Shuttle Second Stage with a Flexible Payload Mounted on Coulomb Dampers

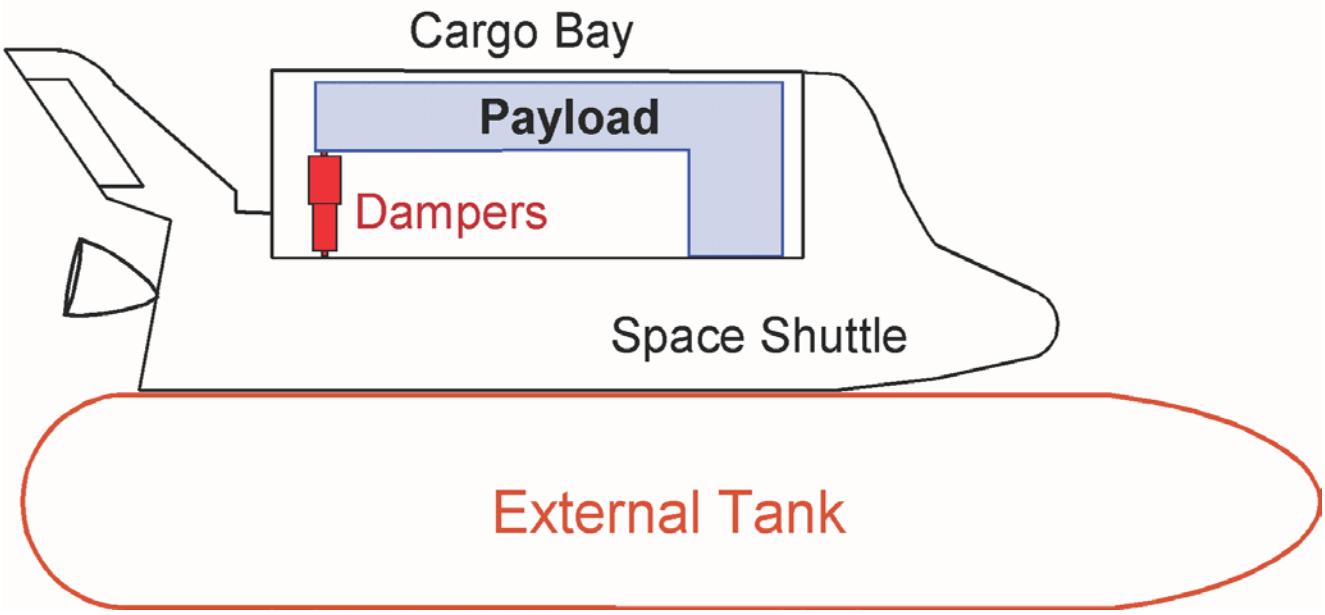

Figure 1 Payload is rigidly attached in one side to the bottom of the Shuttle cargo bay and on the other side it is attached to the cargo bay by means of two Coulomb Dampers.

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 2nd 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.

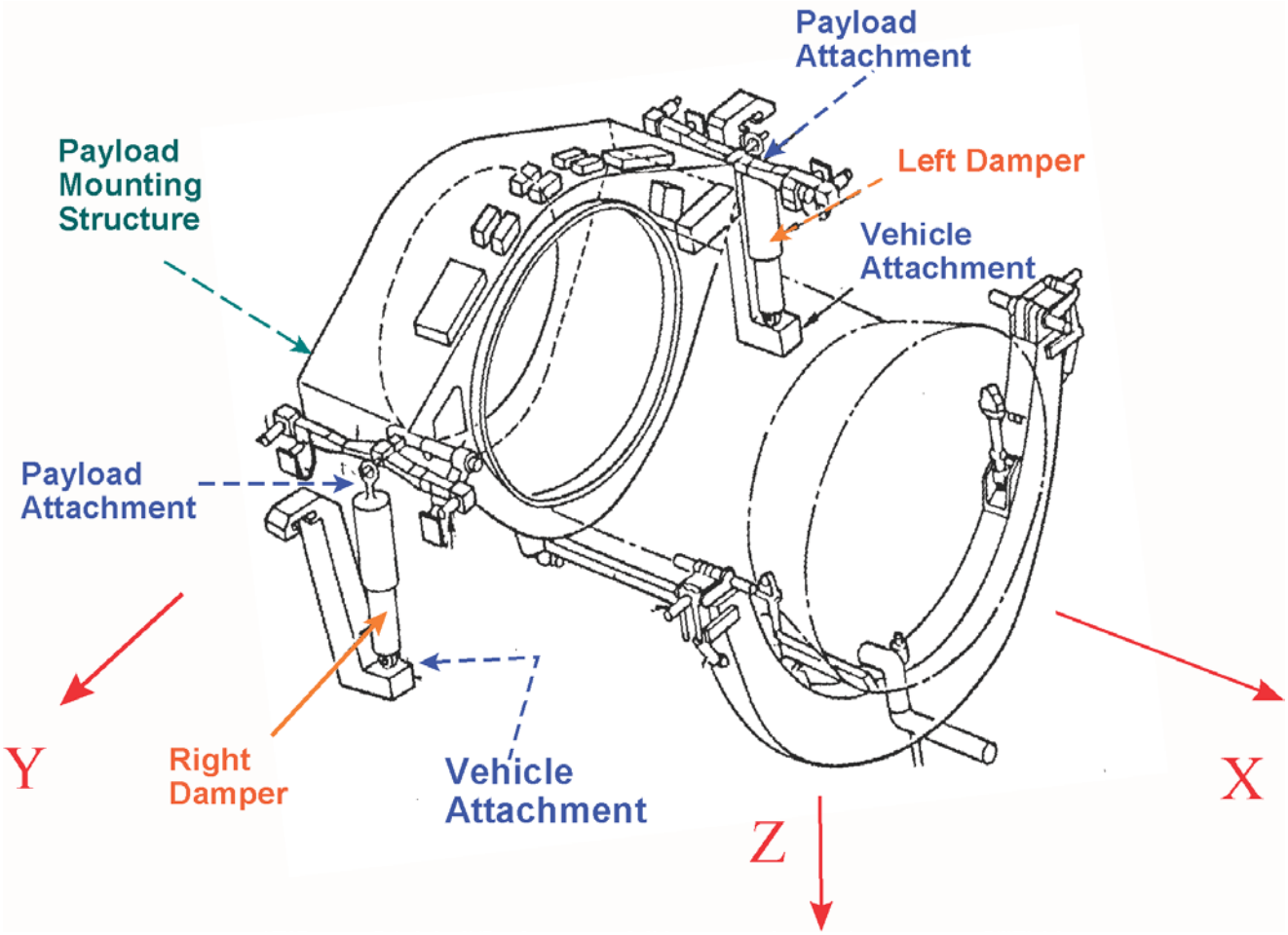

Figure 2 The Payload Cradle is attached on the aft side of the Payload Bay by means of two Coulomb Dampers.

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 non-linear 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*".