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Analysis Driven Design:

Optimization of a Hexapod Isolator

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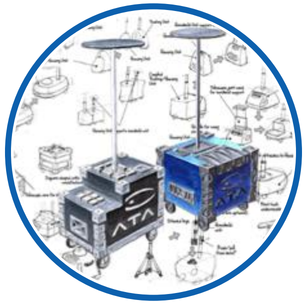
Prepared By:
Greg Mathy
Project Engineer
ATA Engineering
(858) 480-2087
greg.mathy@ata-e.com

Outline

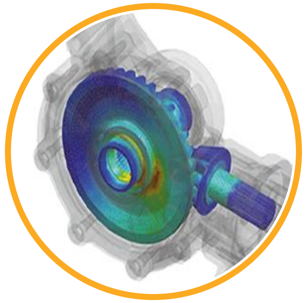
- Design and Analysis iterative workflow
- Hexapod Overview
  - Typical uses for hexapods
  - Design goals and constraints
- Increasing iteration speed with optimization and parametric modeling
  - Nastran Solution 200 (Sol200) overview
  - Practical application of Sol200 to optimize a hexapod
  - Parametric modeling of hexapod in NX CAE
  - Coupling Nastran Sol200 output data into NX CAE
- Interesting details
  - Local minima
  - Mode shape tracking
- Simple example deck of a cantilevered beam
  - Use Sol200 to find the beam length that results in a first bending mode of 200 Hz

Who is ATA Engineering?



Design

From initial concept development to detailed structural design



Analysis

Comprehensive structural, fluid, acoustic, and thermal analysis services

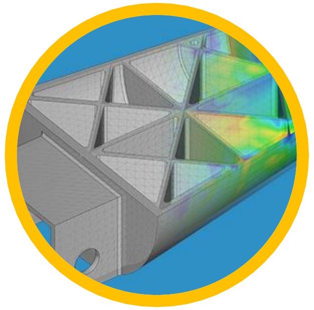
Test

Industry-leading structural test services for extreme loading environments

ATA is an employee owned engineering consulting firm that provides innovative solutions through test and analysis-driven design

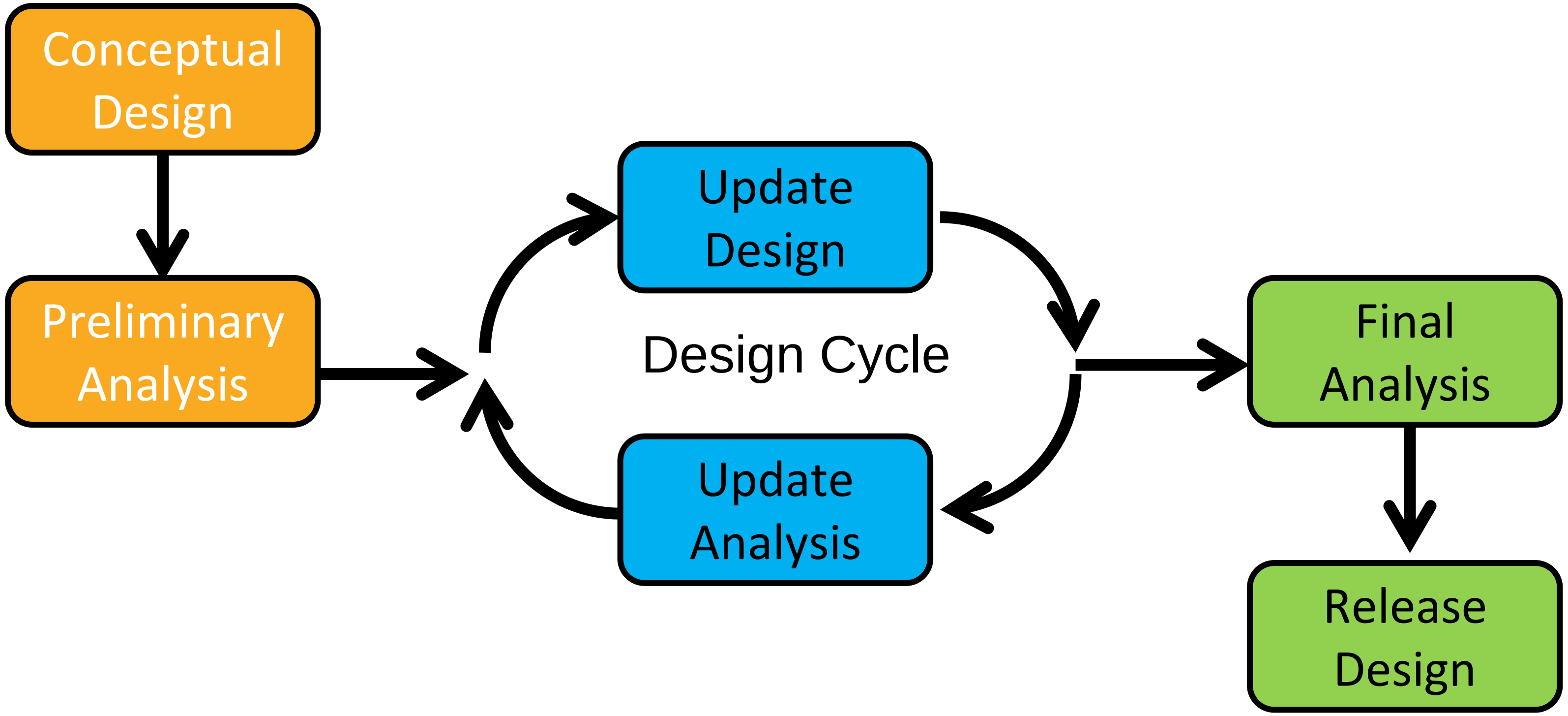
ATA's Software Services

ATA is a value-added reseller for Siemens PLM Software



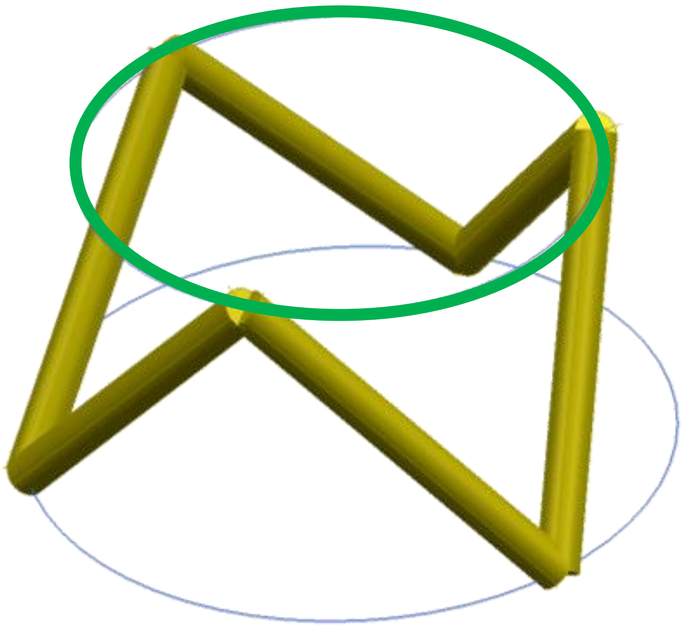
- Femap
- NX Nastran
- NX CAD, CAM, & CAE
- Teamcenter
- Solid Edge
- Developer of the official NX Nastran training materials
- Preferred North American provider of NX Nastran training

Design and Analysis Workflow



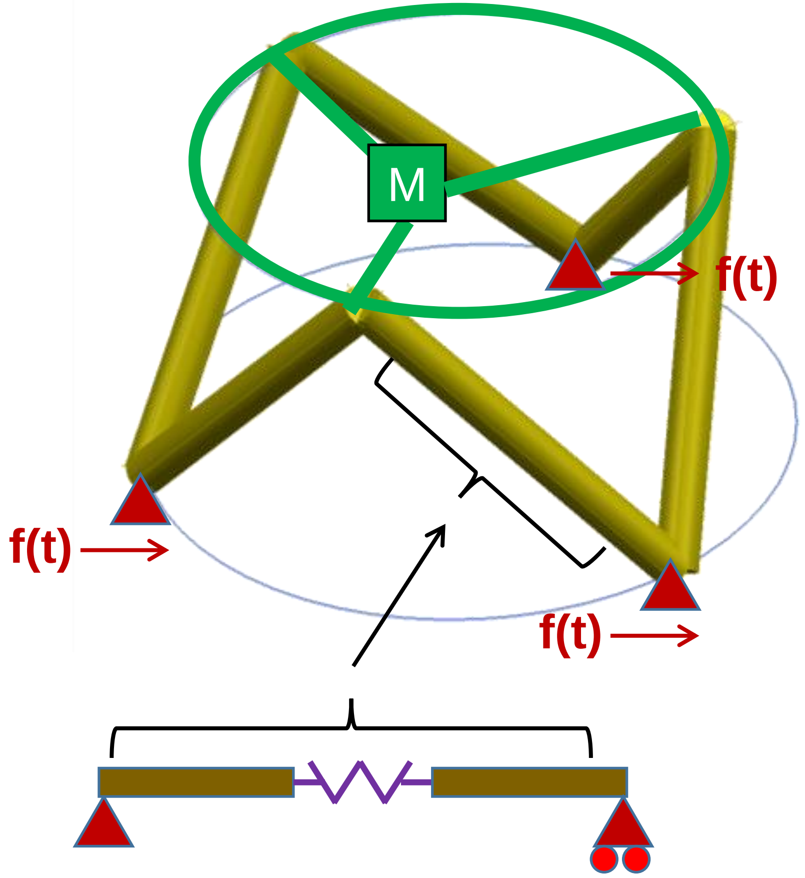
Hexapod Overview

- **A hexapod is a system of 6 uniaxial struts that attach two components**
  - The arrangement of 6 uniaxial struts results in a kinematic connection.
  - Hexapods are commonly found in many applications such as optics, isolators and motion simulators.
- **Hexapods can be active or passive**
  - An example of an active hexapod is one where linear actuators are used for struts. With that, the hexapod can control all 6 DOF independently between the two components. This type of hexapod could be used in a roller coaster motion simulator.
  - An example of a passive hexapod is a vibration isolator where each strut's axial stiffness is tuned to achieve a desirable modal frequency of the mounted component.



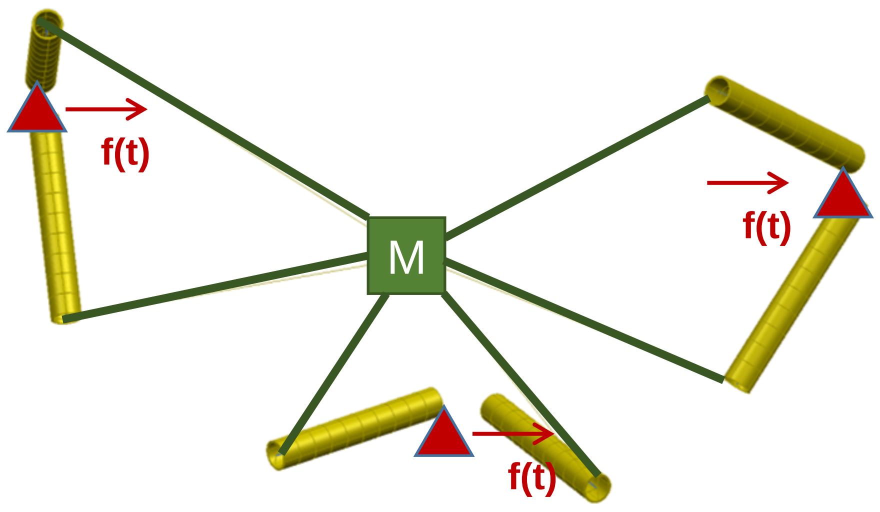
Passive Hexapod for Vibration Isolation: Theory

- Hexapod must isolate mass M from base excitation f(t)
- Hexapod stiffness tuned such that hexapod modes are far away from excitation frequency
- This can be achieved via sizing strut axial stiffness, or by introducing a compliant element in each strut (e.g. a soft spring in series with strut as shown in the lower right)



Passive Hexapod for Vibration Isolation: Practical Application

- **In general a passive hexapod isolator has 12 variables**
  - 6 strut vectors and 6 strut stiffnesses.
- **The isometric isolator shown on the previous slide would be relatively easy to optimize due to its symmetric nature**
  - The symmetry effectively reduces the system to 4 variables: strut stiffness, diameter of base ring, diameter of component ring, and vertical offset between base and component rings.
- **However many times it is not possible to have an isometric hexapod due to packaging constraints. An example of an asymmetric hexapod is shown to the right**
  - Now the system has all 12 variables and it is not intuitively obvious how to optimize the system.

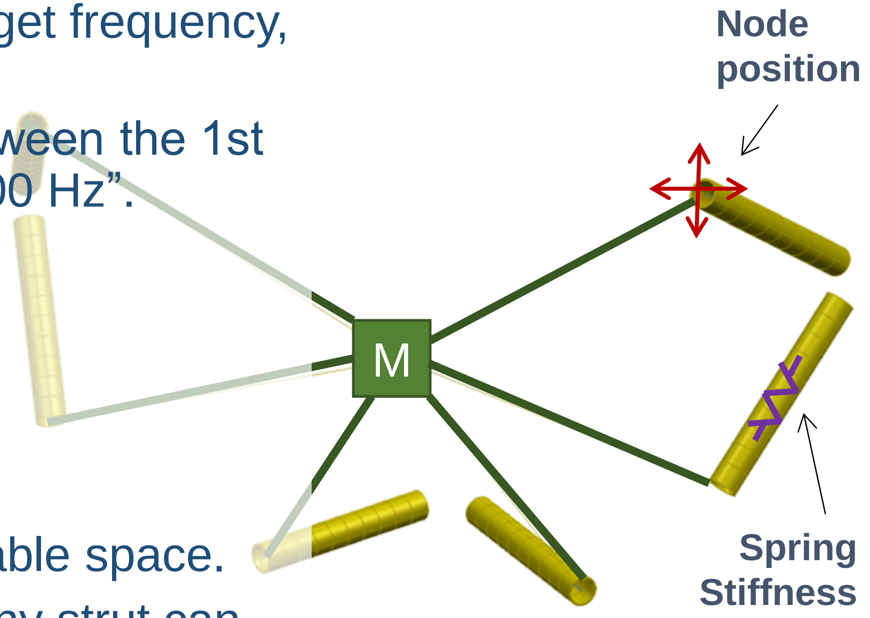


Nastran Solution 200 Overview

- **NASTRAN Sol200 is an iterative design modification methodology by which the performance of a design is improved through changes in the design**
- **To be successful, Sol200 requires careful definition of the design space**
  - What is the goal of the design? e.g. minimize stress, maximize stiffness, etc.
  - What are the allowable variables? e.g. material properties, element thickness, beam cross section, spring stiffness, nodal position.
  - What are the constraints? e.g. maximum or minimum thickness, allowable nodal position.

Defining The Hexapod’s Design Space

- **Goal**
  - Tune hexapod translational modal frequencies to be equal to a target frequency, say 100 Hz.
  - Can be alternatively phrased as “minimize the frequency band between the 1st mode and 3rd mode while keeping the modes centered around 100 Hz”.
- **Variables**
  - Nodal positions, all 3 DOF at 12 nodes.
  - Spring stiffnesses, 6 variables.
- **Constraints**
  - Nodal positions. Nodal positions limited to what can fit in the available space.
  - Spring stiffnesses. Stiffness ratio amongst struts limited to 3. i.e. any strut can only be 3x as stiff as any other strut.



How to Input Variables in Sol200

- **Each design variable is defined with two cards**
  - **DESVAR**: This defines a variable as well as its bounds.
  - **DVXXXX**: This defines the relationship between the design variable (DESVAR) and the varying data (e.g. grid location or physical property card).
- **For example, the deck below defines a design variable that varies the K3 term on PBUSH 31**

```
$--1--->$--2--->$--3--->$--4--->$--5--->$--6--->$--7--->$--8--->$--9--->
DESVAR       101SPRG_VAR      1.      .1     10.
DVPREL1      101   PBUSH      31      K3                  0.0000        +
+            101    1.+6
```

- **The deck below defines a design variable that varies the Z position of Grid #3**

```
$--1--->$--2--->$--3--->$--4--->$--5--->$--6--->$--7--->$--8--->$--9--->
DESVAR       102 GRD_VAR      1.      0.      7.
DVGRID       102       2       0     10.      0.      0.      1.
```

How to Input Constraints in Sol200

- **Design constraints typically require 3 cards**
  - **DCONSTR** is the definition of the constraint.
  - **DRESPX** extracts design variable data for use in constraint and/or objective functions
  - **DEQATN** defines an equation that can be used to define constraints.
- **For example the deck below constrains the stiffness ratio amongst the struts to be < 3**

```
$Define equation 516 = K_ratio - 3
DEQATN       516   F2(K1,K2,K3) = MAX(K1,K2,K3)/MIN(K1,K2,K3)-3.
$
$Extract K1,K2,K3 design variables for use in equation 516
DRESP2       303    stiff     516
          DESVAR      101     102     103
$
$Constrain Kmax/Kmin < 3 (Kmax/Kmin-3<0)
DCONSTR      201      303             0.
```

How to Input Goals in Sol200

- **Goals are defined in a similar fashion to constraints**
  - **DRESPX** extracts design variable data for use in constraint and/or objective functions.
  - **DEQATN** defines an equation that can be used to define goal.
  - **DESOBJ** is used to define the design objective.
- **For example the deck below defines the design objective of getting the first 3 modes as close to 100 Hz as possible, i.e. minimize the frequency band between the 1st mode and the 3rd mode**

```
$Define equation that is the sum of the modal deviations from 100 Hz
DEQATN       515  F1(W1,W2,W3) = (W1-100.)**2 + (W2-100.)**2 + (W3-100.)**2
$
$Extract the first 3 modal frequencies and define their use in equation 515
DRESP1       601       W1     FREQ                                1
DRESP1       602       W2     FREQ                                2
DRESP1       603       W3     FREQ                                3
DRESP2       302      obj      515
          DRESP1      601      602      603
$
$Define the design objective (note this is in Case Control)
DESOBJ(MIN) = 302
```

NASTRAN Sol200 Details

- Converged DESVAR values can be found in the f06 file of a Sol200 solution as shown below

INTERNAL DV. ID.	EXTERNAL DV. ID.	LABEL	54	55	56	57
1	101	SPRG_VAR	3.8283E-01	3.8574E-01	3.8376E-01	3.8376E-01
2	102	GRD_VAR	1.1485E+00	1.1438E+00	1.1513E+00	1.1513E+00

```
*** USER INFORMATION MESSAGE 6464 (DOM12E)
    RUN TERMINATED DUE TO HARD CONVERGENCE TO AN OPTIMUM AT CYCLE NUMBER =        57.
```

- Note that these are the converged values of the DESVARs and are not the final values of the parameter. E.g. the final spring stiffness is not 0.38376. Rather the value 0.38376 is the scale factor used by the DVPREL card
- In our case the DVPREL card scales the data by 1e6, so the final spring stiffness is 3.83e5

Building a Parametric Model in NX

- A parametric model is a model that is built using a system of parameters
- In our case, the model has 18 parameters
  - 12 strut end points.
  - 6 spring stiffnesses.
- When built properly, a parametric model allows for automatic geometry and FEM updates with simple changes to the parameters
- Use of this approach is critical for increasing the speed of the design/analysis cycle

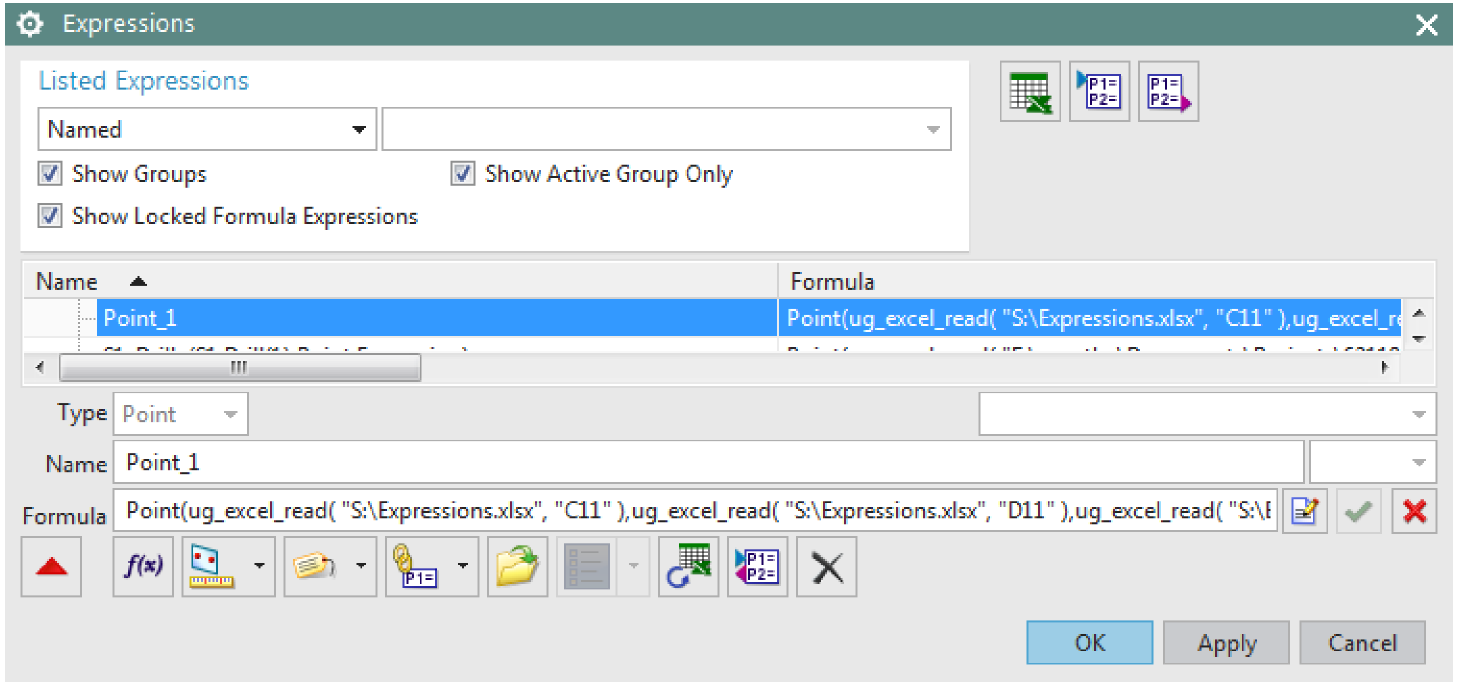
Using Expressions

- First create "expressions" for each point

Choose "Point" as type

Create a convenient label

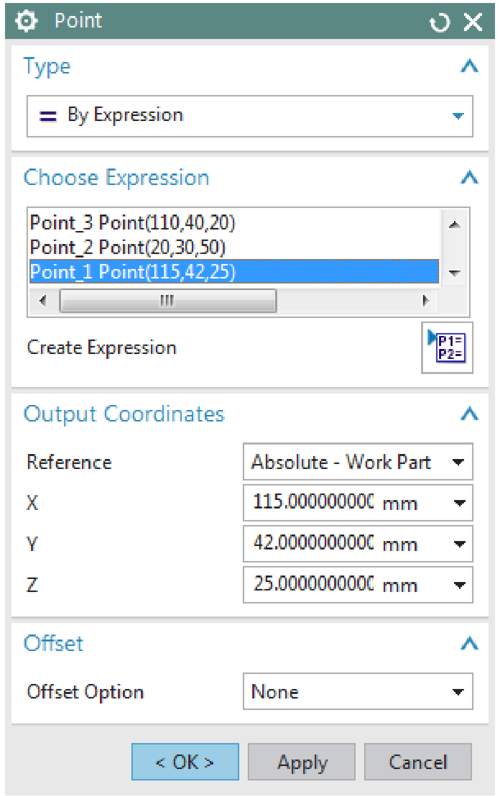
Define XYZ coordinates*

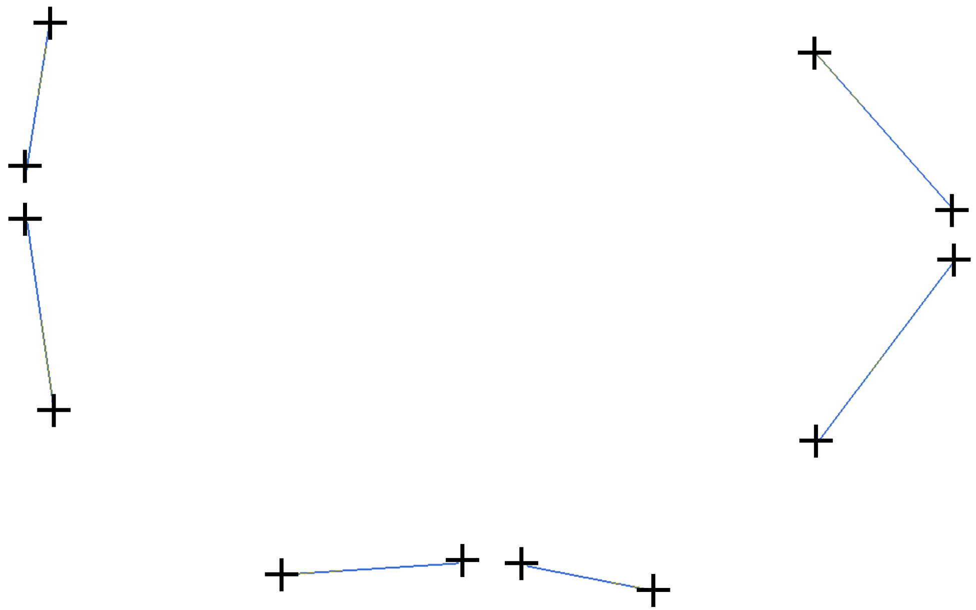


*You can enter in coordinates directly as, Point(X,Y,Z)
OR
You can link them to an Excel file as is done above. The formula above takes data from cell C11 of "Expressions.xlsx" for the X coordinate of Point_1

Define Points Using Expressions

- Create points and choose “By Expression” for the type.
- Then select the appropriate expression





Simulation is Now Linked to Excel File

	Strut End Points [mm]		
	X	Y	Z
Point 1	15	42	25
Point 2	20	30	50
Point 3	110	40	20
Point 4	17	46	28
Point 5	22	33	55
Point 6	121	44	22
Point 7	18	51	30
Point 8	24	36	61
Point 9	133	48	24
Point 10	20	56	33
Point 11	27	40	67
Point 12	146	53	27

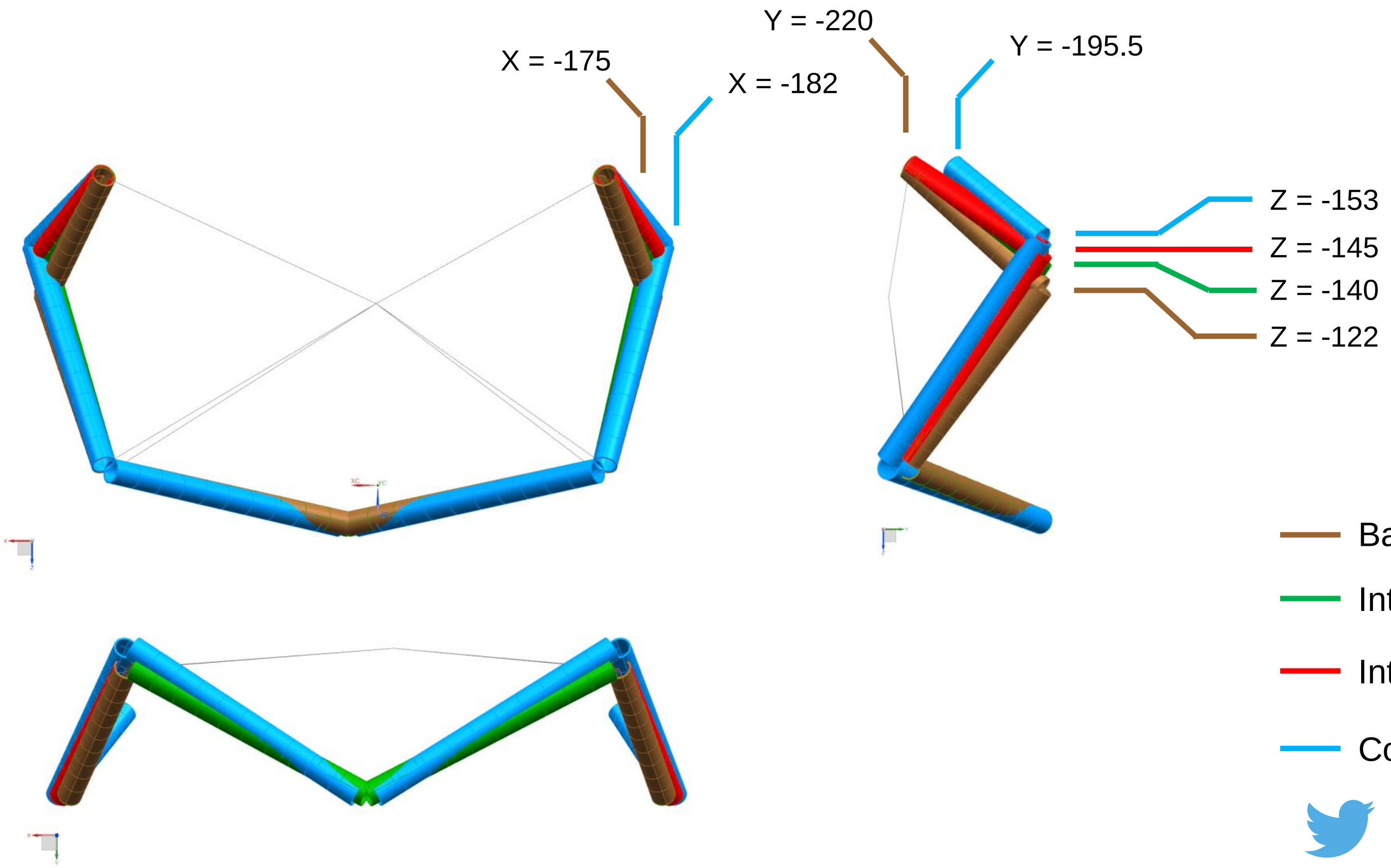
Stiffness [N/mm]	
Strut 1	100
Strut 2	200
Strut 3	300
Strut 4	100
Strut 5	200
Strut 6	300

- Entire hexapod model can now be controlled by the data in the “Expressions.xlsx” Excel file as shown to the left
- Data from NASTRAN Sol200 can be pasted directly to excel to update the desired parameters

Updating NX Expressions with Sol200 Results

- **NASTRAN f06 data gives optimized design variable values**
- **Remember that the DESVAR values are not the value of the parameter. They must be multiplied by the appropriate sensitivities to get the final value**
- **For example, DESVAR 102 varied the Z position of Grid #3, but it had a COEFF factor of 10**
  - Therefore final position of Grid 3 is calculated as follows:
  - $Grid_{final} = Grid_{initial} + COEFF\left(DESVAR_{final} - DESVAR_{initial}\right)$

Optimization Summary



Frequency Band is the frequency of the 3rd mode minus the frequency of the first mode.

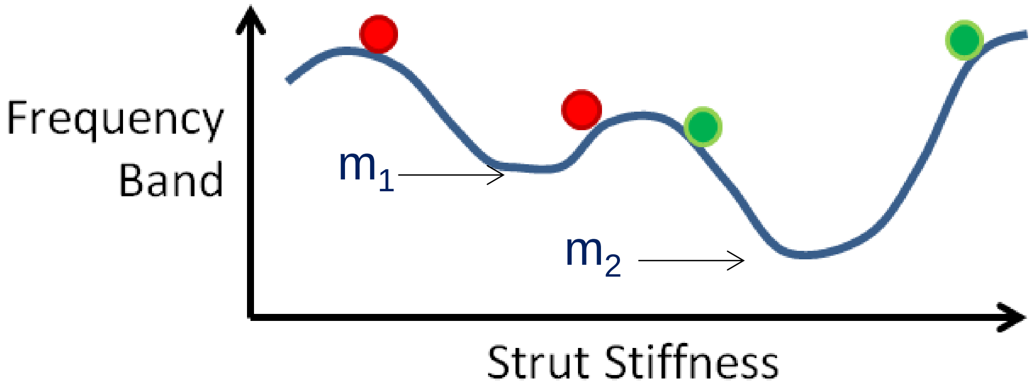
Goal of optimization was to minimize size of band and center modes on 100 Hz.

Sol200 reduced frequency band from 25 Hz to 8 Hz.

- Baseline, 25 Hz band
- Intermediate 1, 18 Hz band
- Intermediate 2, 15 Hz band
- Converged, 8 Hz band

Local Minima

- Sol200 may converge in a local minima and miss a better global minimum
- In the case of the hexapod optimization, we manually perturbed the initial conditions to a few different starting points to check for these effects
- This was done by manually moving nodes in the input deck and resolving the solution



- Initial conditions that lead to m_1 minimum
- Initial conditions that lead to m_2 minimum

Mode Shape Tracking

- **Mode tracking is useful when specific eigenvalues are being optimized and need to be consistently identified**
  - For example: first bending mode, first torsional mode, etc.
- **Modes are "tracked" based on a cross-orthogonality check between mode shapes of the current and previous designs:**
  - Modes with the largest cross-orthogonality are paired.
  - Allows for mode order switching.
- **Mode tracking is requested by Case Control entry: MODTRAK**
- **Parameters for mode tracking are specified by Bulk Data Entry: MODTRAK**

Cantilever Beam Example

```
ID,NASTRAN,Cantilevered_Beam
SOL 200
CEND
$
DESOBJ(MIN) = 301
$
ECHO = NONE
SPC = 1
OUTPUT
DISPLACEMENT(PLOT,REAL) = ALL
METHOD = 101
ANALYSIS = MODES
$
BEGIN BULK
$
EIGRL        101                         10        0        7               MASS
$
PARAM       K6ROT    100.0
PARAM      OIBULK      YES
PARAM     OMACHPR      YES
PARAM        POST       -2
PARAM     POSTEXT      YES
```

Objective

Variables

Note different COEFF values are used to keep nodes from overlapping

Objective equation

Mode extraction

```
$
GRID           1       0      0.      0.      0.       0
GRID           2       0      2.      0.      0.       0
GRID           3       0      4.      0.      0.       0
GRID           4       0      6.      0.      0.       0
GRID           5       0      8.      0.      0.       0
GRID           6       0     10.      0.      0.       0
$
CBAR           1       2       1       2      0.      1.      0.
CBAR           2       2       2       3      0.      1.      0.
CBAR           3       2       3       4      0.      1.      0.
CBAR           4       2       4       5      0.      1.      0.
CBAR           5       2       5       6      0.      1.      0.
$
PBARL          2       1            TUBE                                    +
+             .5    .375
$
MAT1           1    1.+7            0.33  2.59-4
$
SPC            1       1  123456      0.
$*
DESVAR       101  Node_X      1.     -5.      5.
DVGRID       101       2       0      1.      1.      0.      0.
DVGRID       101       3       0      2.      1.      0.      0.
DVGRID       101       4       0      3.      1.      0.      0.
DVGRID       101       5       0      4.      1.      0.      0.
DVGRID       101       6       0      5.      1.      0.      0.
$
DEQATN       501  F1(W1) = (W1-200.)**2
$
DRESP1       601      w1    FREQ                           1
DRESP2       301     obj     501
          DRESP1     601
$
ENDDATA
```

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