Norton-Thevenin Receptance Coupling (NTRC) as a Payload Design Tool

Scott Gordon, NASA/Goddard Space Flight Center

Dan Kaufman, NASA/Goddard Space Flight Center

Arya Majed, Applied Structural Dynamics, Inc.

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Agenda

- Background

- Methodology

- NESC Study

- Future Work

- Summary
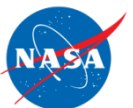
Acknowledgement

- Curt Larsen, Loads and Dynamics Tech Fellow, NESC
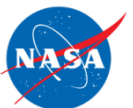
What is NTRC?

- NTRC combines receptance coupling methods with Norton-Thevenin Theory

- Receptance coupling = A method of coupling dynamic structures based on frequency response function (FRF) measurements/analysis

- Norton-Thevenin Theory = An interface impedance-based method for simulating the interaction between dynamic systems

- Allows for the behavior of the coupled system to be derived from measurements at the boundary of the two systems to be coupled

- Does not require launch vehicle models or forcing functions
  - Unloaded launch vehicle accelerations at interface (free acceleration)
  - Launch vehicle interface impedance (accelerance)

Why Was NTRC Developed?

- There is a need for a design tool that the LV payload community can use to estimate launch loads
- Limited methods for preliminary estimates of launch loads for subsystems and components
  - MAC/MMAC
  - Base-drive
- Payload community has limited access to CLA during life of a program (Typically 2 to 3 cycles)
  - Difficult to address design change that occur between load cycles
  - Difficult to assess impact of "as-built" hardware
- Allow payload community to assess launch loads with minimal amount of information required from the launch vehicle provider
- Not intended to replace the formal load cycles!

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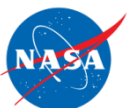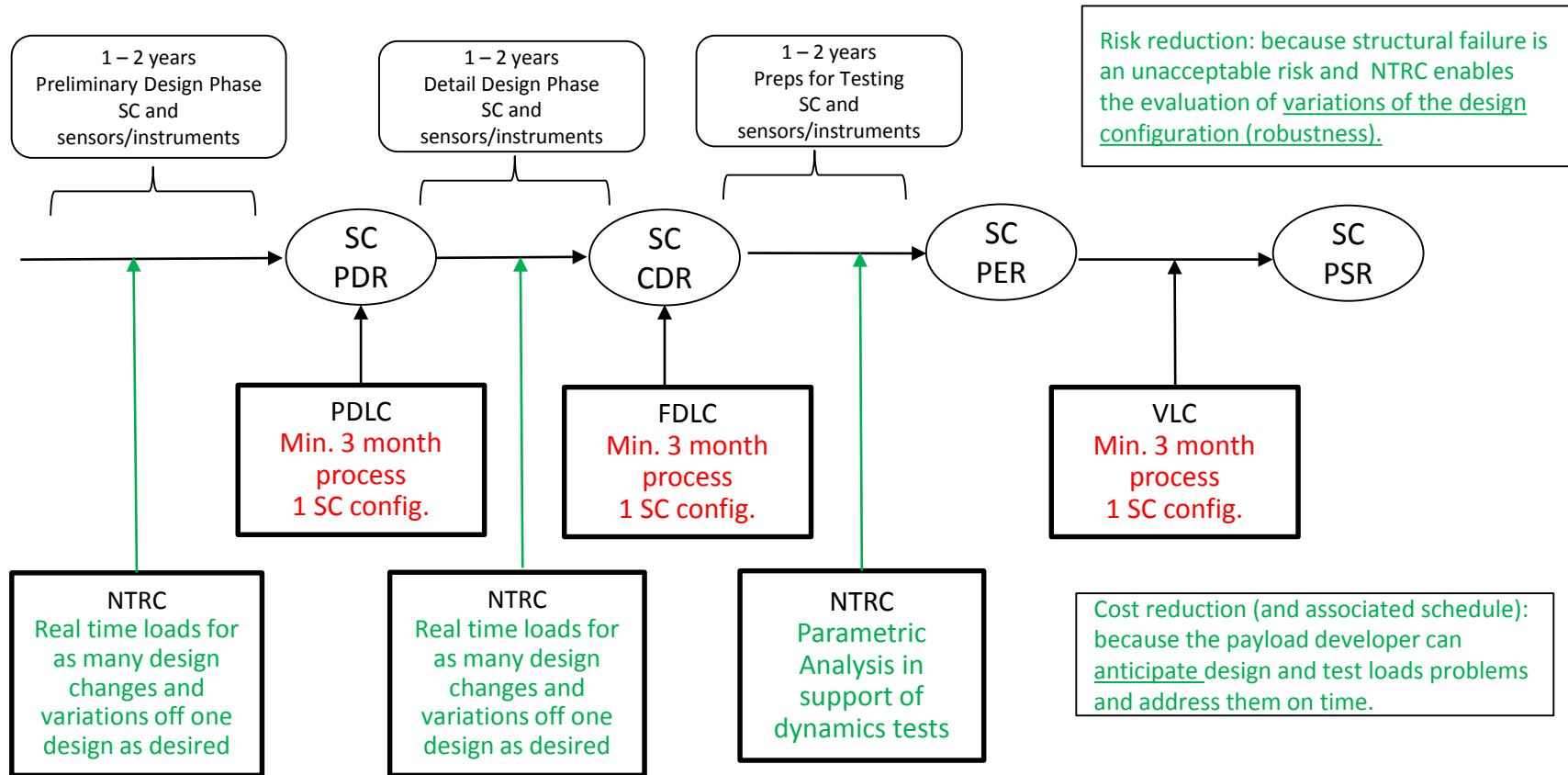
Typical Payload Development Process

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┌──────────────────────┐    ┌──────────────────────┐    ┌──────────────────────┐    ┌────────────────────────────────────┐
│     1 – 2 years      │    │     1 – 2 years      │    │     1 – 2 years      │    │ Risk reduction: because structural   │
│ Preliminary Design   │    │ Detail Design Phase  │    │  Preps for Testing   │    │ failure is an unacceptable risk and  │
│       Phase          │    │       SC and         │    │       SC and         │    │ NTRC enables the evaluation of       │
│       SC and         │    │  sensors/instruments │    │  sensors/instruments │    │ variations of the design             │
│  sensors/instruments │    │                      │    │                      │    │ configuration (robustness).          │
└──────────────────────┘    └──────────────────────┘    └──────────────────────┘    └────────────────────────────────────┘
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        ⎧─────┐          ⎧─────────┐          ⎧─────────┐
   ────────►  ( SC  ) ───────────► ( SC  ) ───────────► ( SC  ) ───────────► ( SC  )
              ( PDR )                ( CDR )              ( PER )              ( PSR )
                ▲                      ▲                    ▲
                │                      │                    │
        ┌───────────────┐    ┌───────────────┐    ┌───────────────┐
        │     PDLC      │    │     FDLC      │    │      VLC      │
        │ Min. 3 month  │    │ Min. 3 month  │    │ Min. 3 month  │
        │   process     │    │   process     │    │   process     │
        │ 1 SC config.  │    │ 1 SC config.  │    │ 1 SC config.  │
        └───────────────┘    └───────────────┘    └───────────────┘
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┌───────────────┐    ┌───────────────┐    ┌───────────────┐    ┌────────────────────────────────────┐
│     NTRC      │    │     NTRC      │    │     NTRC      │    │ Cost reduction (and associated       │
│ Real time     │    │ Real time     │    │  Parametric   │    │ schedule): because the payload       │
│ loads for     │    │ loads for     │    │  Analysis in  │    │ developer can anticipate design and  │
│ as many design│    │ as many design│    │  support of   │    │ test loads problems and address them │
│ changes and   │    │ changes and   │    │ dynamics tests│    │ on time.                             │
│ variations off│    │ variations off│    │               │    │                                      │
│ one design    │    │ one design    │    │               │    │                                      │
│ as desired    │    │ as desired    │    │               │    │                                      │
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Benefits of NTRC

- Provides the payload community with ability to define/assess launch loads before and between official CLA cycles
- Operates on the minimum possible set of coordinates (equal to boundary DoFs) to solve the CLA problem, which improves solution times
- Solves in the frequency domain which allows for faster execution
- Allows for parametric analysis and trade-studies to optimize structural design and limit surprises from official CLA results [4]
- May provide benefit to the LV community
  - Faster response times for evaluating multiple payload configurations than standard CLA
  - Improved assessment of CLA models/forcing functions against measured flight data

NTRC Methodology
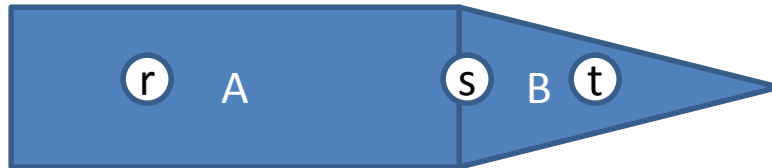
C: coupled system (A+B)
A: source with internal dofs r
B: load with internal dofs t
s: connecting dofs
H: accelerance [g/lb]
W: Impedance [lb/g] = H^{-1}
F: [lb], A: [g]

Coupled System Accelerance [3]

$$\begin{bmatrix} A_{Cr} \\ A_{Cs} \\ A_{Ct} \end{bmatrix} = \begin{bmatrix} H_{Crr} & H_{Crs} & H_{Crt} \\ H_{Csr} & H_{Css} & H_{Cst} \\ H_{Ctr} & H_{Cts} & H_{Ctt} \end{bmatrix} \begin{bmatrix} F_{Cr} \\ F_{Cs} \\ F_{Ct} \end{bmatrix} \qquad (1)$$

H_{xyz} = Accelerance for System X with response at y dofs due to forces applied at z dofs

CLA: $F_{Cs} = F_{Ct} = 0$

From (1) :

$$A_{Cs} = H_{Csr}\ F_{Cr} \qquad (2)$$

$$A_{Ct} = H_{Ctr}\ F_{Cr} \qquad (3)$$

NTRC Methodology (Cont)

Receptance (Accelerance) Coupling for two substructures [3]:

$$
\begin{bmatrix} H_{Crr} & H_{Crs} & H_{Crt} \\ H_{Csr} & H_{Css} & H_{Cst} \\ H_{Ctr} & H_{Cts} & H_{Ctt} \end{bmatrix} = \begin{bmatrix} H_{Arr} & H_{Ars} & 0 \\ H_{Asr} & H_{Ass} & 0 \\ 0 & 0 & H_{Btt} \end{bmatrix} - \begin{bmatrix} H_{Ars} \\ H_{Ass} \\ -H_{Bts} \end{bmatrix} \begin{bmatrix} H_{Ass} + H_{Bss} \end{bmatrix}^{-1} \begin{bmatrix} H_{Ars} \\ H_{Ass} \\ -H_{Bts} \end{bmatrix}^{T} \qquad (4)
$$

From (4) we can define H_{Csr} and H_{Ctr} as:

$$
H_{Csr} = \frac{H_{Bss}\, H_{Asr}}{H_{Ass} + H_{Bss}} \qquad (5)
$$

$$
H_{ctr} = H_{bts}[H_{ass} + H_{bss}]^{-1} H_{asr} \qquad (6)
$$

NTRC Methodology (Cont)

Rewrite (2) using (5):

$$A_{Cs} = [H_{Csr}]F_{Cr} = \frac{H_{Bss} \, H_{Asr}}{H_{Ass} + H_{Bss}} \, F_{cr} \qquad (7)$$

Rewrite (3) using (6):

$$A_{Ct} = [H_{Ctr}]F_{Cr} = H_{Bts} \, [H_{Ass} + H_{Bss}]^{-1} H_{Asr} \, F_{Cr} \qquad (8)$$

Combine (7) and (8):

$$A_{Ct} = H_{Bts} \, H_{Bss}^{\,-1} A_{Cs} \qquad (9)$$

Introduce Norton-Thevenin [1] to relate the free acceleration (A_{As}) to the coupled acceleration at the boundary:

$$A_{Cs} = [H_{Ass}^{\,-1} + H_{Bss}^{\,-1}]^{-1} H_{Ass}^{\,-1} A_{As} \qquad (10)$$

Combine (9) and (10) to get desired expression of coupled payload response (A_{Ct}) as a function of LV free acceleration (A_{As}):

$$\boxed{A_{Ct} = H_{Bts} \, H_{Bss}^{\,-1} [H_{Ass}^{\,-1} + H_{Bss}^{\,-1}]^{-1} H_{Ass}^{\,-1} A_{As}} \qquad (11)$$

NTRC Time Domain Analysis
One implementation of Equation (11)

- NTRC is a frequency domain analysis technique
- FFT/IFFT processing is used to perform NTRC in the time domain
- Steps
  1. Perform transient analysis on LV to derive the free-acceleration (A_{As}) at payload interface
  2. Transform A_{As} to frequency domain via FFT. Extract positive frequency terms and remove the f=0 Hz term (save for later)
  3. Calculate accelerance (H) for payload and launch vehicle at common interface (consistent frequency range and delta-f).
  4. Derive NTRC transform and convert A_{As} to the coupled system interface acceleration (A_{Cs}) in the frequency domain

$$A_{Cs} = [H_{Ass}^{-1} + H_{Bss}^{-1}]^{-1} H_{Ass}^{-1} A_{As}$$

  5. Use IFFT to transform A_{Cs} back to the time domain (w/ f=0 term from FFT of A_{As})
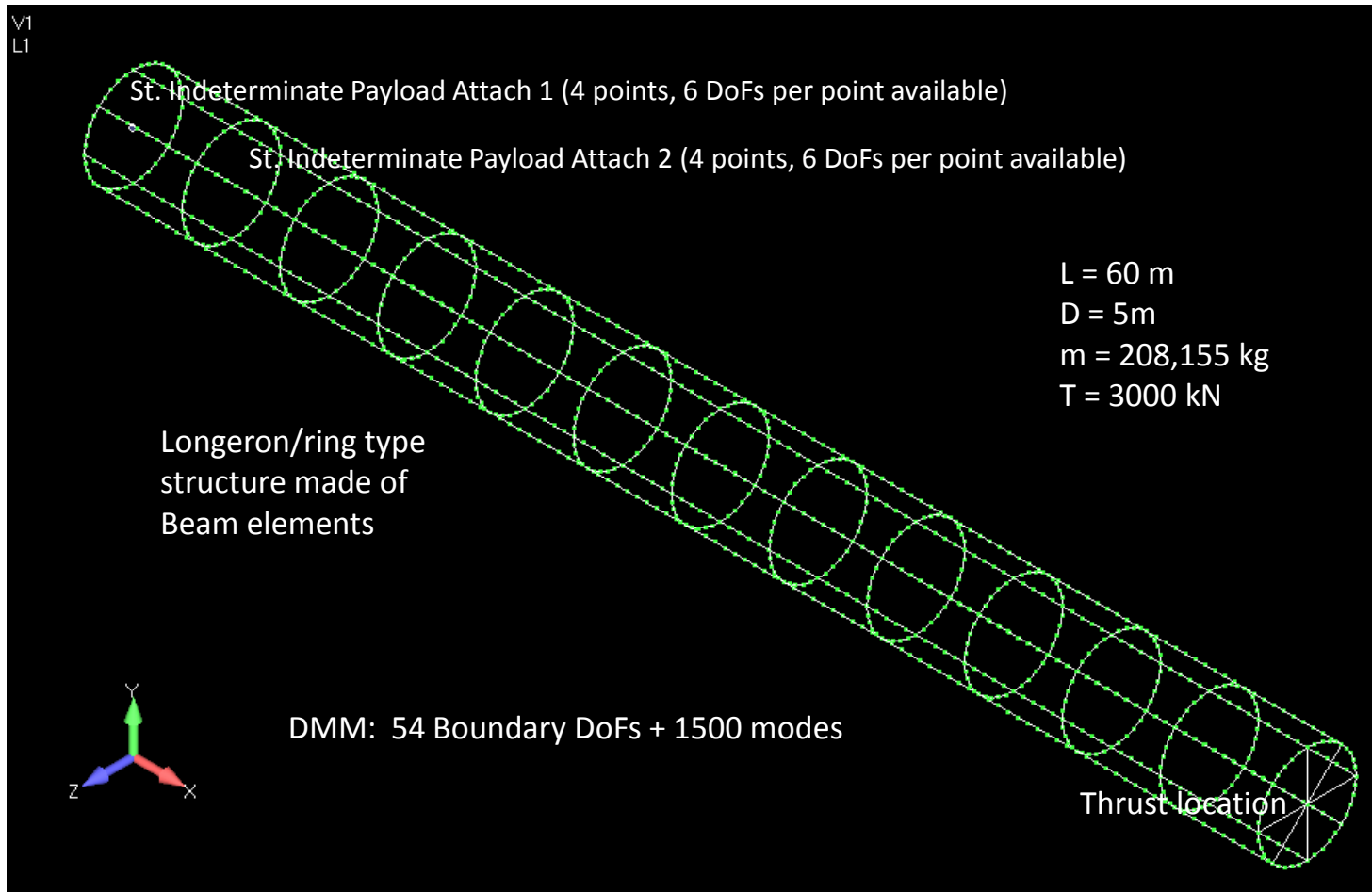 6. Basedrive PL with A_{Cs} to recover internal responses
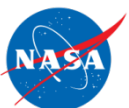
NESC Study

- Study approved December 2015, started January 2016
- NESC approved the funding for a 1year study with effort broken into Quarters
  - Quarter 1 = Frequency domain
    - Heavy payload
    - Determinate and indeterminate interfaces (24 DoFs)
    - Multiple payloads
  - Quarter 2 = Time domain (no steady-state)
    - FFT/IFFT processing
    - LV/Payload model truncation w/ residual vectors
  - Quarter 3 = SLS/Europa + non-linear pad separation study
    - SLS/Europa with in-house forcing functions (no steady).
    - Highly indeterminate interface (144 DoFs)
    - In-house pad separation models and non-linear liftoff simulations
  - Quarter 4 = Liftoff CLA
    - Use in-house non-linear simulation developed in Q3 for benchmarking
    - Liftoff pad sep with initial conditions and quasi-steady content
    - Delta IIH/GLAST [3]
- Additional Q5 Funding Added to benchmark against SLS liftoff and complete final report (Estimated Completion – August 2017)

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Launch Vehicle FEM

St. Indeterminate Payload Attach 1 (4 points, 6 DoFs per point available)

St. Indeterminate Payload Attach 2 (4 points, 6 DoFs per point available)

L = 60 m
D = 5m
m = 208,155 kg
T = 3000 kN

Longeron/ring type structure made of Beam elements

DMM: 54 Boundary DoFs + 1500 modes

Thrust location

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Heavy Payload FEM
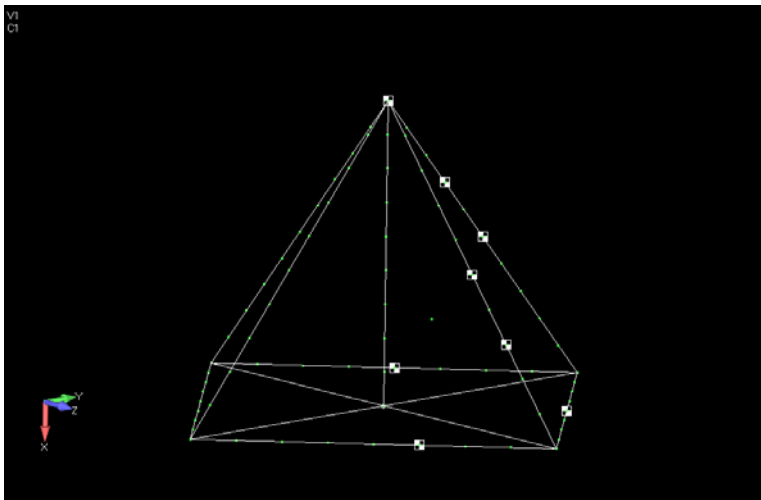
- Heavy payload FEM constructed to meet following requirements:
  - Weight: 3717 kg (8177 lbs)
  - Off-axis CoG
  - 1st lateral/rocking frequency 10-20 Hz (FEM: 10.6 Hz)
  - 1st axial frequency 20-40 Hz (FEM: 31.6 Hz)
    - All frequencies wrt st. det. constraints
- DMM: 24 physical DoFs + 200 modes
- Acceleration and Stress Transformation Matrices (ATM, STM) generated for internal response computations

NTRC Reminders

- Operates on LV free accelerations/accelerance at payload interface
  - No mass loading of interface required
  - Calculate LV free accelerations one time for multiple payload configurations
- Operates on the minimum possible set of coordinates to solve CLA problem. For in-house LV + PL example:
  - NTRC = 24 DoFs
  - CLA = 1554 + 224 – 24 = 1754 DoFs
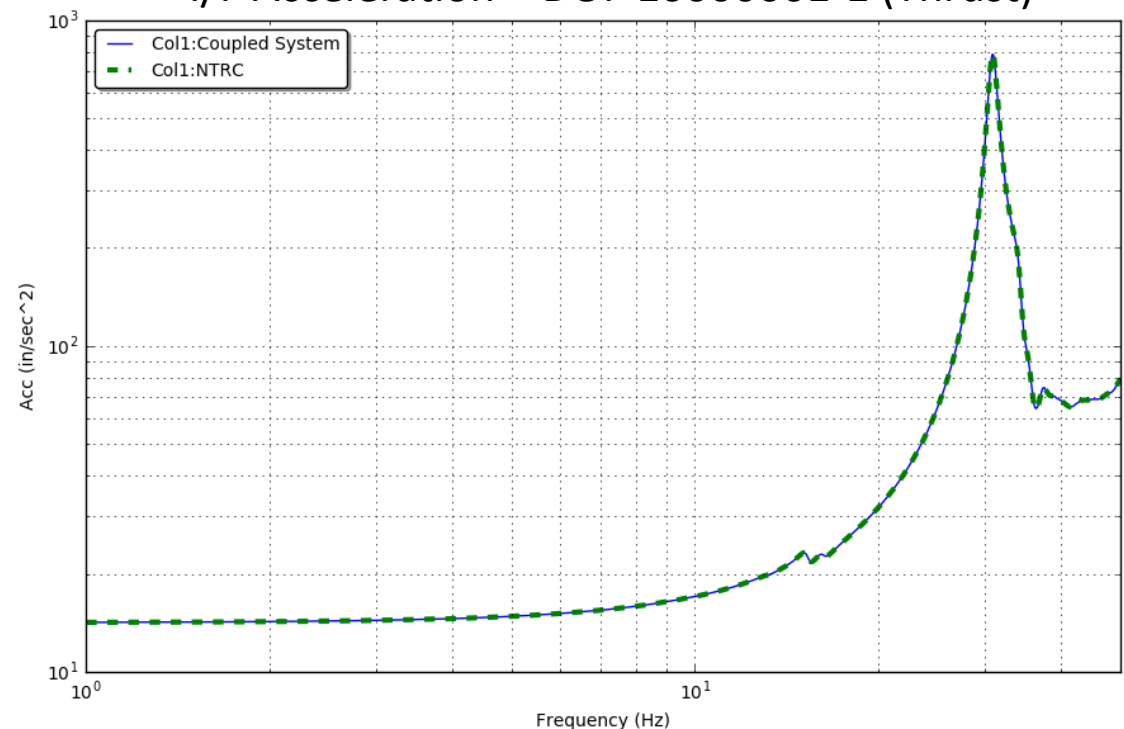- Solves in frequency domain
  - Fast executions

Frequency Domain Results

- NTRC in the frequency domain is exact
- Results match within numerical accuracy of analysis
- All Hurty Craig-Bampton (HCB) modes must be used **or**
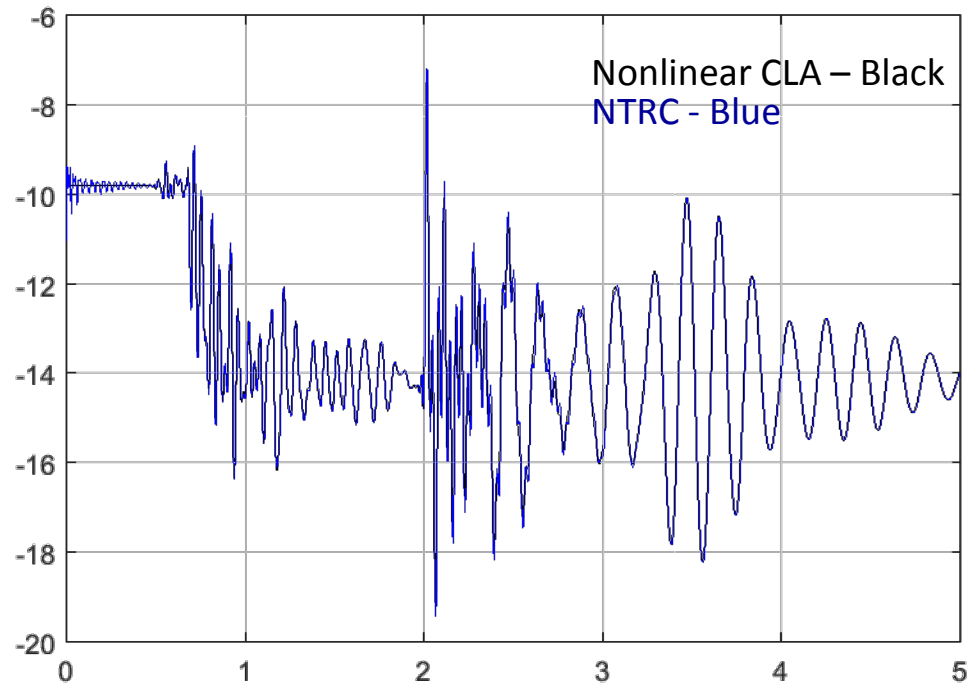- Free-free modes must be augmented with residual vectors

I/F Acceleration – DOF 10000001-1 (Thrust)

NTRC Time Domain Results

- NTRC results captures all relevant characteristics of a transient CLA
- NTRC matches CLA w/o steady-state to < 5%
- Time domain NTRC with steady-state matches CLA < 5% for significant payload responses
- Source of differences
  - Convergence of time domain analysis
  - FFT/IFFT processing
- Will continue to refine time domain analysis for Q5 activities (SLS)

I/F Acceleration – DOF 10000001-1 (Thrust)

Nonlinear CLA – Black
NTRC - Blue

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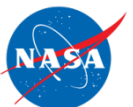
Items Addressed During NTRC Study

- Development of NTRC routines in Python
- Damping for free-free and HCB modes
- Use of residual vectors to address modal truncation
- Use of free-free vehicle modes for non-linear pad separation analysis
- Development of methodology to address transient analysis with steady-state
- Identification of time history artifacts(ringing) created by FFT/IFFT process and possible solution schemes.
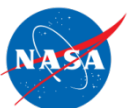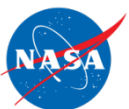
Upcoming Activities

- Benchmarking (Q5)
  - SLS + Europa Clipper - Liftoff
  - Delta II + GLAST – Liftoff and Airloads
- Release NESC report

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References

1. Mechanical Impedance: Modelling/Analysis of Structures, Vernon H. Neubert, 1987. Jostens Printing and Publishing Company, Science Park Road, State College, PA 16801

2. Flight Force Measurements on a Spacecraft to Launch Vehicle Interface, Kaufman, Daniel S.; Gordon, Scott A., Proceedings of the 12th European Conference on Spacecraft Structures, Materials and Environmental Testing, held 20-23 March, 2012 at ESTEC, the Netherlands. ESA SP-691. ISBN 978-92-9092-255-1., p.142

3. Cuppens, K., Sas, P., and Hermans, L., "Evaluation of the FRF Based Substructuring and Modal Synthesis Technique Applied to Vehicle FE Data," Proceedings of the Twenty-Fifth International Seminar on Modal Analysis, Leuven Belgium, September, 2000.

4. Arya Majed, Kevin Partin, Ed Henkel Applied Structural Dynamics, Inc., Houston, Texas and Thomas P. Sarafin, Instar Engineering and Consulting, Inc., Littleton, Colorado "Variational Coupled Loads Analyses: Reducing Risk in Development of Space-Flight Hardware"

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Summary

- NTRC is an alternate coupling approach that can be used to replicate a standard LV CLA

- NTRC developed as a design tool for payload community with the minimum information required from LV providers

- NTRC is exact for frequency domain analysis

- NTRC shows excellent agreement with results from time domain CLA

- Completion of SLS liftoff benchmarking and release of final report expected August 2017