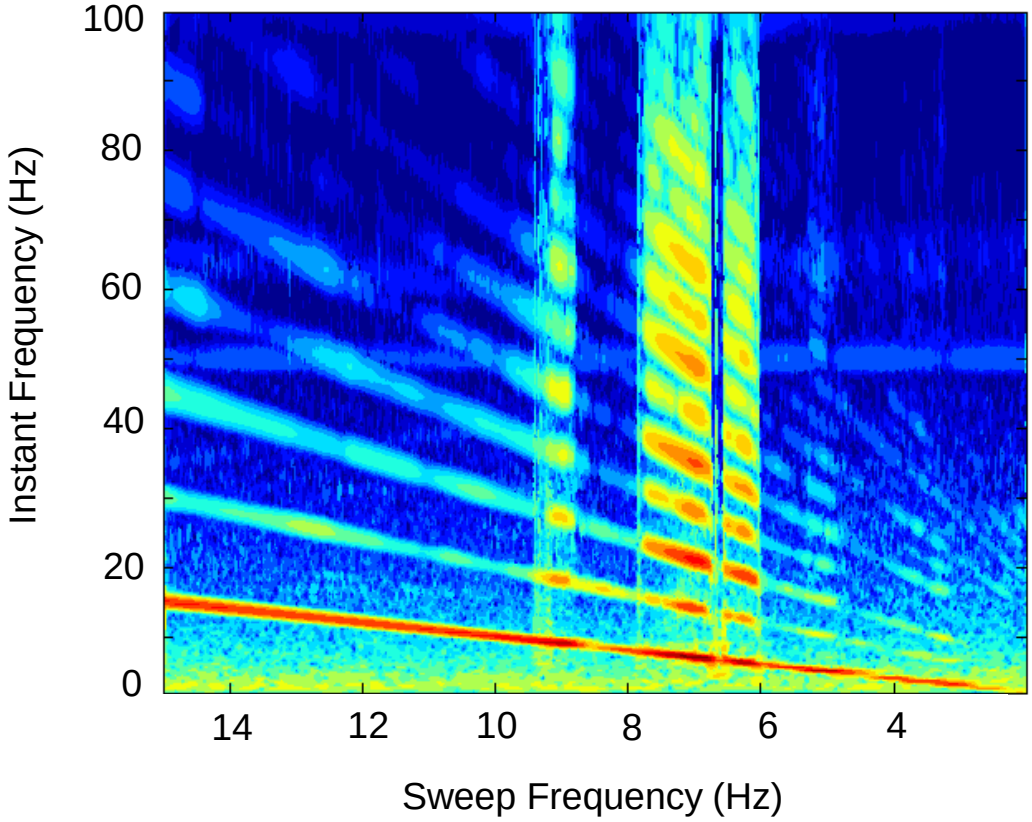
High Level Fully Reveals the Nonlinear Mechanisms



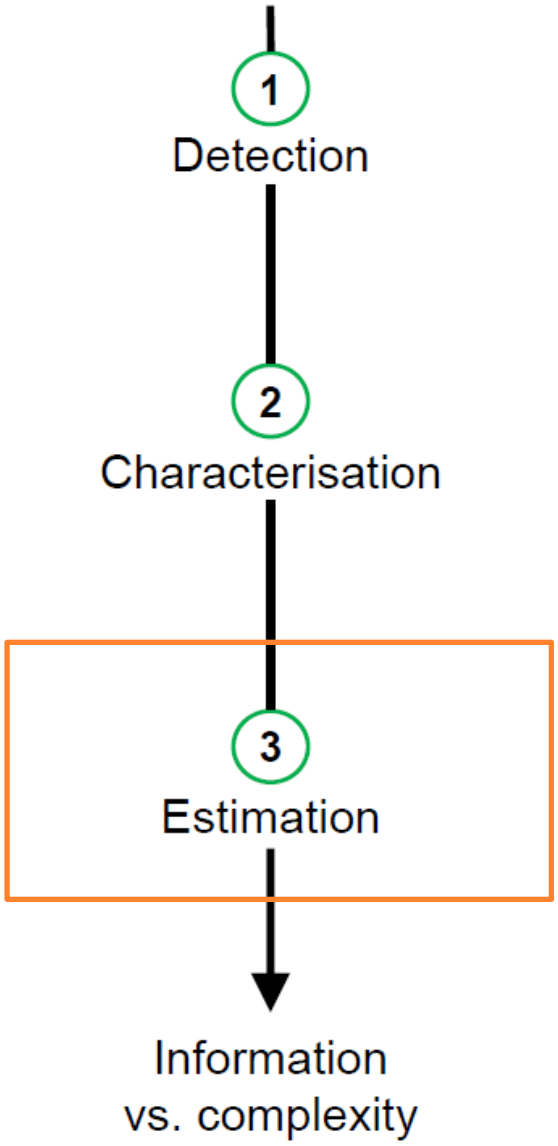


Sine sweep down of 95.6N

Wide harmonics



The Nonlinear System Identification Process



Do I observe nonlinear effects? **YES**

Should I build a nonlinear model? **YES**

Where is the nonlinearity located ? **WING TIP**

What is the underlying physics? **IMPACTS**

What mathematical model? **PIECEWISE LIN.**

Model parameters?

How uncertain are they?

Finite Element Model of the F-16 Wing

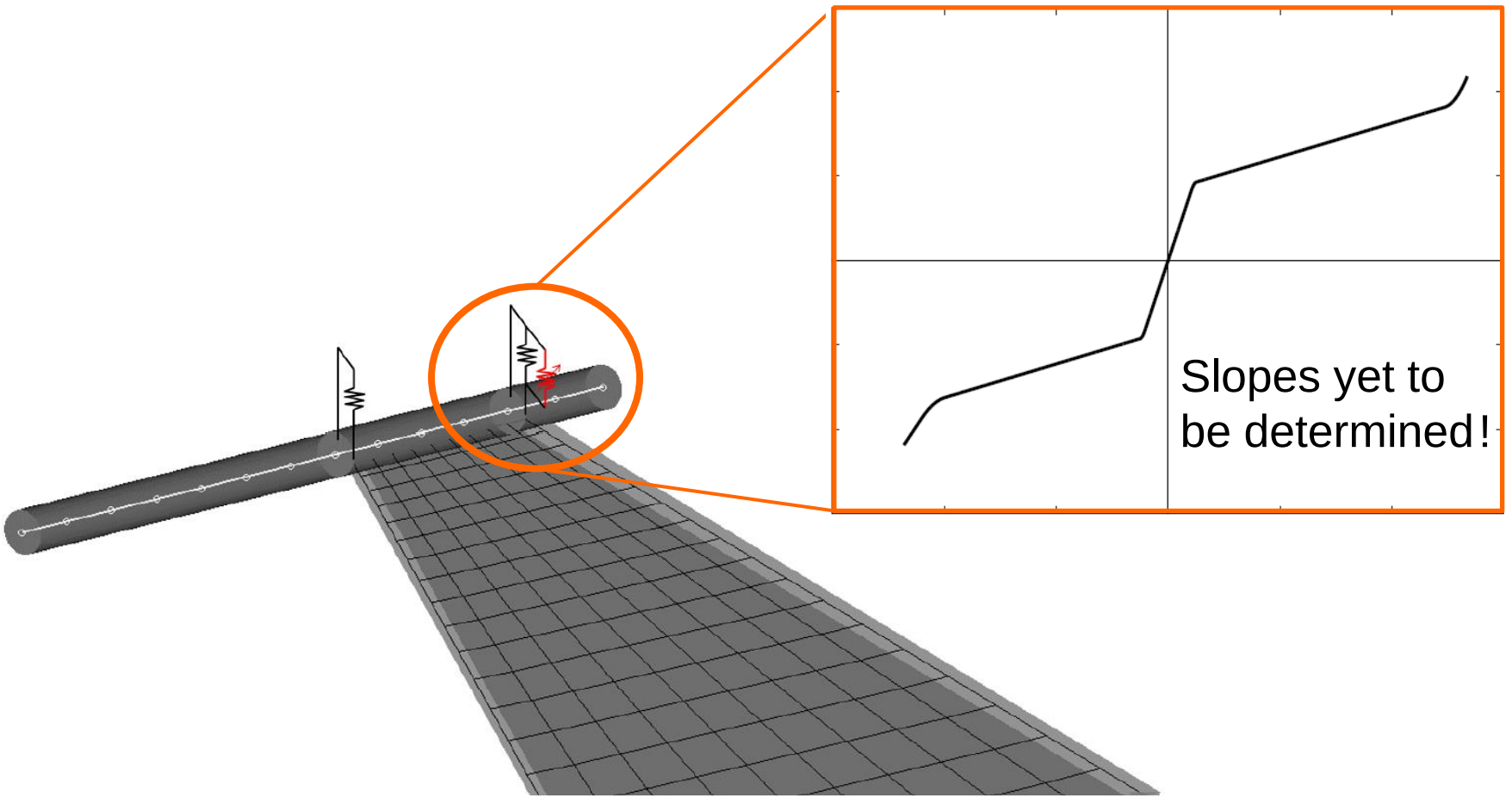


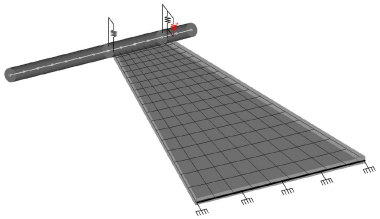
Table 2 Nonlinear parameters of the piecewise-linear spring and damper

Nonlinear element	Clearances	Slopes
Spring	$[-4.09\ ;\ -0.04\ ;\ 0.05\ ;\ 5.40] \times 10^{-4}$m	$[0.60\ ;\ 0.16\ ;\ 0.60\ ;\ 0.14\ ;\ 1.72] \times 10^{7}$N/m
Damper	$[-0.54\ ;\ -0.41] \times 10^{-2}$m/s	$[-0.05\ ;\ 5.51\ ;\ 0.65] \times 10^{4}$Ns/m

Concluding Remarks

VIBRATION MEASUREMENTS

LINEAR FINITE ELEMENT MODEL



MEASURE → **IDENTIFY** → HYBRID MODELING → UNDERSTAND → DESIGN

Detection

Characterization

Parameter estimation

Nonlinear modes

Nonlinear FRFs

Bifurcations

Input and Output Measurements for Nonlinear ID

Checklist:

1. Did you select appropriate excitation signals?
2. Did you record response signals properly?
3. Did you measure enough data?

Specifically,

Increase the sampling frequency.

Record time histories, not spectra.

Record throughput time histories, do not average/filter upfront.

Store the input signal. Consider multiple levels of excitation.

Instrument potential nonlinearities with sensors on both sides.

Thank you for your attention.

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Aerospace and Mechanical Eng. Dept.

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