SIX DEGREES OF FREEDOM VIBRATION TESTING OF SPACECRAFT AND LAUNCH VEHICLES

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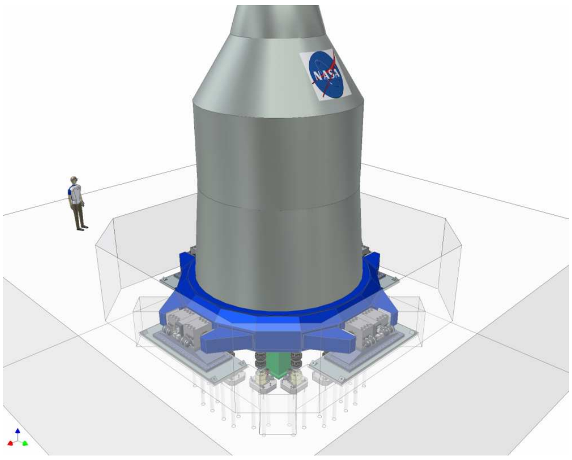
ABSTRACT

Testing of large payloads and full launch vehicles can require more force than can be produced by a single actuator. One solution to this problem is a table with multiple actuators to produce the higher force levels. These systems include hydrostatic bearings and couplings that may also allow the table to produce multiple degree of freedom of vibration. This configuration presents a number of challenges for the vibration control system. In this paper, we describe a novel multi-axis sine vibration control system designed by Data Physics Corporation for single-axis testing using multiple degree of freedom vibration tables.

One of the major technical challenges of Multi-Exciter Single-Axis (MESA) testing is the suppression of the angular and crossaxis motion that is not restrained via hardware fixturing. This paper describes how such a system can be controlled with the help of input transformations and virtual nulling channels.



NASA Plum Brook Mechanical Vibration Facility

1. BACKGROUND

The multi shaker control system described in this paper has been installed at the new Mechanical Vibration Facility (MVF) at NASA Plum Brook Station in Sandusky Ohio. This facility was originally designed for qualification testing of the Orion spacecraft. The mechanical vibration facility consists of a 20 foot diameter table driven by a total of 20 hydraulic actuators with 16 aligned vertically and 4 aligned horizontally. The actuators are connected to the table through hydrostatic couplings and bearings that allow the table to be driven simultaneously in all six rigid body degrees of freedom.

The objective of the Mechanical Vibration Facility is to allow large spacecraft to be tested sequentially – one axis at a time – in all three axes without having to re-fixture the spacecraft between tests. The table vibration requirements are for swept sine testing from 5 to 150 Hz at sweep rates from 1 to 4 octaves per minute. The controller must also support both force and acceleration limiting.

For vertical testing, the 16 vertical actuators are used to drive the vertical motion of the table. The four horizontal actuators are used to actively prevent horizontal motion and to actively prevent rotations about the vertical axis.

During horizontal testing, the vertical actuators are locked and the in-axis horizontal actuators drive the table while cross axis actuators prevent cross axis motion and assist in preventing rotations about the vertical axis.

One of the primary requirements in controlling a multi degree of freedom table is that any unrestrained degree of freedom must be included in the multi shaker control scheme. In the case of the MVF, the number of unrestrained degrees of freedom depends on the axis being tested.

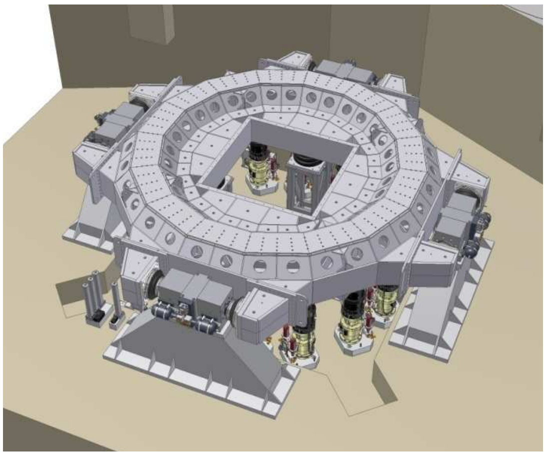
When testing vertically, all 6 rigid body degrees of freedom (X, Y, Z, Θ_x, Θ_y, Θ_z) are unrestrained. This means that control in the vertical axis not only requires control of the vertical motion, but also active cancellation of any translation in the two horizontal axes and cancellation of rotations about all three axes.

When testing horizontally the vertical actuators are locked, restraining vertical translation, and also the rotations about both horizontal axes. The table is unrestrained in both horizontal translations and in the rotation about the vertical axes. In this configuration the MVF has 3 rigid body degrees of freedom (X, Y, Θ_z).

The table is controlled using a separate drive signal for each of the 4 horizontal shakers and a common drive signal to groups of 4 vertical shakers in each of the 4 quadrants of the table for a total of 8 drive signals (4 horizontal and 4 vertical). In this arrangement all 6 DOF can be controlled.

The control system installed at the NASA Plum Brook Mechanical Vibration Facility is a Data Physics Matrix multi shaker controller. The system has 8 output channels to drive the shakers with an additional output that can be used as a Constant Output Level Adapter (COLA). The COLA is used by external measurement systems to determine the sine sweep frequency.

The test data presented here is from validation testing done a much smaller 6 DOF table at the Center for Advance Life Cycle Engineering at the University of Maryland in College Park, Maryland.



NASA Plum Brook MVF Shaker Arrangement

2. SIX DEGREE OF FREEDOM VIBRATION CONTROL

The first step in 6 degree of freedom vibration control is to obtain a nominal model of the entire dynamic system by performing a benign pretest system identification. This pretest system identification is a multi input, multi output FRF measurement using all the drive signals to the shakers as inputs and all the control accelerometer channels as output. The FRF matrix produced by the system identification is inverted to determine the initial required amplitude and phase of the drive signals.

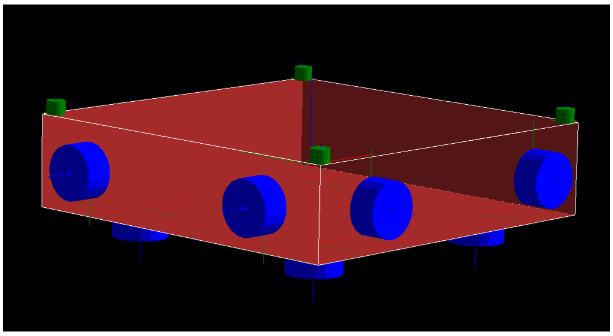
There are two control strategies for 6 DOF control. The first is direct control of the linear acceleration measurements at each control point. Rotational vibration can be canceled using the technique by setting the phases of the reference profiles for all control channels in the same axis to be equal. Control accelerometers in the cross axis directions are designated "null" channels and the control scheme cancels the vibration in these locations.

Another option for 6 DOF control is to use kinematic transformation to convert the linear acceleration measurements to 6 rigid body degrees of freedom - 3 Translations (X, Y, Z) and 3 Rotations (Θ_x, Θ_y, Θ_z). A (local) coordinate frame is fitted to each device (shaker or sensor) on the shaker table. Measurements are made in the local coordinate frame and transformed to the global coordinate frame in which the control References are specified. As an example, accelerometers measure point-wise linear accelerations at various positions.

This is accomplished in a two-step process. An inverse kinematics computes the rigid body accelerations of the global frame. Accomplishing this through a set of homogenous coordinate transformations allows one to consider the effects of velocity dependent Coriolis and centrifugal terms as well as angular acceleration terms.

If needed, "virtual channels" or test points can then be computed through the application of a "direct" kinematics process which involves a set of matrix transformations.

In the figure below, 4 triaxial accelerometers (green) located at the corners are used to measure 12 linear accelerations in the 3 axes (X, Y, Z).



Kinematic Transformation from 12 Linear Accelerations to 3 Translations (X, Y, Z) and 3 Rotations (Θ_x, Θ_y, Θ_z)

Using kinematic transformation in this example, the 12 linear accelerations can be transformed to 3 translations (X, Y, Z) and 3 rotations (Θ_x, Θ_y, Θ_z).

Regardless of which technique is used, the selection of sensor location is critical. There must be sufficient number of sensors and the locations must enable measurement of all control DOF, including rotational DOF.

Since rigid body motion is assumed for 6 DOF control, test article flexibility complicates the control for both techniques. The control accelerometer locations should be carefully selected to avoid locations that are subject to local modal deflection. Available FEA data can be useful in selecting control accelerometer locations.

Since the table will have flexible modes within the frequency range, the control scheme must account for this flexibility. One way in which this can be mitigated for both direct control technique and kinematic transformation technique is through the use of an *over determined* control scheme. An over determined control scheme involves the use of more control channels than required based on the number of output (drive) and rigid body (control) degrees of freedom.

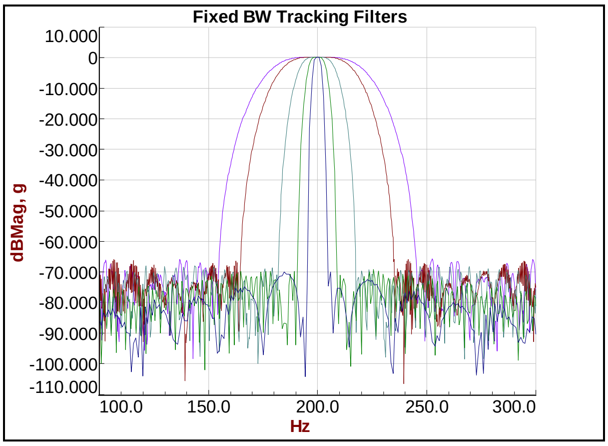
Over determined control can produce better control results in situations where some of the control accelerometers locations are not ideal for the system dynamic response. This technique requires the use of a singular value decomposition technique for inversion of the pretest system identification matrix because it will not be a square matrix.

A second method of dealing with flexible modes, particularly those of the device under test, is the use of acceleration limiting. Acceleration limiting allows the assignment of independent vibration profiles to any accelerometer. The controller will automatically notch the drive signals to the shakers at any frequency where the limit profile is exceeded. There are special considerations in the implementation of limiting in multi degree of freedom testing. These considerations, as they apply to both acceleration and force limiting, are discussed in this paper.

3. MULTI SHAKER SWEPT SINE TESTING

Multi shaker single axis vibration qualification testing must meet all of the same requirements as when performed on a single axis test system. This presents a number of additional challenges for the MDOF test system.

When testing large test articles on single shaker systems, flexible modes will be present, as they are from MDOF tables. The overall table motion is typically characterized using an average value from 2 or more accelerometers at different locations on the table. In the single shaker case, phase can be ignored and only the magnitude of the response of each accelerometer is averaged.



Digital Tracking Filter Shapes

Control of a multi degree of freedom vibration table requires that the control accelerometers are arranged such that all control degrees of freedom are measured. The phase between control accelerometers must be accurately measured and controlled. Accurate measurement of the acceleration amplitude and phase in swept sine testing requires high quality digital tracking filters.

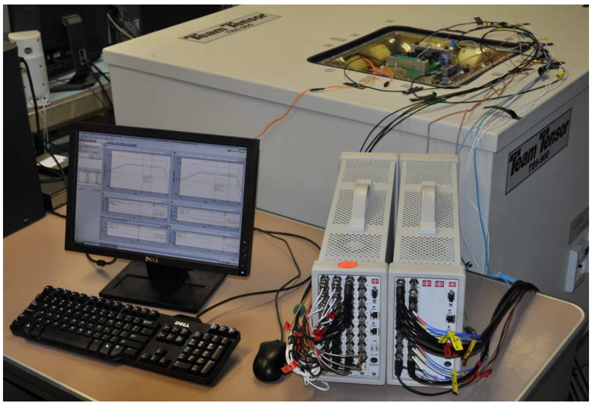
Unlike single shaker sine testing, multi shaker swept sine profiles include both amplitude and phase reference profiles. The relative phase between control channels is defined by the relative phase between the reference profiles for each control channel.

Single axis testing on a MDOF table requires nulling, or cancellation of unwanted rotations and cross axis translations.

Rotations and cross axis motion can be caused by a number of reasons. Any asymmetry in the table payload, overturning moments and table, fixture, and test article resonances can cause rotations and cross axis vibration for which the controller must compensate.

The controller must also be capable of both acceleration and force limiting. Limiting in single shaker tests is done by directly reducing the level, or “notching” the drive signal to reduce the level on the limit channel. For MDOF testing, limiting is complicated by the requirement to prevent any rotations and cross axis translations. The limiting ise implemented in a manner that does not produce any unwanted rotations or cross axis vibration.

In satellite testing it is desirable to limit not only on the measured force, but also on vector forces and moments from multiple force transducers. The kinematic transformation capability provides the additional benefit of enabling vector force and moment calculations.

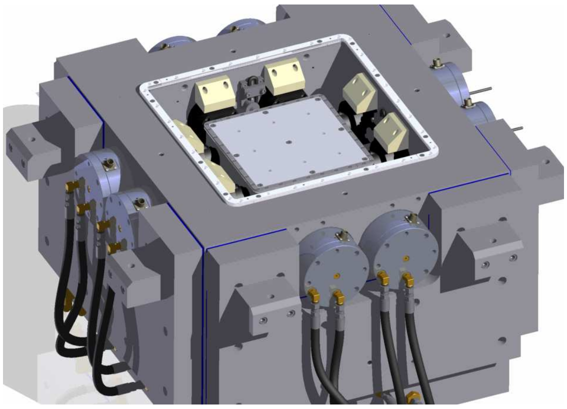


Data Physics Matrix Controller and 6 DOF Table with 12 Shakers

4. TEST SYSTEM SETUP

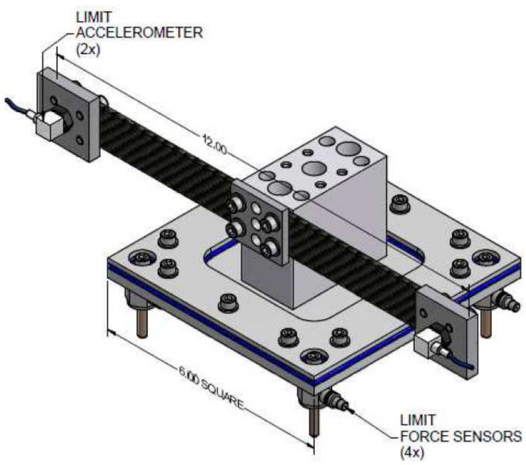
Controller validation was done on a much smaller 6 DOF shaker table at the Center for Advanced Life Cycle Engineering at the University of Maryland. This table is a Team Tensor with a total of 12 electrodynamic shakers (4 vertical and 8 horizontal). The tests were done using only 8 shakers (4 vertical and 4 horizontal) to simulate the control scheme used at NASA Plum Brook Station.

A test article was fabricated using a damped carbon fiber beam with different masses attached to the ends of the beam. The objective was to produce high-Q resonances at low frequency for testing the control performance. Accelerometers were placed on the masses at the ends of the beams to measure the response and to allow for limiting of the test based on response levels.



Six DOF Table Showing Horizontal Shaker Locations

The test article is further mounted on four load cells to allow force measurement and limiting. Four triaxial accelerometers were mounted at the corners of the test article plate – these were used in the kinematic transformations to convert twelve linear accelerations into the rigid body linear and rotational accelerations. These accelerations were used for the feedback control of the shaker table for each of the tests.



Resonant Test Article Showing Force and Acceleration Limit Sensor Locations – Horizontal Configuration

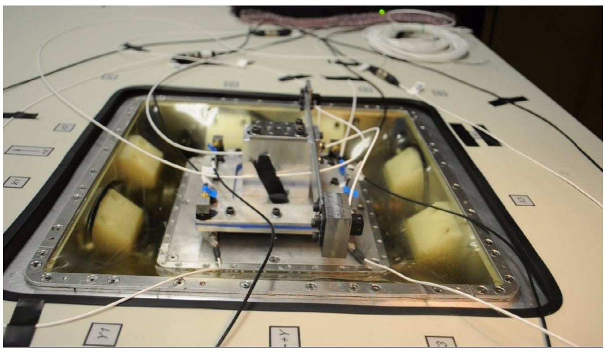
5. TEST RESULTS

A battery of tests were run on the six degree of freedom vibration table at the Center for Advanced Life Cycle Engineering at the University of Maryland in College Park, Maryland. The test included swept sine from 5 to 150 Hz at sweep rates from 1 to 4 octave per minute. All tests were done with triaxial control accelerometers at the 4 corners of the test article. Kinematic transformation was used to transform the 12 linear acceleration values to 3 rigid body translations and 3 rigid body rotations. The test article was attached in both horizontal and vertical configurations to produce the desired low frequency, high Q resonance.

Acceleration limiting was done using accelerometers on the ends of the resonant beams. Force limiting was also done using the four uniaxial load cells at the interface between the test article and the table.

The test results are shown in the graphs on the following page. Only the horizontal X axis results are shown here. Results for vertical tests yielded similar results. The graphs on the next page show the X axis control response along with the 4 individual X axis responses. The technique produced good control and minimal rotations as indicated by the amplitude and phase match of the X axis control accelerometers.

The second set of graphs show the results when limit profiles were assigned to the accelerometers on the ends of the beams. Comparison of the control and limit signals show effective notching. The individual control response show that amplitude and phase match is maintained during limiting, indicating no unwanted rotations.



Test article mounted on Six DOF Table

6. SUMMARY

An innovative multi shaker control system for sequential single axis swept sine testing of large spacecraft is presented. Issues related to flexible modes in the shaker table and device under test are discussed and a strategy for control using over determined control and kinematic transformation is outlined. Careful selection of the control accelerometer location is critical to successful rigid body control in the presence of flexible modes. High quality digital tracking filters are essential to successful implementation of multi degree of freedom swept sine control. Special considerations for multi shaker single axis testing are also discussed.

Tests of a small test article with low frequency, lightly damped resonances were run on a small 6 DOF shaker system. Test results are presented showing good results for both control and acceleration limiting.

7. REFERENCES

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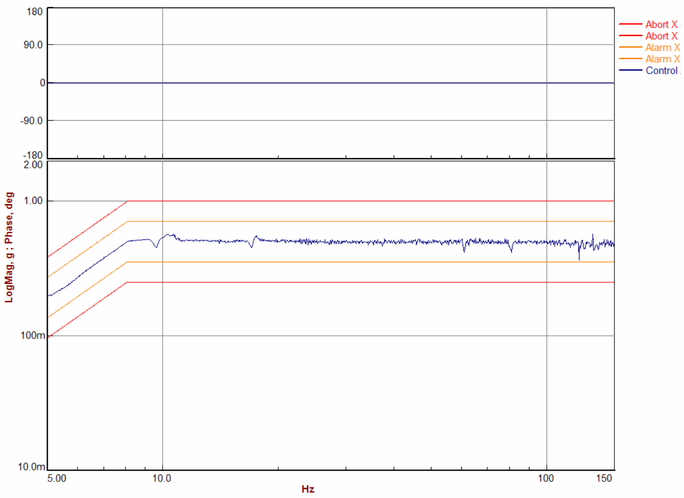
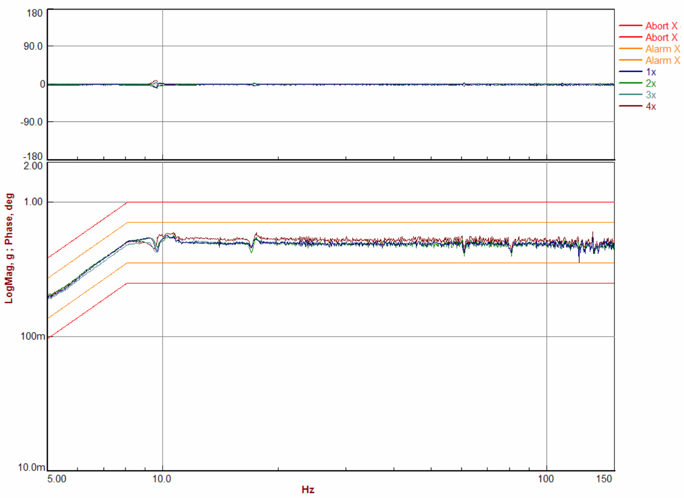
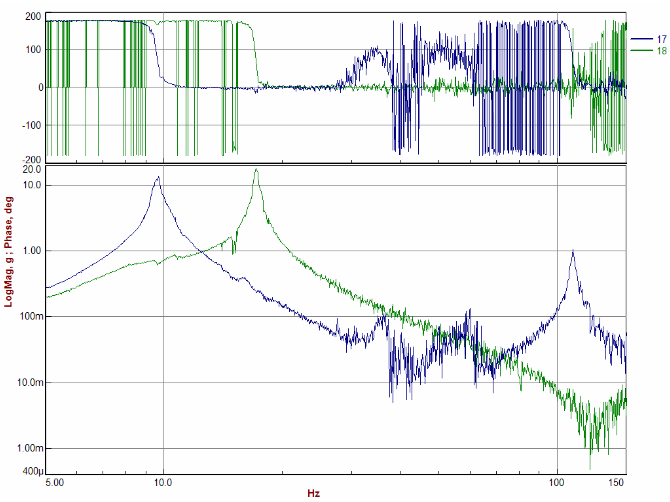
Control Results



X Axis Control Using Kinematic Transformation

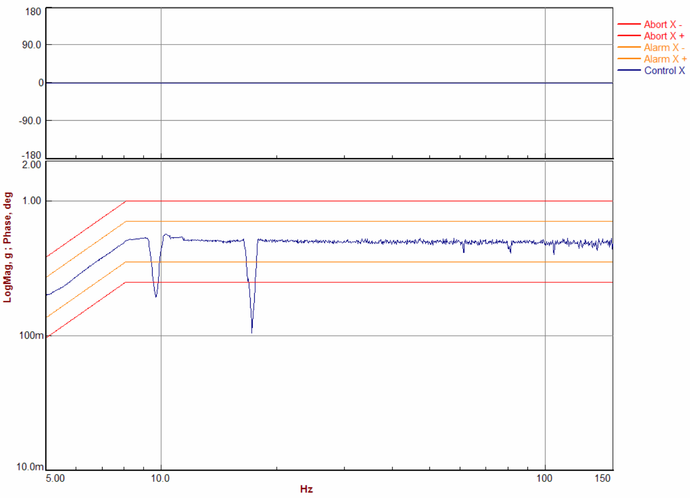


Individual X Axis Control Channels

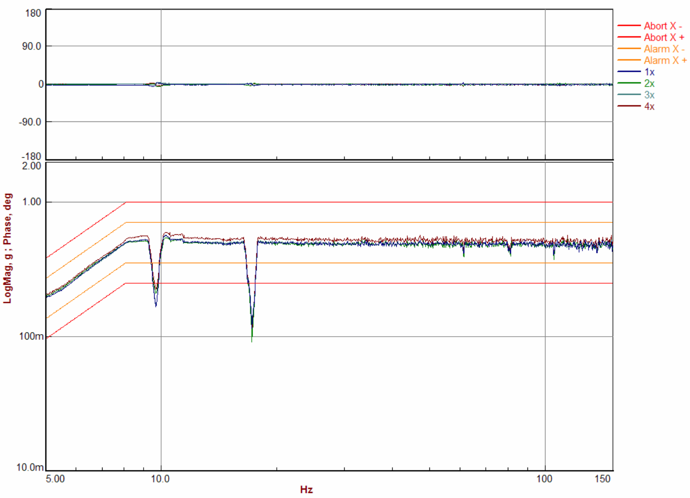


Measurement Channel Response

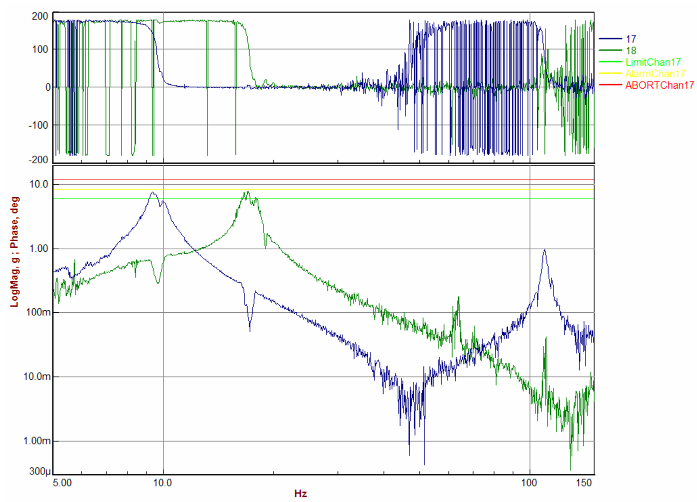
Acceleration Limiting Results



X Axis Control with Acceleration Limiting



Individual X Axis Control with Acceleration Limiting



Limit Channel Response