Contact Dynamics Predictions Utilizing a Parameter-less Contact Model

Spacecraft and Launch Vehicle (SCLV) Dynamic Environments Workshop

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Objectives

Parameterized contact models in FEA

Parameter-less contact model

NASA major use case: nonlinear coupled loads analysis

Tutorial problems

Software Tools Utilized for Executing the Contact Dynamics Problems in this Presentation

- **MSC/NASTRAN**
  - Finite element modeling of structural components
- **MSC/NASTRAN DMAP**
  - Residual Flexibility Mixed Boundary (RFMB) dynamic math model (DMM) reductions and output transformation matrix development (OTMs)
  - Outputting required data-blocks for the contact solver
- ***ASD's nonlinear solver**
  - Contact dynamics simulations

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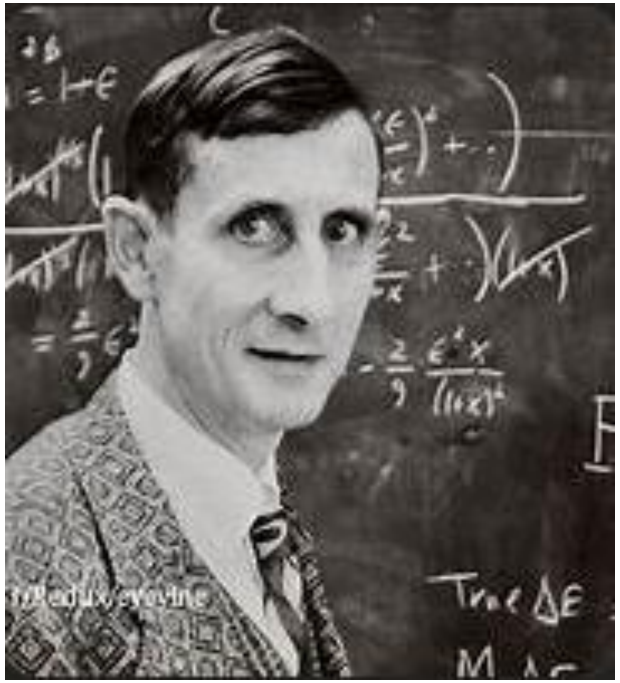
A Historical Note from Physics

John von Neumann
American mathematician,
physicist, and engineer.

Enrico Fermi (experimentalist)



Freeman Dyson (theoretician)

Conversation between Freeman Dyson and Enrico Fermi in 1953 where Dyson believed that the excellent agreement of his model with Fermi's experiment was proof that the model worked.

Later, Dyson's model was proven to be wrong!

Dyson: What do you think about the numerical agreement of our model with your experiment?

Fermi: How many free parameters are in your model?

Dyson: Four.

Fermi: You know, Johnny von Neumann used to always say that with four free parameters, I can fit an elephant and with five, I can make him wiggle his trunk.

General Criteria for a <u>Predictive</u> Model
(Enrico Fermi)

Clear physical model

or

Rigorous mathematical basis

If neither is present, any numerical agreement to experiment may be illusory and due to the presence of “free” parameters rather than the predictive qualities of the model

Parameterized Contact Models in FEA

Parameterized Contact Models

- Parameterized contact models are typically borrowed from the Hertzian (rigid-body) contact models and incorporated into finite element analysis packages
- Basic idea is to introduce a *contact stiffness* parameter into the contacting surfaces of the finite element mesh
- A contact force is then generated from *contact stiffness* x *surface penetration raised to an exponent;* i.e., this model requires contact mesh penetration to generate a contact force
  - Typically, these models also include contact damping and a surface penetration limit at which a max damping value activates
- Typical contact model parameters include:
  - *Contact stiffness*
  - *Surface penetration*
  - *Stiffening exponent*
  - *Penetration velocity*
  - *Smoothing functions*
  - *Max contact damping*
  - *Penetration depth (interface penetration limit at which max contact damping is applied)*

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A Parameter-less Contact Model

Parameter-less Contact Models (1/2)

- Models the physics of the contact problem
- There are no equations relating contact force to *surface penetration*; as a matter of fact, surface penetration (mesh penetrating mesh) is disallowed (zero)
- By definition, there are no other parameters besides the Coefficient of Friction (CoF)
  - The contact model operates directly on the finite element model’s contacting surfaces
- All potential state transitions are accounted:
  - No contact to contact
  - Contact to loss of contact
  - Re-contact due to rebound or vibrations of contacting surfaces
  - Stick to slip
  - Slip to stick

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Parameter-less Contact Models (2/2)

- Contact model accounts for the change in modal states as contacting surfaces transition
  - e.g., N contact surfaces require 2^N modal states; the mathematical frame work of the contact model must accurately represent all 2^N modal states without actually computing these mode sets
- An overlying "precedence" algorithm determines the plausibility of events where multiple contacting surfaces want to transition within the same time-step
  - Determines which of the contacting surfaces wants to transition first, transitions that contact, and then determines whether the other contacting surfaces still want to transition
- As a result, the parameter-less contact model is algorithmically much more complex than parameterized contact models

NASA 2005 Study
Space Shuttle Nonlinear Coupled Loads Analysis Applications

NASA Study on Incorporating Contact Dynamics in Coupled Loads Analyses

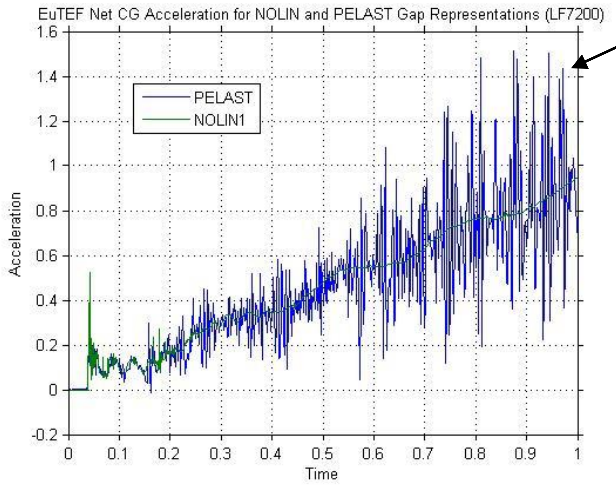
- In 2005, NASA conducted a study to test a number of commercially available solvers in predicting contact forces in transient coupled loads analysis (CLA).
- This was necessitated by the Space Shuttle Program's (SSP) decision (post-Columbia accident) to include contact dynamics in Space Shuttle Transient CLA [liftoff and landing] to capture the impact of contact nonlinearity.
  - This rendered the entire CLA process nonlinear.
- The study found difficulties simulating contact in transient dynamic environments using commercially available solvers.
- A special purpose nonlinear solver* was numerically tested by NASA and passed all initial screenings producing rational/physically realizable contact forces. Subsequently, the solver was validated by NASA in a "blind" validation against test data. It was then selected to execute all NASA/SSP CLAs from 2005-2011 (final flight).
  - Solver incorporates the parameter-less contact model**

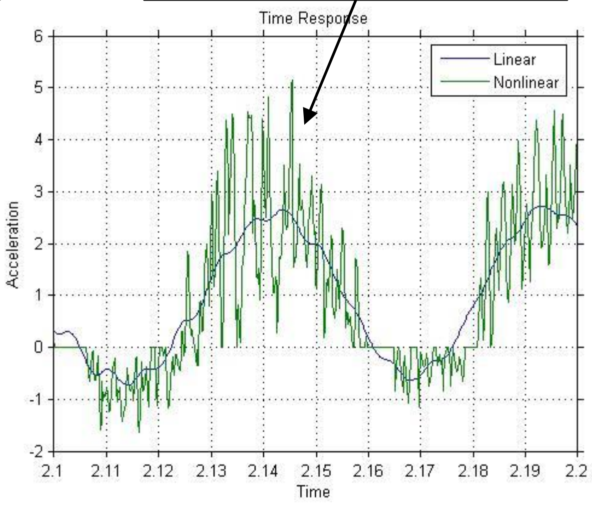
*,** Developed by ASD, Inc: A. Majed and E. E. Henkel

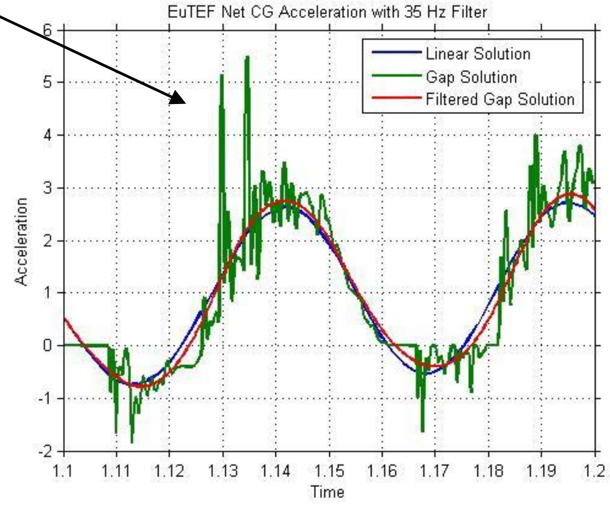
Difficulties Predicting Contact Dynamics in CLAs with Commercially Available FEA (NASA Study – 2005)

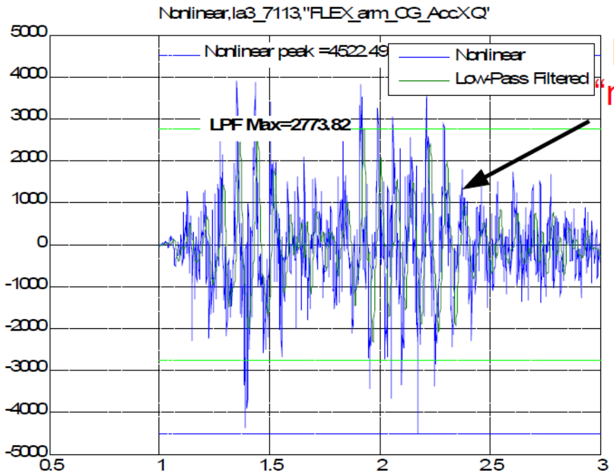
Dominated by “Numerical high frequency noise/chatter

Results from Space Shuttle CLA utilizing various commercial available FEA packages with contact models.

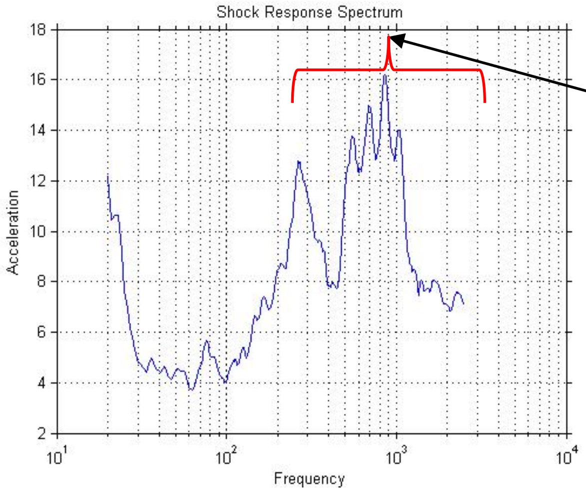








Dominated by “numerical” high frequency noise/chatter



SRS shows **numerical** high frequencies not present in coupled system structural frequencies (system modes truncated at 35 Hz)

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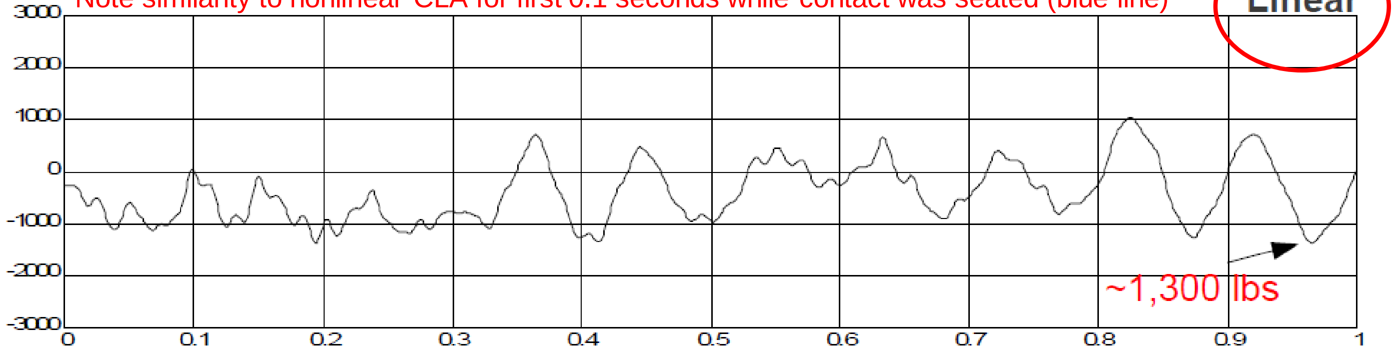
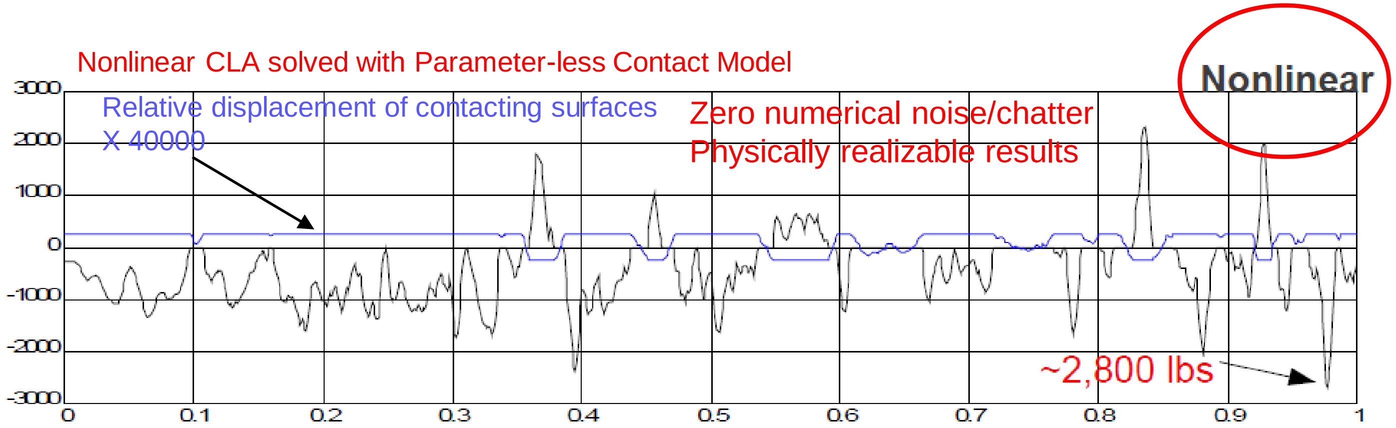
Accurate Capture of Contact Dynamics in Nonlinear CLAs: Parameter-less Contact Model

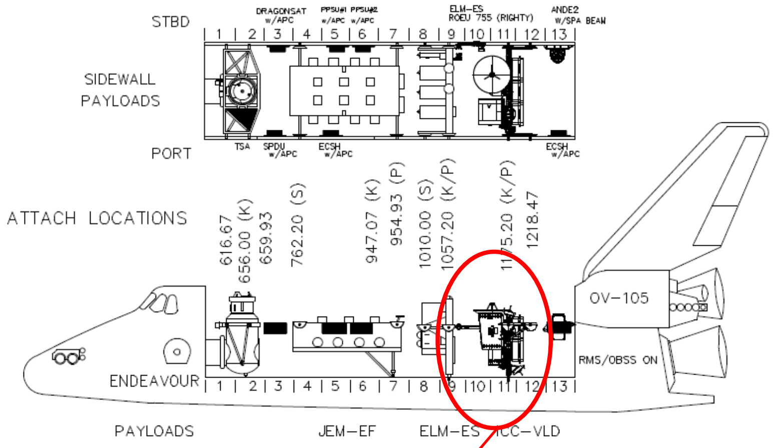
Contact Dynamics – Linear vs Fully Nonlinear CLA
Space Shuttle Flight 2J/A Verification CLA

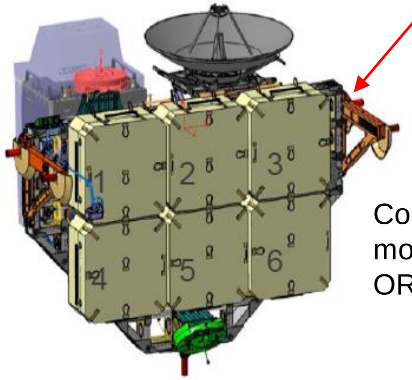
Standard linear CLA without contact modeling
Note similarity to nonlinear CLA for first 0.1 seconds while contact was seated (blue line)



Nonlinear CLA solved with Parameter-less Contact Model







Contacts at all kinematically mounted battery interfaces and ORUs

In general, Nonlinear CLA contact interface force predictions were significantly higher than linear CLA

Battery 5 Shear Interface Force (Node 653, Zorb) and relative displacement x 40000 – Orbiter Landing Case LG 7525

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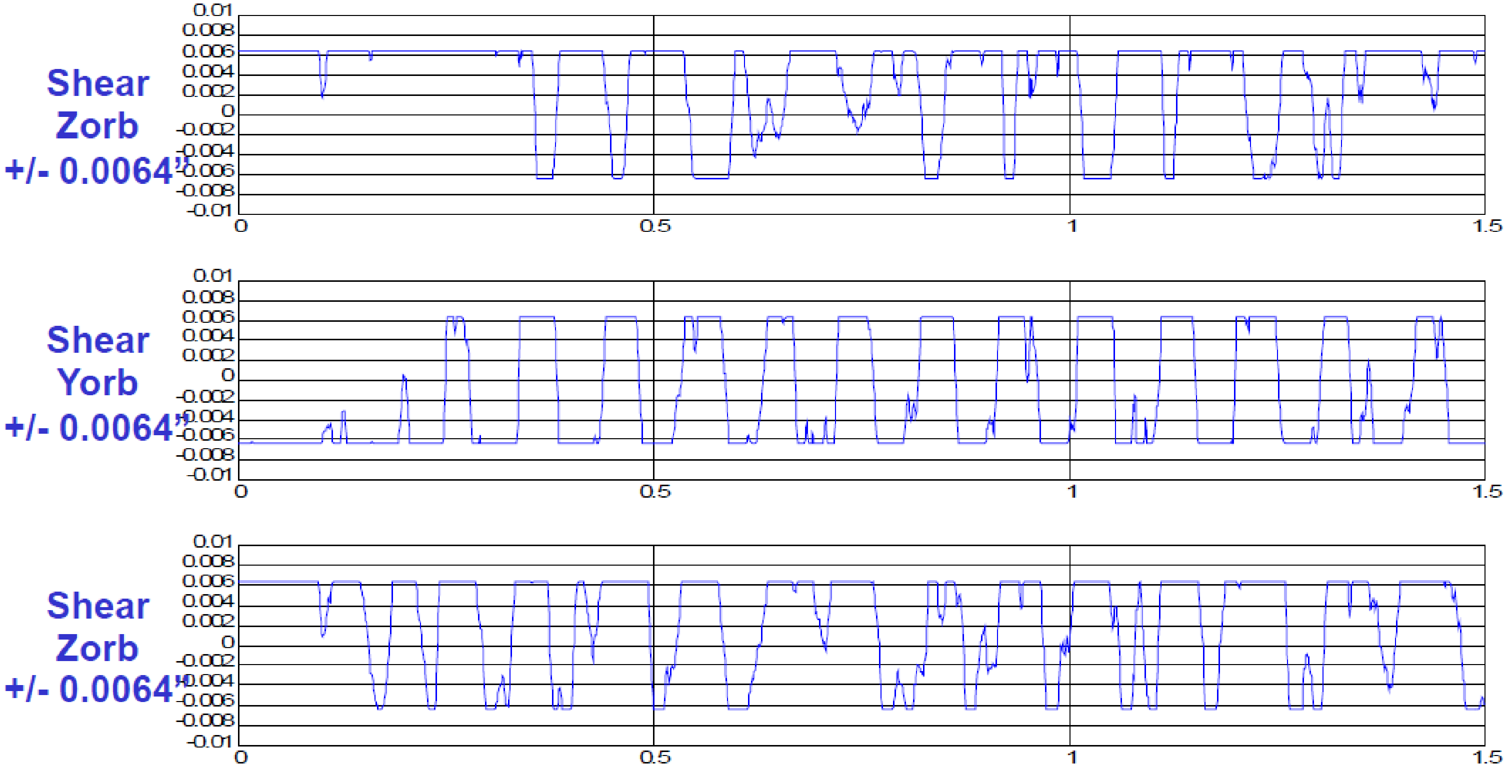
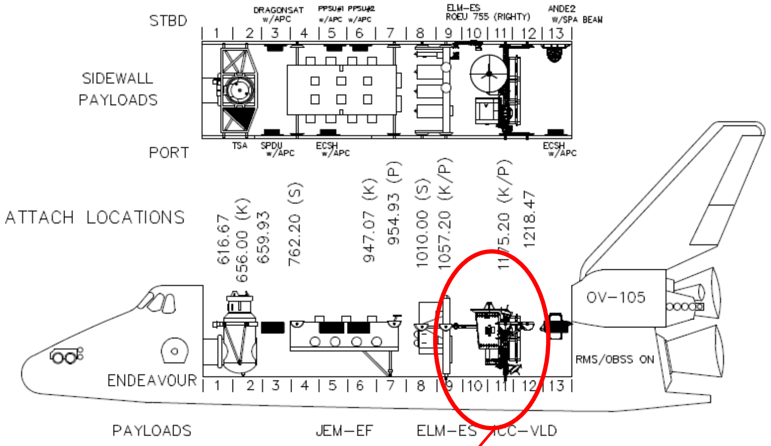
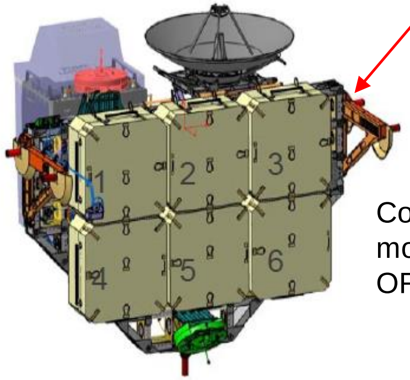
Zero Surface Penetration in Nonlinear CLAs: Parameter-less Contact Model







Contacts at all kinematically mounted battery interfaces and ORUs

Predictions using the parameter-less contact model showing <u>zero</u> penetration of contacting surfaces (contact occurs at +/- 64 mils)

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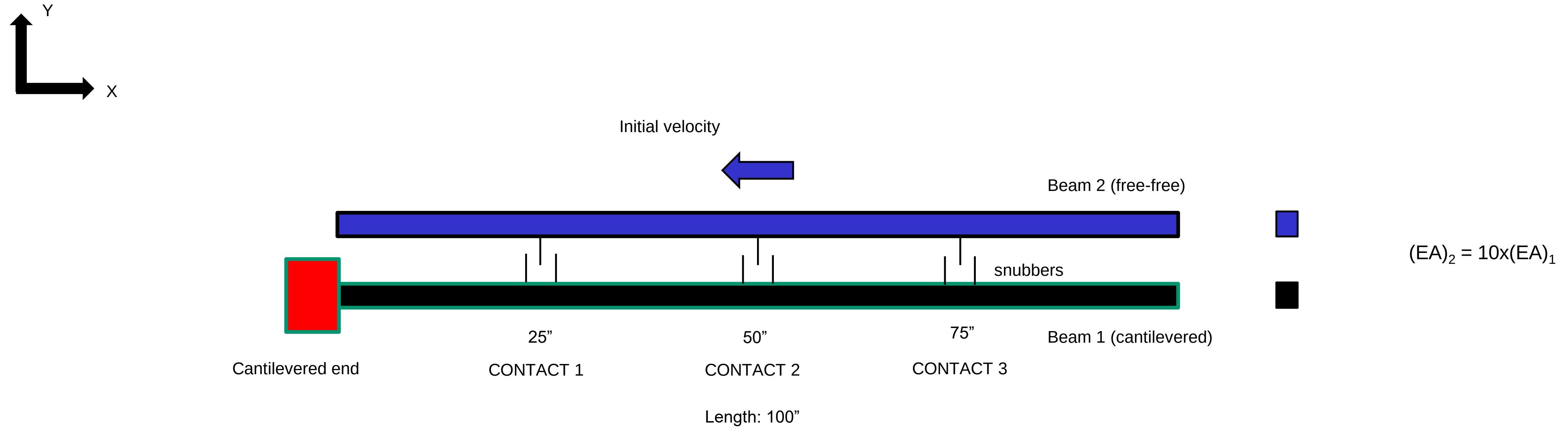
Major NASA and NESC Use Cases
Parameter-less Contact Model

- Space Shuttle Program: trunnion friction stick/slip transient coupled loads analyses (CLAs)
- Space Shuttle Program: Contact/friction transient CLAs involving ISS ORU nonlinear interfaces (2005 – Final flight)
- Space Launch System (SLS): Nonlinear CLAs
- SLS: Nonlinear CLAs including umbilical disconnects
- Other NASA usage: e.g., provide guidance to help in setting parameters for parameterized contact model

Tutorial Examples
Understanding Contact Dynamics

Design of the "Simple" Contact Problem
Axial Contact



Residual Flexibility Mixed Boundary* Dynamic Math Model Reduction

Coordinate Transformation:

$$\begin{Bmatrix} x_b \\ x_c \\ x_o \end{Bmatrix} = \begin{bmatrix} I_{bb} & 0 & 0 \\ 0 & I_{cc} & 0 \\ \phi_{ob}^{C} - G_{oc}^{R} {G_{cc}^{R}}^{-1} \phi_{cb}^{C} & G_{oc}^{R} {G_{cc}^{R}}^{-1} & \phi_{ok}^{N} - G_{oc}^{R} {G_{cc}^{R}}^{-1} \phi_{ck}^{N} \end{bmatrix} \begin{Bmatrix} x_b \\ x_c \\ q_k \end{Bmatrix}$$

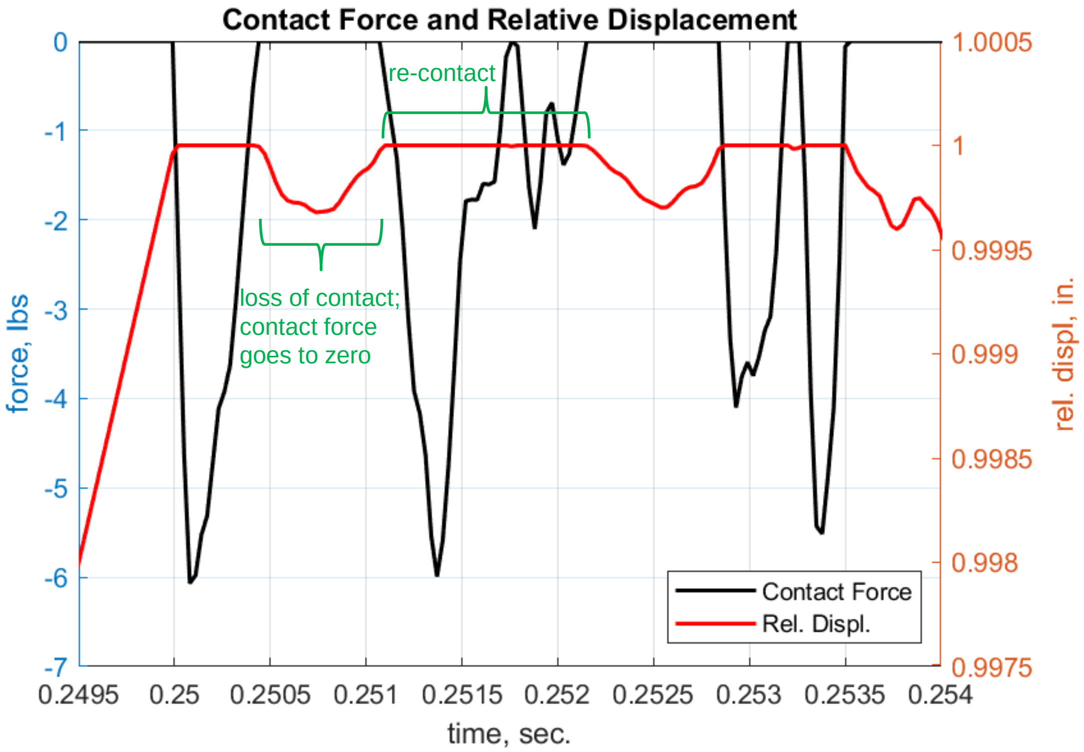
Beam 1 truncated to 10 kHz relative to its cantilevered frequencies (i.e., cantilevered boundary conditions in B-set; all contact DoFs in C-set)

Beam 2 truncated at 10 kHz relative to its free-free frequencies (all contact DoFs in C-set)

*Developed by Applied Structural Dynamics (ASD), Inc.
Default in MSC/NASTRAN

Contact 1 Force and Relative Displacement Time-History Left Snubber

$\mu = 0.0$
ζ = 1% for f≤400 Hz
ζ = 0.25% for f>400 Hz

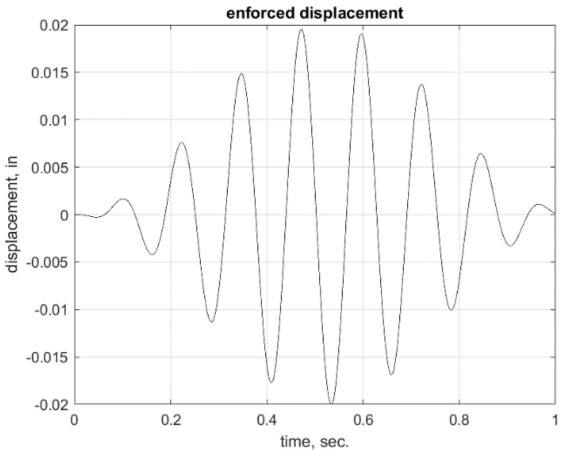


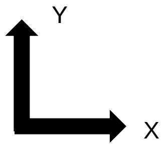
Contact at Contact 1 as well as the other contacts sets off higher frequency axial vibrations resulting in multiple contact/re-contact at the left snubber 1

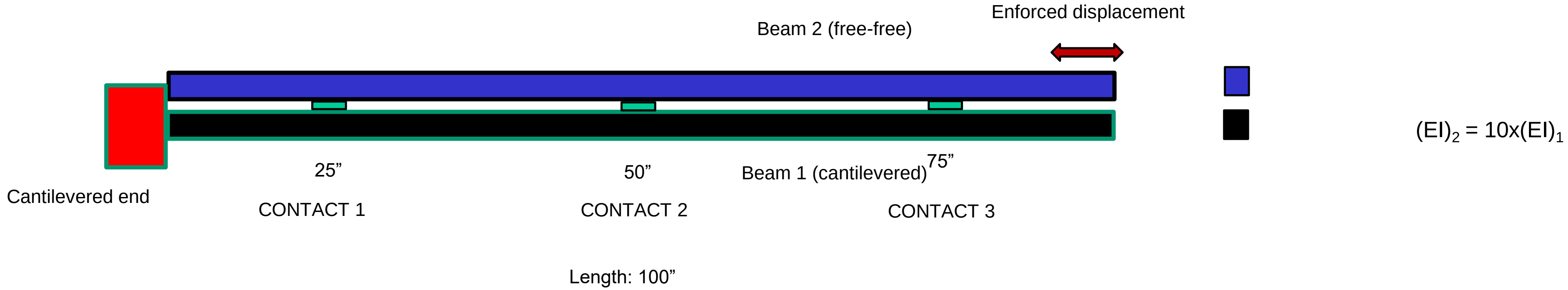
Plotting the contact force and relative displacement of contacting surfaces on the same plot must show corresponding behavior

This entire contact event is approx. 3 msec

Design of the "Simple" Contact Problem
Stick/Slip Friction Contact

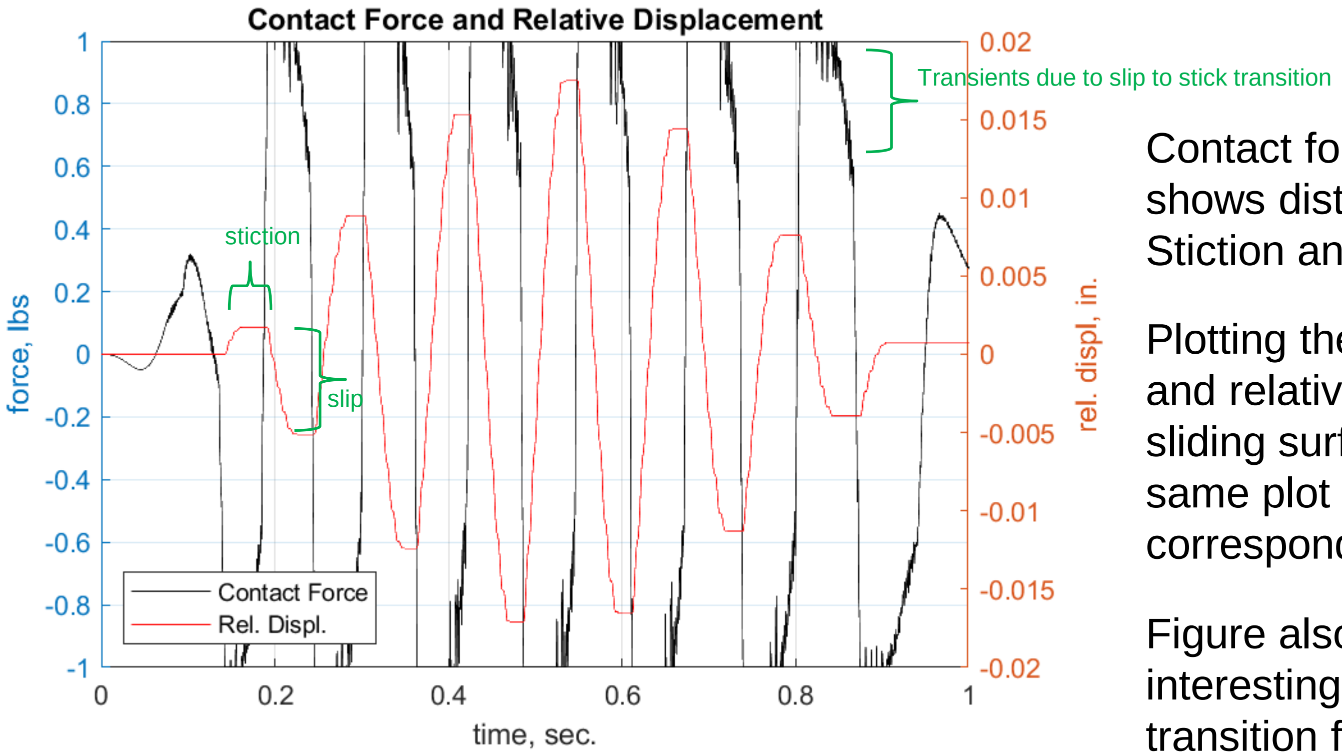






Contact 3 Force and Relative Displacement Time-History

μ = 0.1
N = 10 lbs
ζ = 1% for f≤400 Hz
ζ = 0.25% for f>400 Hz



Contact force at Contact 3 shows distinct regions of Stiction and sliding friction

Plotting the contact force and relative displacement of sliding surfaces on the same plot must show corresponding behavior

Figure also shows some interesting transients due to transition from slip to stick

Concluding Remarks

- The contact nonlinear model utilized in NASA’s mission critical manned space flight CLAs is parameter-less requiring no contact stiffness, surface penetration, contact damping, penetration limits, smoothing functions, …
  - The model operates directly on the FEM’s contacting surfaces
- Most recent usage of the parameter-less contact model involved advising on setting the parameters for parameterized contact models in general FEA
  - Work in progress
- Besides zero numerical noise and chatter, another self-validation goodness check for contact dynamics can be the super-imposed plot of contact force and associated relative displacement of the contacting surfaces vs time
  - There should be a correspondence in the two independent nonlinear time-histories; otherwise, there is a strong likelihood of a problem