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IDENTIFICATION OF SUPPORT CONDITIONS

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ABSTRACT: In this paper, a support and preload system is presented in which the frequencies and damping of the test article are affected by the stiffness and damping of the supporting structure. A dynamic model is derived for the support system that includes the damping as well as the mass and stiffness of the supports. The frequencies, damping, and mode shapes are compared with the experimentally determined parameters. It is shown that for a seemingly simple support system, deriving a predictive model is not a trivial task.

Introduction

Free-free modal tests are popular because it is felt that boundary conditions are often negligible. However, most free systems are usually supported by soft springs such as bungee cords. Although the "rigid" modes may be of low enough frequency to have a negligible effect on the flexible frequencies of the test article, the damping of the bungees may affect the measured damping of the test article. In situations where a preload is necessary on the test article, the effects of the supports can have an even more drastic effect on the damping and may affect the frequencies. Through an understanding of the support structure, the true damping and frequencies may be predicted for the test article alone. This is done by updating the model of the rig/structure with modal test data, and then removing the model of the rigging to reveal the frequencies and damping of the structure alone.

Previously Wolf [1], performed a study on the influence of a mounting system on a modal test of a car. Initially he analytically studied the effects of a spring to ground on a simple two Degree of Freedom (DOF) system. He then analyzed data from a full-up modal car test. He concluded that to minimize the influence of the suspension system, the support system should be attached to the most massive portion of the test structure. This paper deals with the situation in which the support structure, or rig, has predefined attachment positions and the modal parameters of the support structure must be identified in order to understand its effects on the test article.

Test Setup

A schematic of the test setup is shown in Figure 1. The actual configuration of the test can not be discussed in detail. The test structure needed to be tested in a loaded configuration. Some simple analysis indicated that the support structure could significantly affect the frequencies and damping of the lower modes of the test structure. To isolate the rig dynamics, a rigid version of the test structure with the same dimensions as the test article was constructed for a test in the rig. Because it was rigid, the test article mock-up would not affect the rig stiffness and damping.

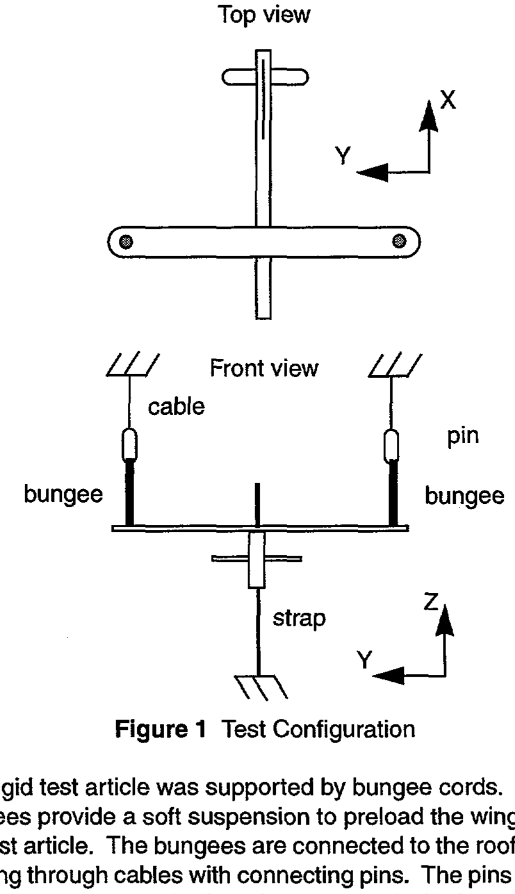

Figure 1 Test Configuration

The rigid test article was supported by bungee cords. The bungees provide a soft suspension to preload the wings of the test article. The bungees are connected to the roof of the building through cables with connecting pins. The pins where the bungees are attached are instrumented with force sensors to insure (i) the proper load is being applied, and (ii) the

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load in each bungee is equal.

The nylon strap underneath the test article is used to react the preload of the test structure. The nylon strap was connected to a shackle which was clamped to ground. It was realized after the test that although the shackle-clamp assembly acted as a pinned joint in one direction, it acted as a clamped joint in the orthogonal direction. This will be discussed more completely in the next section.

Bungee Stiffness

The bungee stiffness was bracketed by a dynamic test on the bungees alone. Figure 2 shows the setup for the bungee stiffness identification test. The input to the test was provided by a modal hammer. Accelerometers were placed on the mass load to measure the response. The mass load ranged from twice the mass of the pins used in the test to 30 times the mass of the pins. The bungees were loaded to approximately the loads anticipated in the actual test.

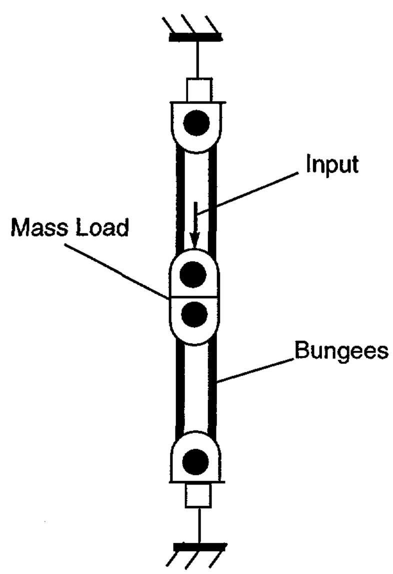

Figure 2 Bungee Test Configuration

It was determined that the bungees behave as a softening spring. Because of this, a range of "linear" stiffnesses were identified. For the extension used in this test, the bungees had a stiffness between 63 and 75 in/lbf. When the final model of bungee stiffness was identified based on the test of the mock-up vehicle in the rig, the bungee stiffness fell within the tested range.

Equation of Motion Issues

Initially, the system was broken into a series of single or two-Degree of Freedom (DOF) models. Lateral stiffnesses for the strap and the bungee-cable system were assumed to behave as a pendulum and therefore the stiffnesses were modeled using the small angle approximation with T/L where T is the tension and L is the effective length perpendicular to the direction of motion. This simple lateral stiffness model for the strap and the bungee/cable combination proved to be insufficient for an accurate model as described in the next two subsections.

The Bungee Connection

It was discovered that the bungee connection to ground could not be modeled as a simple lateral spring. A cable was run from a winch bolted to ground, through a pulley connected to ground, to the instrumented pins to which the bungees were attached. It was determined from test data that the mass of the pins contributed significantly to the dynamics of the test rig. To account for the pins, equations of motion were developed which assumed the pins had mass and length but no rotational inertia. This allowed the rotational DOFs of the pins to be removed from the overall equations of motion of the system.

During the initial tests when the rigid test structure was used to characterize the support structure, the pins only had the force transducer and no accelerometers. After the analysis showed that the pins participated significantly in the mode shapes, they were each instrumented with a triaxial accelerometer.

The Non-Linear Nylon Strap

The effective length was different for the strap depending upon which direction was being modeled. This was basically due to the difference in where the strap pivoted at the point of attachment. This was a factor at both the top and the bottom of the strap.

T/L stiffnesses scale linearly with load as the tension in the bungees was increased. The strap, however, could not be modeled with simple T/L lateral stiffness. First of all, the width of the strap resulted in a bending stiffness as well as a T/L effect in the θ_y direction. This was due to the attachment point to ground. The shackle behaved as a pin in the θ_x direction but would bind up in the θ_y direction.

The bending stiffness did not scale linearly with load. Using axially loaded beam theory, an estimate of the nonlinear scaling function was determined. This proved adequate for the prediction of the affected frequencies within a few percent.

Results

Table 1 shows the values of the Modal Assurance Criteria (MAC) for the analytic vs. experimental mode shapes for the test setup (with both test article and support structure). The sensor placement used did not allow a differentiation between the first and second Yaw modes. The difference between these two modes was the motion of the pins. In the full test, triax accelerometers on the pins allowed for the differentiation. The pitch and fore-aft modes have a strong correlation because the sensor set used did not represent the rotation about the Y axis very well.

Table 1: MAC between Analytic and Experimental Mode Shapes

	Experimental Modes					
Analytic Modes	Fore-Aft (X)	Lateral (Y)	Yaw (θ_z)	Pitch (θ_y)	Roll (θ_x)	Yaw (2nd)
Fore-Aft (X)	1.00	0.02	0.00	0.99	0.00	0.00
Lateral (Y)	0.00	0.98	0.00	0.00	0.01	0.00
Yaw (θ_z)	0.00	0.00	1.00	0.01	0.01	1.00
Pitch (θ_y)	1.00	0.00	0.00	1.00	0.00	0.00
Roll (θ_x)	0.00	0.01	0.00	0.00	0.95	0.00
Yaw (2nd)	0.00	0.00	1.00	0.01	0.01	1.00

The updated support model frequencies were within two percent of the six measured frequencies (only one of the four pin modes was measured). As a review this was achieved with four major steps:

1. Developing a model which accounted for the mass and length of the pins;

2. Identifying a parameter for the stiffness of the bungees (that was within the range of test values);

3. Assuming T/L lateral stiffnesses values based on measurements of T and L; and

4. Including a nonlinear tension rotational stiffness effect in the strap based on the theory of an axially loaded beam.

As a final check on the strap stiffness, the rigid test article was hung upside down with the same strap hardware from the roof. Five pendulum frequencies were obtained experimentally. The model, with the tension in the strap equivalent to the weight of the vehicle, predicted frequencies within 2.6% of the five measured pendulum frequencies.

Damping Identification

Because the true damping of only the structure (without the rig) was desired, estimates of viscous damping for the rig had to be identified. This identification was accomplished with the rigid mock-up of the test article in the support structure, so that all damping effects were assumed to be associated with the support structure. By the time the damping identification was performed, the support model with the rigid test article had evolved into a nine DOF system. Four degrees of freedom were associated with the two lateral directions for each pin. Five degrees of freedom were associated with the rigid test article (two lateral, pitch, roll and yaw). By a brute force optimization, viscous damping values were derived by comparing the model damping ratios to the experimental damping ratios. Five damping values were identified that brought the model damping ratios into conformance with 6 measured damping ratios. The same value of damping was used for each lateral direction of the cables. A value was determined for the vertical displacement of the bungee cords. A yaw degree of freedom damping was required for the strap. The same damping value was used for both lateral directions of the strap. Different damping values were required for the pitch and roll degrees of freedom associated with the strap. Most of these damping values were relatively small, since the damping ratio for all modes was below 0.6%, except for the roll mode at 2.67%. The damping for the bungee cords vertical displacement was highest, which most affects the roll mode. The rig and rigid vehicle model's damping ratios were within four percent of the measured values. The damping ratios of the modes were determined by running a complex eigenvalue solution in MATLAB.

Conclusions

In conclusion, a method to develop a mass, stiffness and damping model of a test support structure has been developed. A model updated with test data for a structure in this rig can now be utilized to predict the test structure's frequencies, damping and mode shapes by simply removing the model of the support structure. A "rigid" mock-up structure was used in modal testing to validate the model of the test structure. What was initially thought to be able to be modeled with simple one or two DOF systems ended up as a nine DOF system. Specific testing was done to determine bungee cord stiffness. T/L lateral stiffnesses were validated by the test. Special effort was required to model the strap as an axially loaded beam because the test hardware did not provide a pinned condition for the strap attachment in each lateral direction. Damping values were identified with a simple optimization based on modal test damping ratios for the rigid mock-up structure in the test support structure. The updated support model agreed within a few percent to measured frequencies and damping.

Acknowledgments

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References

[1] Wolf, J. A. (1984), "The Influence of Mounting Stiffness on Frequencies Measured in a Vibration Test," SAE paper No. 840480.