## Shuttle Second Stage with a Flexible Payload Mounted on Coulomb Dampers

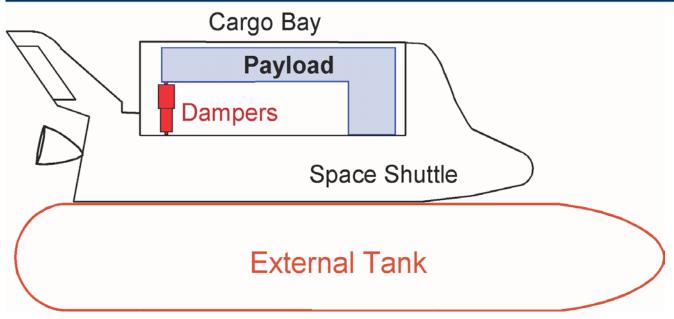


Figure 1 Payload is rigidly attached in one side to the bottom of the Shuttle cargo bay and on the other side it is attached to the cargo bay by means of two Coulomb Dampers.

Control engineers are often challenged with dynamics and control interaction problems that require smart control design solutions that include flexibility compensation filters. There are some situations, however, where the only practical and robust solution to structural instability is a mechanical fix. The following example presents such a design challenge requiring a non-linear control analysis approach and the application of the Describing Function (DF) method because it involves non-linearities and the presence of limit-cycles due to structural vibrations. This problem was predicted on the Space Shuttle 2<sup>nd</sup> stage ascent in a mission where it was carrying a large and flexible payload and shortly after separating from the solid rocket boosters. Linear analysis indicated that this heavy and flexible payload had the potential of causing flex mode instability. A software fix using a notch filter was not practical because the modal resonance was very strong and at low frequency. Filtering would deteriorate the rigid-body phase margin and degrade robustness. A hardware solution was implemented instead by mounting a pair of non-linear coulomb dampers to attenuate this structural instability to acceptably small oscillation levels.

Figure 1 shows the attachment of the flexible payload inside the Shuttle cargo bay. The payload is rigidly attached to the Shuttle on the forward side and on the other side it is attached to the Shuttle by means of two coulomb dampers. The coulomb dampers are non-linear energy dissipating devices (shock absorbers) connected between the payload and the cargo bay. Figure 2 shows the Shuttle payload mounting mechanism inside the cargo bay. The partially shown payload is mounted inside a cradle. The front side of the cradle is directly attached to the Shuttle cargo bay and the rear side of the cradle is attached to the cargo bay by means of the two dampers. One damper is on the left side of the cradle and the other is on the right side. The purpose of the coulomb dampers is to attenuate structural vibrations which otherwise would have been divergent if the payload was directly attached to the vehicle structure on both sides.

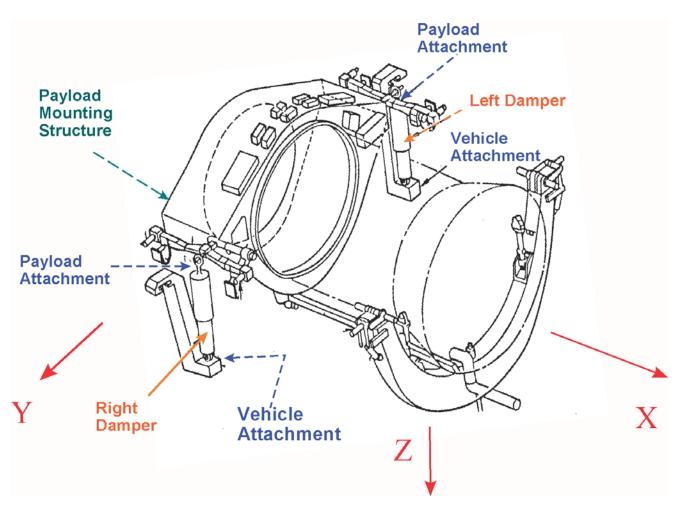


Figure 2 The Payload Cradle is attached on the aft side of the Payload Bay by means of two Coulomb Dampers.

## **Analysis Overview**

In the analysis that follows we will demonstrate the structural instability of the payload and introduce the mechanical dampers that will attenuate it. The purpose of this example is to analyze the dynamic interaction between the flexible structure and the non-linear Coulomb dampers. We will use the Describing Function method to estimate the size and frequency of the limit-cycles caused by the nonlinear devices, and simulations to validate the stability analysis. The files for this Shuttle second stage analysis example are located in directory "*Flixan*/*Examples*/*Payload Damper*". The input data file is already prepared in file "*Stg2\_Damper.Inp*". The title of the vehicle data-set is "*Shuttle Second Stage with Payload Damper, at T=123 sec*". The Matlab analysis files are located in subdirectory "*Payload Damper*/*Matan*". The input data file "*Stg2\_Damper.Inp*" can be processed quickly by running the batch set located on the top of the file "*Batch for evaluating Shuttle Coulomb Damper stability*", as shown below. However, for tutorial purposes we will demonstrate the execution of each data-set separately. The following analysis we will be performed in the upcoming sections:

- Extract a set of structural modes and develop linear dynamic models with flexibility for the Shuttle vehicle during second stage.
- Generate state-space models for the engine actuators, sensors, TVC, and the flight control system.

- Combine the continuous vehicle, actuators, TVC, and sensors into a plant system and discretize it using a sampling rate of 40 msec.
- Convert the vehicle and the flight control systems to Matlab format and perform classical stability analysis in Matlab/ Simulink.
- Create a dynamic model for the Coulomb damper and derive its Describing Function (DF)
- Use the Describing Function methodology in the frequency domain using Nichols charts to analyze limit-cycle stability of the flight control system.
- Create time-domain simulations to validate the limit-cycle predictions from the DF analysis.

## Batch processing of the input file "Stg2\_Damper.Inp".

Utilities File Management Program Functions View Quad Help	
Managing Input Files (.Inp)   Edit / Process Batch Data Sets	
Managing System Files (.Qdr)   Edit / Process Input Data Files	
Managing Input Data Files	
To Manage an Input Data File, Point to the Filename and Click on "Select Input File" The following Input Data Sets are in File: Stg2_Damper.Inp	Exit
Stg2_Damper.Inp Select Input File Run Batch Mode : Batch for evaluating Shuttle Coulomb Damper stability	
Stg2_Damper.Inp         Edit Input File         Shuttle         Shuttle         Main Engine Hydraulic Actuator (Type-I)           System Connection:         Actuator/IVC (Second Stage)	
Process Input Data         Transf-Functions         Sensor Dynamics           System Connection:         Plant Model, Vehicle/Actuators/Sensors         S-Z-Transform         : Plant Model, Vehicle/Actuators/Sensors	
S-Z-Transform         : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.002)           Delete Data Sets in File         Transf-Functions : Shuttle Stage-2 Discrete Flight Control System	
Relocate Data Set in File To Matlab Format : Plant Model, Vehicle/Actuators/Sensors	
To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)           CopySetto Another File         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.002)           To Matlab Format : Shuttle Stage-2 Continuous Filght Control System	
View Data-Set Comments	
Comments, Data-Set User Notes This batch set generates models for the Space Shuttle Ascent Stage-2 that will be used for non-linear stability analysis using the Describing Function Method.	
This burror set generates moders for the space sharthe riscent stages, that will be used for home means stagenty analysis using the describing function method.	
	-
	T
Managing Input Data Files	T
Managing Input Data Files To Manage an Input Data File, Point to the Filename and Click on "Select Input File" The following Input Data Sets are in File: Sta2 Damper.Inp	Exit
To Manage an Input Data File, Point to the Filename and Click on "Select Input File" The following Input Data Sets are in File: Sta2 Damper.Inp Batch Mode Execution	Exit
To Manage an Input Data File, Point to the Filename and Click on "Select Input File" The following Input Data Sets are in File: Sta2 Damper.Inp Batch Mode Execution  Flight Vehicle : Shuttle Second Stage with Payload Damper, at T=123 sec Actuator Model : Shuttle Main Engine Hydraulic Actuator (Type-I)	Exit
To Manage an Input Data File, Point to the Filename and Click on "Select Input File" The following Input Data Sets are in File: Sto2 Damper.Inp Batch Mode Execution Filight Vehicle : Shuttle Second Stage with Payload Damper, at T=123 sec Actuator Model : Shuttle Main Engine Hydraulic Actuator (Type-I) System Connection : Actuators/TVC (Second Stage) Transf-Function : Sensor Dynamics System Connection : Plant Model. Vehicle/Actuators/Sensors T=0.04)	Exit
To Manage an Input Data File, Point to the Filename and Click on "Select Input File" The following Input Data Sets are in File: Sto2 Damper.Inp Batch Mode Execution  Flight Vehicle : Shuttle Second Stage with Payload Damper, at T=123 sec Actuator Model : Shuttle Main Engine Hydraulic Actuator (Type-I) System Connection: Actuators/TVC (Second Stage) Transf-Function : Sensor Dynamics System Connection: Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04) S-Z-Transform : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)	Exit
To Manage an Input Data File, Point to the         Filename and Click on "Select Input File"       The following Input Data Sets are in File: Sta2 Damper.Inp         Batch Mode Execution       Flight Vehicle : Shuttle Second Stage with Payload Damper, at T=123 sec         Actuator Model : Shuttle Main Engine Hydraulic Actuator (Type-I)       System Connection: Actuators/TVC (Second Stage)         Transf-Function : Sensor Dynamics       System Connection: Plant Model, Vehicle/Actuators/Sensors         System Connection: Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       T=0.04)         S-2-Transform : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.002)       Transf-Function : Shuttle Stage-2 Continuous Flight Control System         Transf-Function : Shuttle Stage-2 Continuous Flight Control System       Sec, Mixed Modes	Exit
To Manage an Input Data File, Point to the         Filename and Click on "Select Input File"       The following Input Data Sets are in File: Sto2 Damper.Inp         Batch Mode Execution       Event Sets are in File: Sto2 Damper.Inp         Flight Vehicle : Shuttle Second Stage with Payload Damper, at T=123 sec       Actuator Model : Shuttle Main Engine Hydraulic Actuator (Type-I)         System Connection: Actuators/TVC (Second Stage)       Transf-Function : Sensor Dynamics       a T=0.04)         System Connection: Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       a T=0.04)       a T=0.02)         S-Z-Transform : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.002)       Transf-Function : Shuttle Stage-2 Continuous Flight Control System       To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       a T=0.04)       sec, Mixed Modes	Exit
To Manage an Input Data File, Point to the         Filename and Click on "Select Input File"       The following Input Data Sets are in File: Sto2 Damper.Inp         Batch Mode Execution       Flight Vehicle : Shuttle Second Stage with Payload Damper, at T=123 sec         Actuator Model : Shuttle Main Engine Hydraulic Actuator (Type-I)       sec         System Connection: Actuators/TVC (Second Stage)       Transf-Function : Sensor Dynamics         System Connection: Plant Model, Vehicle/Actuators/Sensors       1 T=0.04)         S-2-Transform : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.002)       1 T=0.002)         Transf-Function : Shuttle Stage-2 Continuous Flight Control System       sec, Mixed Modes         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       a T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       a T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       a T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       a T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       a T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       a T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       a T=0.04)         To Matlab Format : Plant Model, Vehicle/Actu	Exit
To Manage an Input Data File, Point to the         Filename and Click on "Select Input File"       The following Input Data Sets are in File: Sto2 Damper.Inp         Batch Mode Execution       Flight Vehicle : Shuttle Second Stage with Payload Damper, at T=123 sec         Actuator Model : Shuttle Main Engine Hydraulic Actuator (Type-I)       sec         System Connection: Actuators/VVC (Second Stage)       r=0.04)         Transf-Function : Sensor Dynamics       sec         System Connection: Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       s=0.002)         S-2-Transform : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       sec, Mixed Modes         Transf-Function : Shuttle Stage-2 Continuous Flight Control System       sec, Mixed Modes         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       sec, Mixed Modes         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       sec, Mixed Modes	Exit
To Manage an Input Data File, Point to the Filename and Click on "Select Input File"       The following Input Data Sets are in File: Sto2 Damper.Inp         Batch Mode Execution       Flight Vehicle : Shuttle Second Stage with Payload Damper, at T=123 sec Actuator Model : Shuttle Main Engine Hydraulic Actuator (Type-I) System Connection: Actuators/TVC (Second Stage) Transf-Function : Sensor Dynamics System Connection: Plant Model, Vehicle/Actuators/Sensors       ty         S-2-Transform : Plant Model, Vehicle/Actuators/Sensors       1 T=0.04)         S-2-Transform : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.002)       n T=0.002)         Transf-Function : Shuttle Stage-2 Discrete Flight Control System Transf-Function : Shuttle Stage-2 Discrete Flight Control System To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       n T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       n T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       n T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       n T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       n T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       n T=0.02)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       n T=0.02)	Exit
To Manage an Input Data File, Point to the Filename and Click on "Select Input File"       The following Input Data Sets are in File: Sto2 Damper.Inp         Batch Mode Execution       Flight Vehicle : Shuttle Second Stage with Payload Damper, at T=123 sec Actuator Model : Shuttle Main Engine Hydraulic Actuator (Type-I) System Connection: Actuators/TVC (Second Stage) Transf-Function : Sensor Dynamics System Connection: Plant Model, Vehicle/Actuators/Sensors       ty         S-2-Transform : Plant Model, Vehicle/Actuators/Sensors       1 T=0.04)         S-2-Transform : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.002)       n T=0.002)         Transf-Function : Shuttle Stage-2 Discrete Flight Control System Transf-Function : Shuttle Stage-2 Discrete Flight Control System To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       n T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       n T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       n T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       n T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       n T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       n T=0.02)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       n T=0.02)	Exit
To Manage an Input Data File, Point to the         Filename and Click on "Select Input File"       The following Input Data Sets are in File: Sto2 Damper.Inp         Batch Mode Execution       Flight Vehicle : Shuttle Second Stage with Payload Damper, at T=123 sec         Actuator Model : Shuttle Main Engine Hydraulic Actuator (Type-I)       sec         System Connection: Actuators/TVC (Second Stage)       Transf-Function : Sensor Dynamics         System Connection: Plant Model, Vehicle/Actuators/Sensors       1 T=0.04)         S-2-Transform : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.002)       1 T=0.002)         Transf-Function : Shuttle Stage-2 Continuous Flight Control System       sec, Mixed Modes         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       a T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.04)       a T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       a T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       a T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       a T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       a T=0.04)         To Matlab Format : Plant Model, Vehicle/Actuators/Sensors (Z-Transform T=0.02)       a T=0.04)         To Matlab Format : Plant Model, Vehicle/Actu	Exit
To Manage an Input Data File, Point to the         Filename and Click on "Select Input File"       The following Input Data Sets are in File: Sto2 Damper Input Data Sets are	Exit