Vehicle Dynamics and NVH Trade-off Studies Using ADAMS

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ABSTRACT

Ford is interested in evaluating noise, vibration, and harshness (NVH) implication of system design concepts prior to the availability of detailed system/component design. During the earlier design stage, ADAMS models created for ride, handling, and durability studies are usually available. Although these models were not designed for the high-frequency NVH studies, they can be readily enhanced to include these capabilities. This will significantly reduce the time and effort required to prepare separate NVH models. The common tool can also be utilized for vehicle dynamics/NVH trade-off studies.

INTRODUCTION

In the automotive industry, NVH performance is critical to customer satisfaction. In addition to NVH performance improvement, the time, cost, and weight reductions are also needed to keep the company competitive or in the leadership position. Many system design concept decisions made in pre-program stage have major effects on vehicle NVH performance that customers perceive.

To support pre-program in system design concept selection, Ford NVH engineers required a tool to conduct NVH studies which was powerful enough to obtain the relevant information, yet user-friendly, before detailed designs were available.
They inquired to MDI about the possibility of using existing ADAMS models to conduct NVH results. This would reduce the effort of building a separate model for NVH and the common tool can be easily applied for NVH and vehicle dynamics trade-off studies. However, there was some concern over ADAMS ability to produce good results in the required frequency range for NVH studies (0 - 200 Hz). MDI and Ford engineers worked together to determine the feasibility and difficulty of modifying an vehicle dynamics model for NVH studies.

This paper details the process by which MDI and Ford engineers converted the model to conduct NVH studies. The first phase was to use recorded spindle acceleration data to excite a vehicle dynamic model for validation to NVH test results Next, the bushings and flexible suspension components were enhanced in order to provide results consistent with equivalent MOTRAN models. Finally, an ADAMS frequency-dependent bushing was developed for use in NVH studies. The results of this work is that Ford's NVH group can now take existing ADAMS vehicle dynamics models and use them for NVH studies.

APPROACH

1.0 Spindle Excitation

Since spindle accelerations can be easily measured on the test track, they are used as excitation sources. The first modification of the vehicle dynamics model was to remove the wheels and replace them with user-supplied spindle acceleration data. This was provided in a series of harmonics (magnitude, direction, and phase) and ADAMS subroutine was developed which read this information, and calculated the corresponding time-domain displacement during the ADAMS simulation.

A kinematic mechanism was created at each spindle point so that the three directions of displacement could be specified. This was achieved by adding eighteen degrees of freedom (ADAMS Part's) and constraining fifteen (ADAMS translational joint). The remaining three degrees of freedom were then available for specification in the MOTSUB. This mechanism was placed between the ground and each spindle. The MOTSUB has been configured to accept either time series or frequency spectrums for either displacement, velocity, or acceleration. Figure 1 shows the configuration of the mechanism.

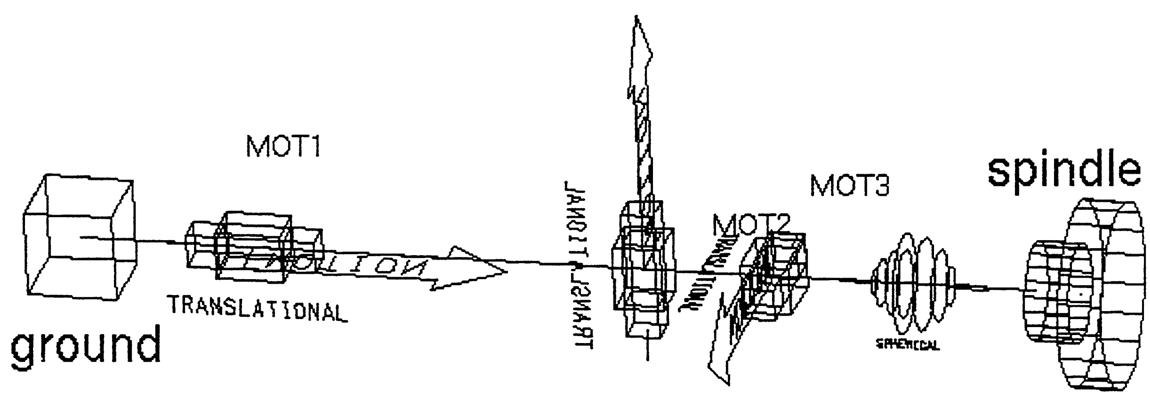


Figure 1: ADAMS Representation of 3 DOF Spindle Mechanism

2.0 Frequency Dependent Bushing

ADAMS bushings are designed to behave like linear springs. The force produced by the bushing is calculated by the distance between the bushing's reference markers. The relative velocity is also used to modify the bushing's force to account for linear approximation of the internal hysterisis of the bushing material. Although this type of bushing is generally useful for most dynamics modeling applications, NVH studies require a somewhat more realistic representation of bushing behavior. As such, a frequency-dependent bushing capability was developed. This bushing is implemented as an ADAMS GFORCE. The parameters of this GFORCE are calculated based on frequency response data from bushing test data.

The typical approach for the dynamic analysis of frequency dependent force elements is to construct an equivalent set of springs and dampers in series which is in parallel with a second spring. The explicit formulations of the three components, spring constants, and damping coefficients are derived analytically as functions of the diameters of the physical component of the properties being modeled. These formulations for a given system can be used efficiently for calculating the equivalent transfer function. The determination of these parameters generally requires the use of numerical procedures such as finite element analysis.

Since the goal of this work is to create a method for conducting NVH studies using ADAMS, the formulation of the parameters required for constructing an equivalent spring-damper system was not focused on. Instead a method for creating the necessary transfer functions direct from the frequency response curve was developed. This method relieves the burden of formulations to account for complex occurrences such as asymmetric bending and internal combined loading. With this method, an ADAMS TFSISO is created for each degree of freedom. TFSISO stands for Transfer Function, Single-Input, Single-Output. These transfer functions are created automatically for each given frequency response curve.

The transfer functions uses a modification of a numerical algorithm for calculating the root locus of a given function in terms of the complex variable $s = x + iy$. This formulation takes the form of the following equation:

$$G(s) = \frac{F(s)}{D(s)} = K\frac{\prod_{m=1}^{M}(s - z_m)}{\prod_{j=1}^{N}(s - p_j)}$$

The amplitude of *G(s)* represents the stiffness of the bushing. Figures 2 and 3 show the stiffness vs. frequency and phase angle vs. frequency. For a given curve, the user needs to choose the proper order of the polynomial for the numerator and denominator and then calculated the coefficients. For example, Figures 2 and 3 show the amplitude and phase angle for first order polynomials. In general, higher orders will provide better results. The comparison between ADAMS results and test data are shown in Appendix A.

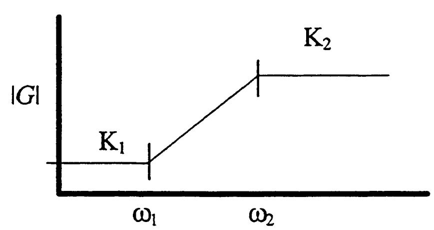


Figure 2: Stiffness vs. Frequency

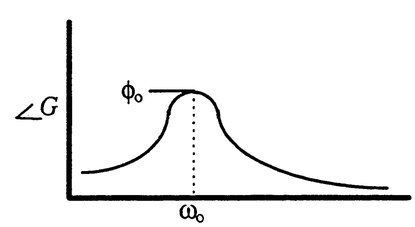


Figure 3: Phase Angle vs. Frequency

ANALYSIS AND VALIDATION

In order to ensure that the resulting formulations and modeling techniques provided correct results, two sets of simulations were performed. The results were validated against existing NVH code (MOTRAN) and available test data. The two case studies involved the standard NVH investigations on noise and harshness.

Noise analysis consists of high frequency vibrations which are relatively constant over time. In order to simulated a noise study, spindle excitations for a standard noise test simulation were introduced to the ADAMS model and the resulting bushing forces were compared. The goal of the noise analysis was to make sure that ADAMS could produce correct results for these noise profiles. The X, Y, Z spindle excitations and resulting strut forces can be found in Appendix B. The results were found to correlate well with test data.

The other test case was to simulate a harshness condition. In this case, the input excitations contained a large impact at the spindle. This test was used to make sure that the formulations were correct and that ADAMS implicit integrator could solve through the sharp changes in force magnitudes. As in the previous case, the results of the simulations correlated well with the test results. These results of the simulations are shown for the front left spindle in Appendix C.

CONCLUSIONS

The results of this work is that engineers in Ford's NVH department now have a validated tool for predicting NVH characteristics of new platforms as well as an aid in reducing these types of problems for existing programs. The use of the ADAMS software allows NVH engineers to save time and money by starting with an existing vehicle dynamics model. Another result is that a common methodology which spans other departments allows for increased effectiveness through cooperation and economics of scale. This work, however, is only the first step in institutionalizing the methodology for NVH analysis.

FUTURE WORK

Now that the methodology for creating NVH ADAMS models is completed and validated, more work needs to be done to build a complete solution for these studies. The next step is to enhance the models so that they correlate better with other NVH characteristics. This efforts falls into the two general categories of improving simulation correlation and increased model complexity.

Although the general amplitude and trend of the current results correlate well with test data, there is room for improvement. General NVH problems can take place in very sensitive environments and improvement of correlation is a consistent goal. These improvements will be made by further refinements to the modeling process and validations against several academic codes such as MATLAB.

Several simplifications were allowed in the preliminary correlation's in order to account for inadequacies of existing codes. Since these correlation's are now complete. New functionality can be included to further improve the capabilities, and thus, the results of the simulations. Among these functionalities are the inclusion of several flexible components such as a flexible frame and flexible strut. The new modal flexibility capabilities of ADAMS will be employed to determine system and component modals. Finally, the ability to apply transient excitations to the model will be added along with the corresponding post-processing capabilities.

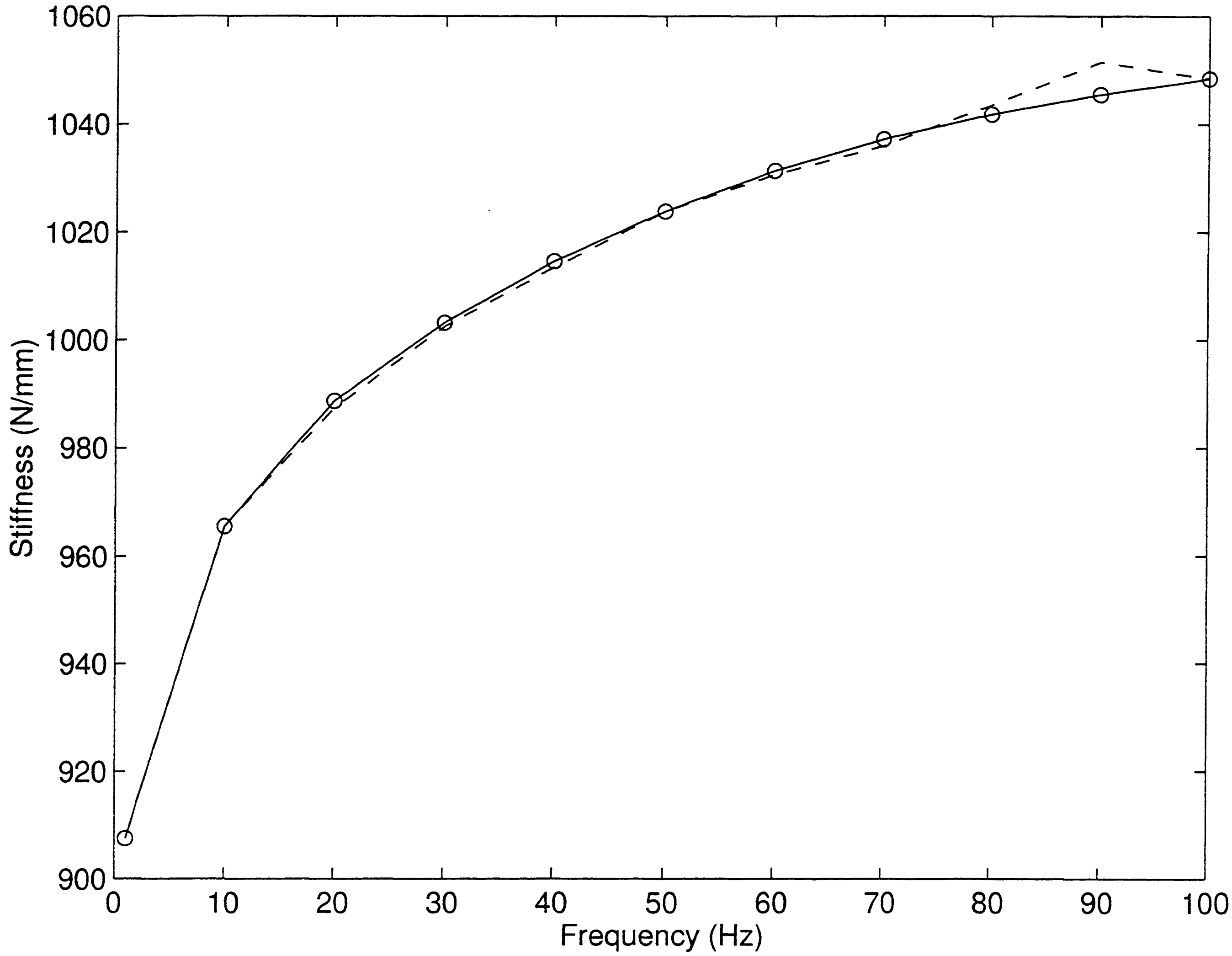
Once these refinements and enhancements have been made, then Ford engineers will be able to more readily use the tool for complete NVH studies. The first major goal is to have the ability to identify major load paths for several of Ford's preproduction platforms. Once this level of capability is reached and validated, then the technology will be considered fully integrated into Ford's vehicle dynamics/NVH trade-off studies.

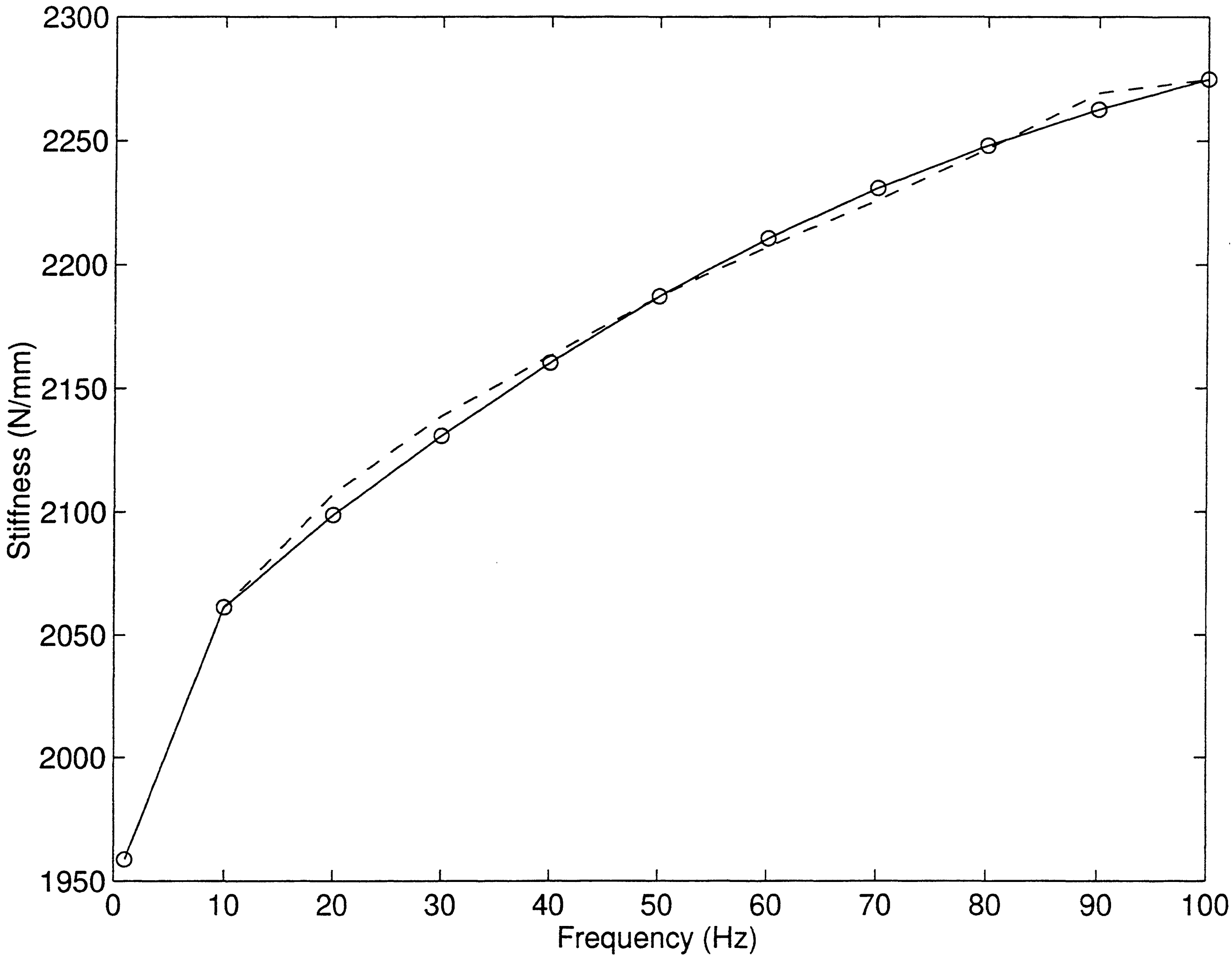
REFERENCES

Grantham, Walter J., Vincent, Thomas L., Modern Control Systems: Analysis and Design, John Wiley and Sons, Inc., New York, 1993.

Lin, Yeong-ching, Cunningham, David C., Stiffness and Stress of a Fluid-Filled Circular Diaphragm, AIAA Structures, Structural Dynamics and Materials Conference, April 13, 1992, pp. 1504-1513.

APPENDIX A: Frequency Dependent Bushing Correlations


1060
1040
1020
1000
980
960
940
920
900
Stiffness (N/mm)
0
10
20
30
40
50
60
70
80
90
100
Frequency (Hz)

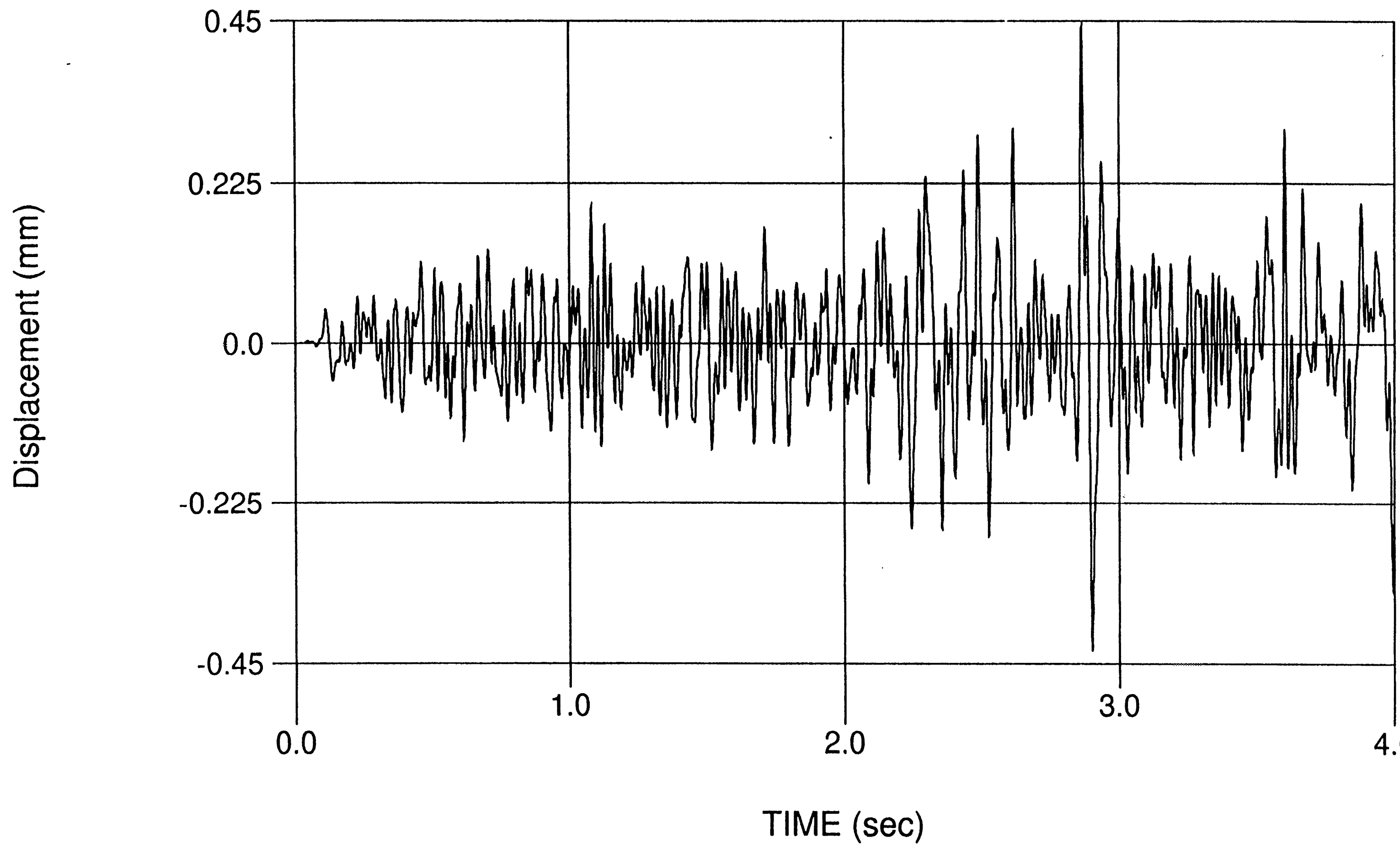


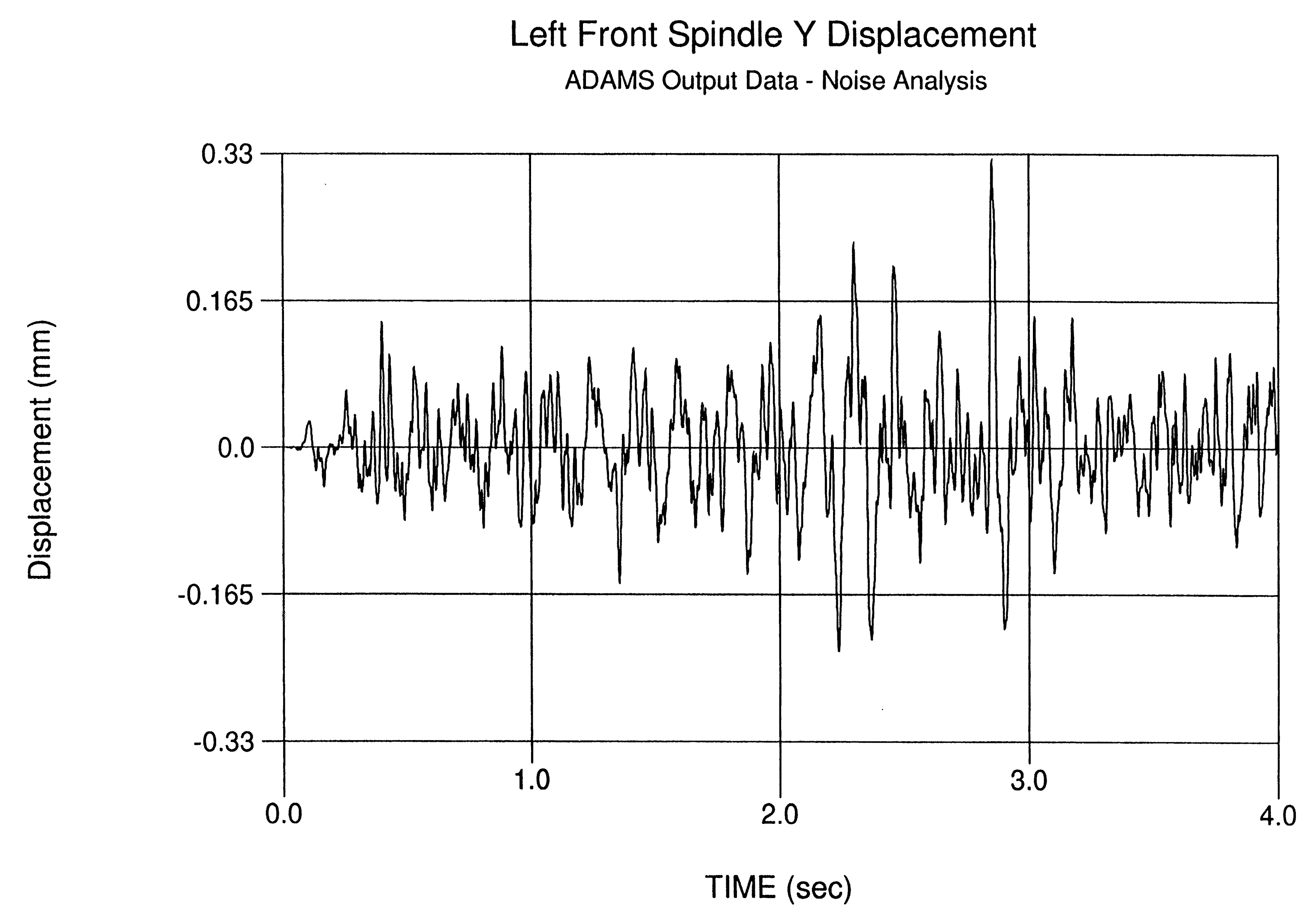
2300
2250
2200
2150
2100
2050
2000
1950
Stiffness (N/mm)
0
10
20
30
40
50
60
70
80
90
100
Frequency (Hz)

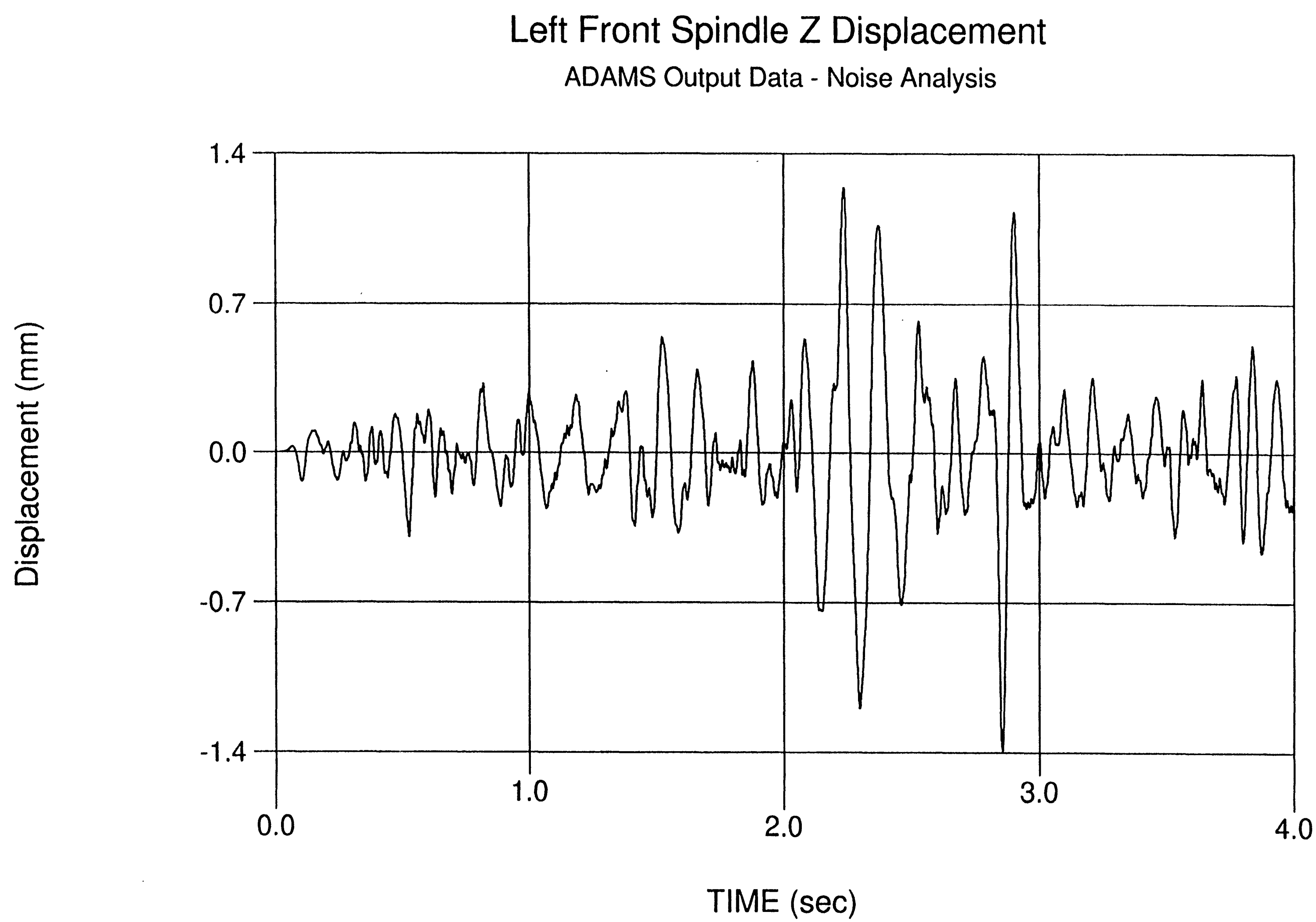
APPENDIX B: Noise Case Study Results

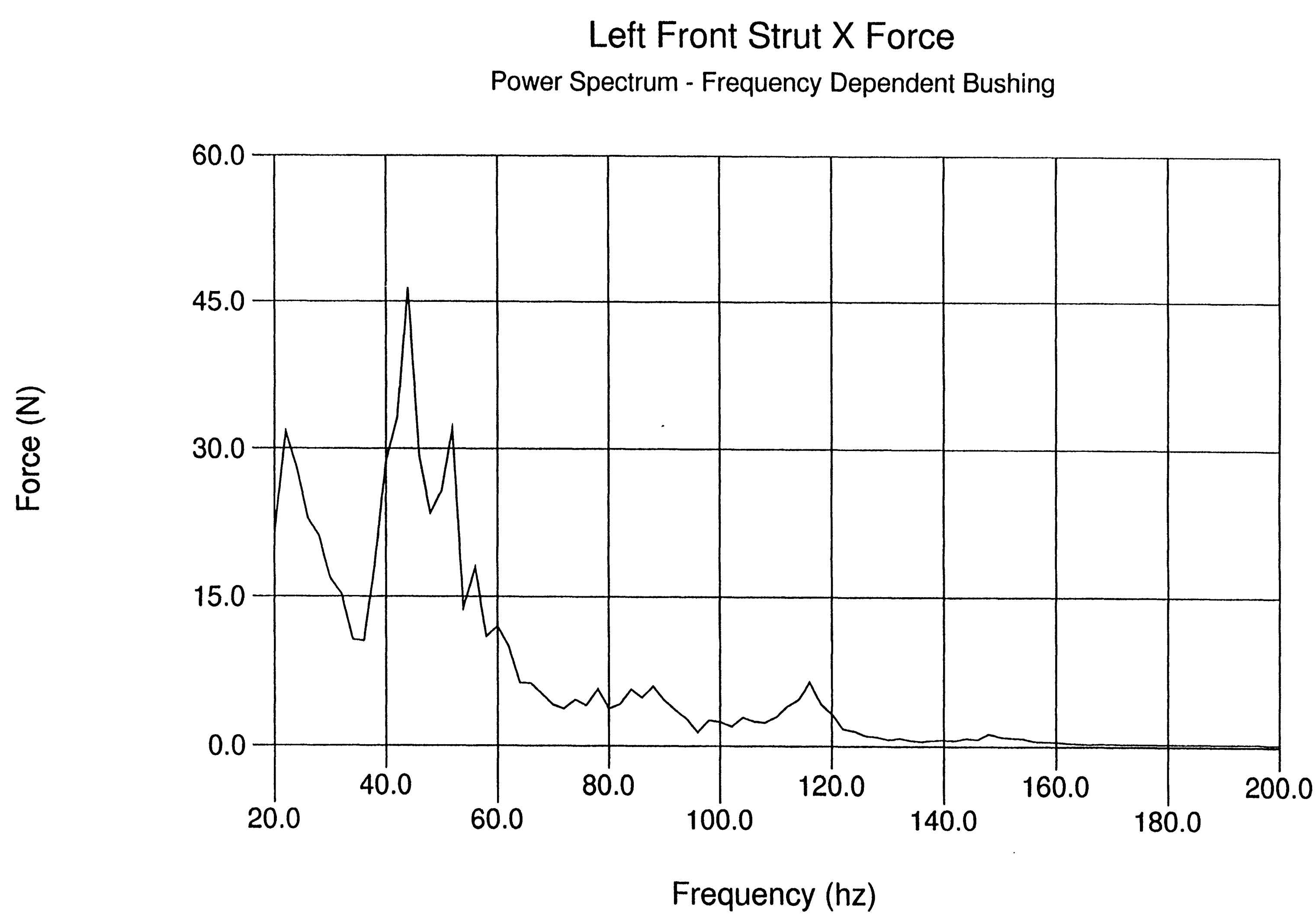
Left Front Spindle X Displacement

ADAMS Output Data - Noise Analysis




Left Front Spindle Y Displacement
ADAMS Output Data - Noise Analysis
0.33
0.165
0.0
-0.165
-0.33
Displacement (mm)
0.0
1.0
2.0
3.0
4.0
TIME (sec)

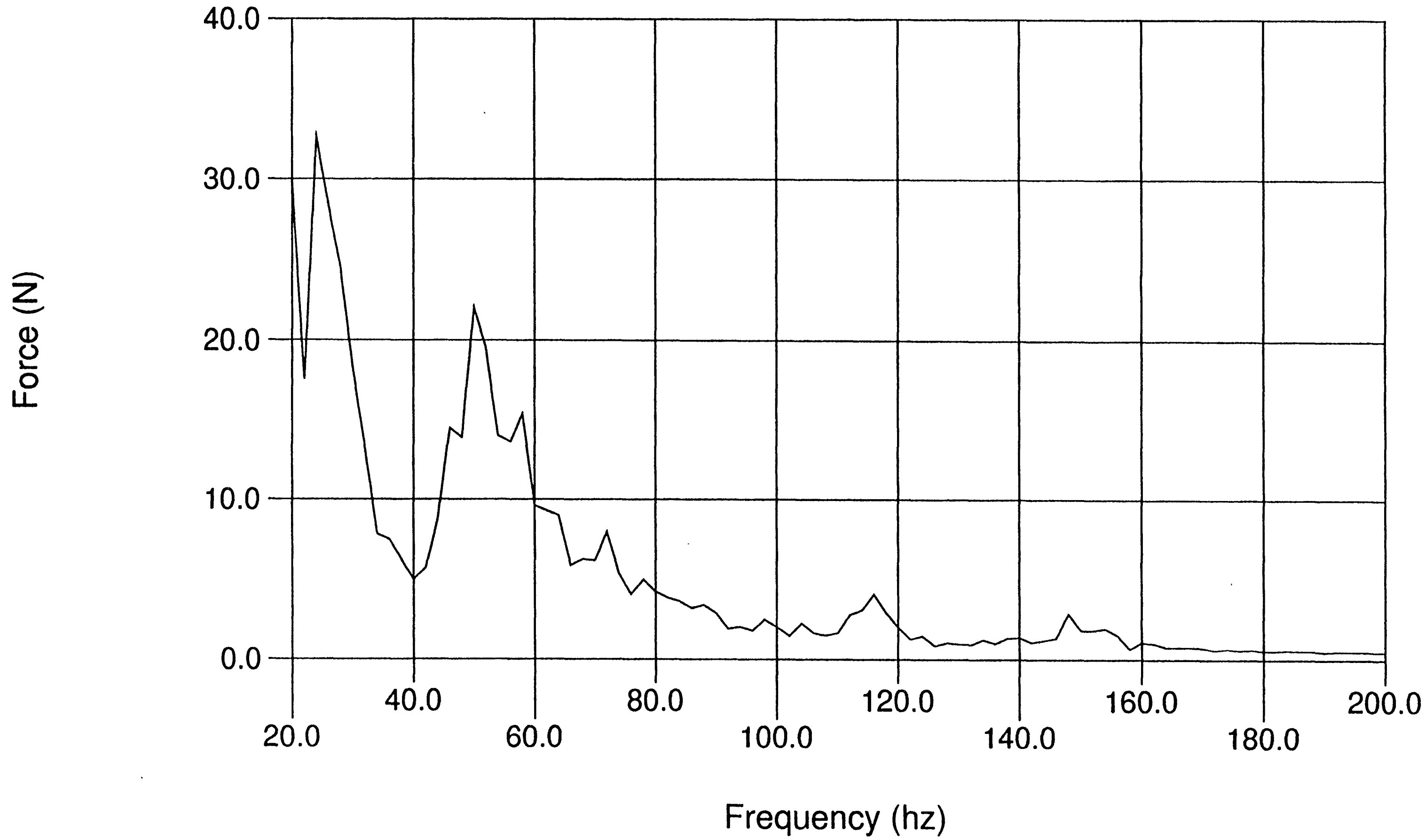

Left Front Spindle Z Displacement
ADAMS Output Data - Noise Analysis
1.4
0.7
0.0
-0.7
-1.4
Displacement (mm)
0.0
1.0
2.0
3.0
4.0
TIME (sec)

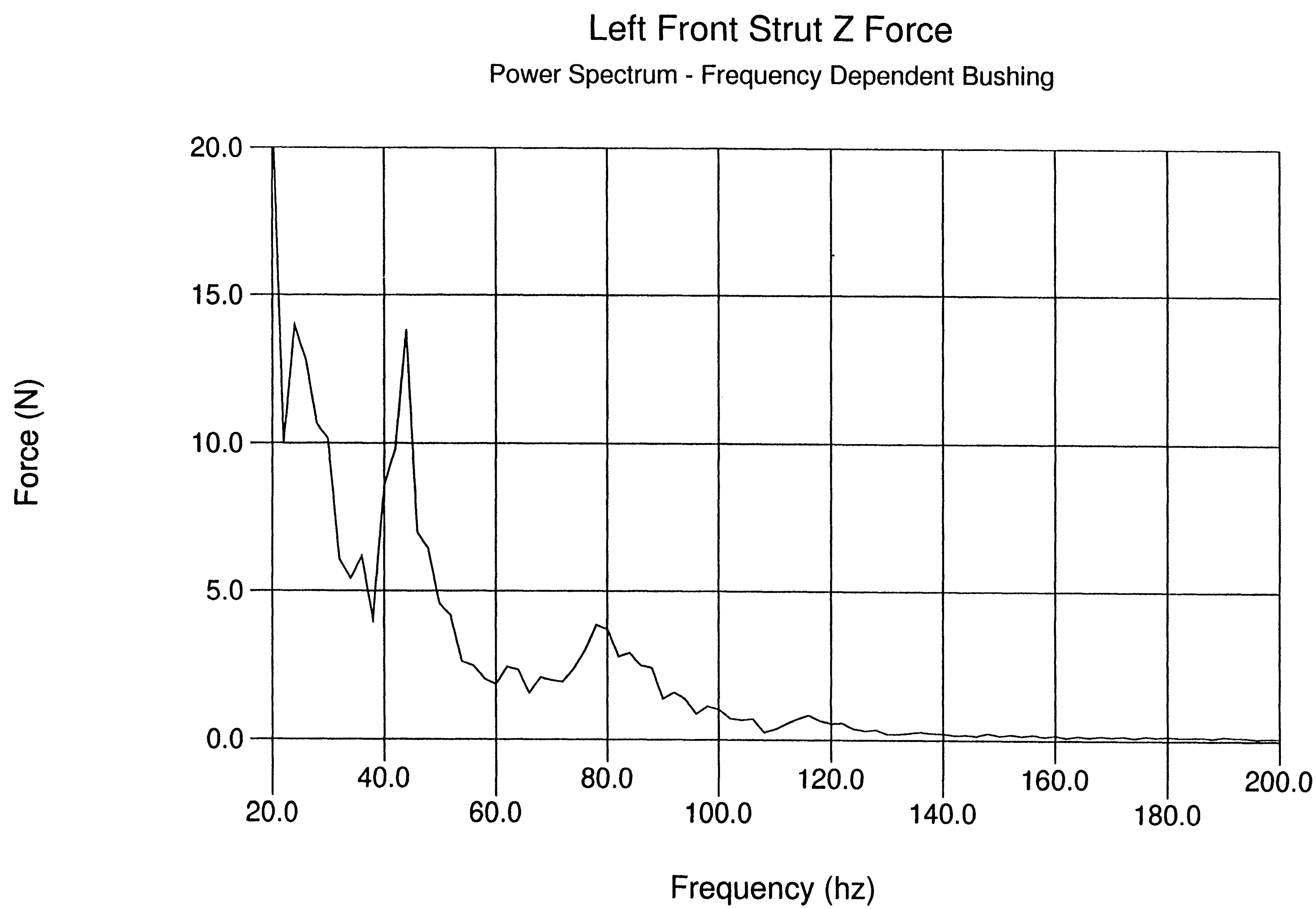


Left Front Strut X Force
Power Spectrum - Frequency Dependent Bushing
Force (N)
60.0
45.0
30.0
15.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
Frequency (hz)

Left Front Strut Y Force

Power Spectrum - Frequency Dependent Bushing

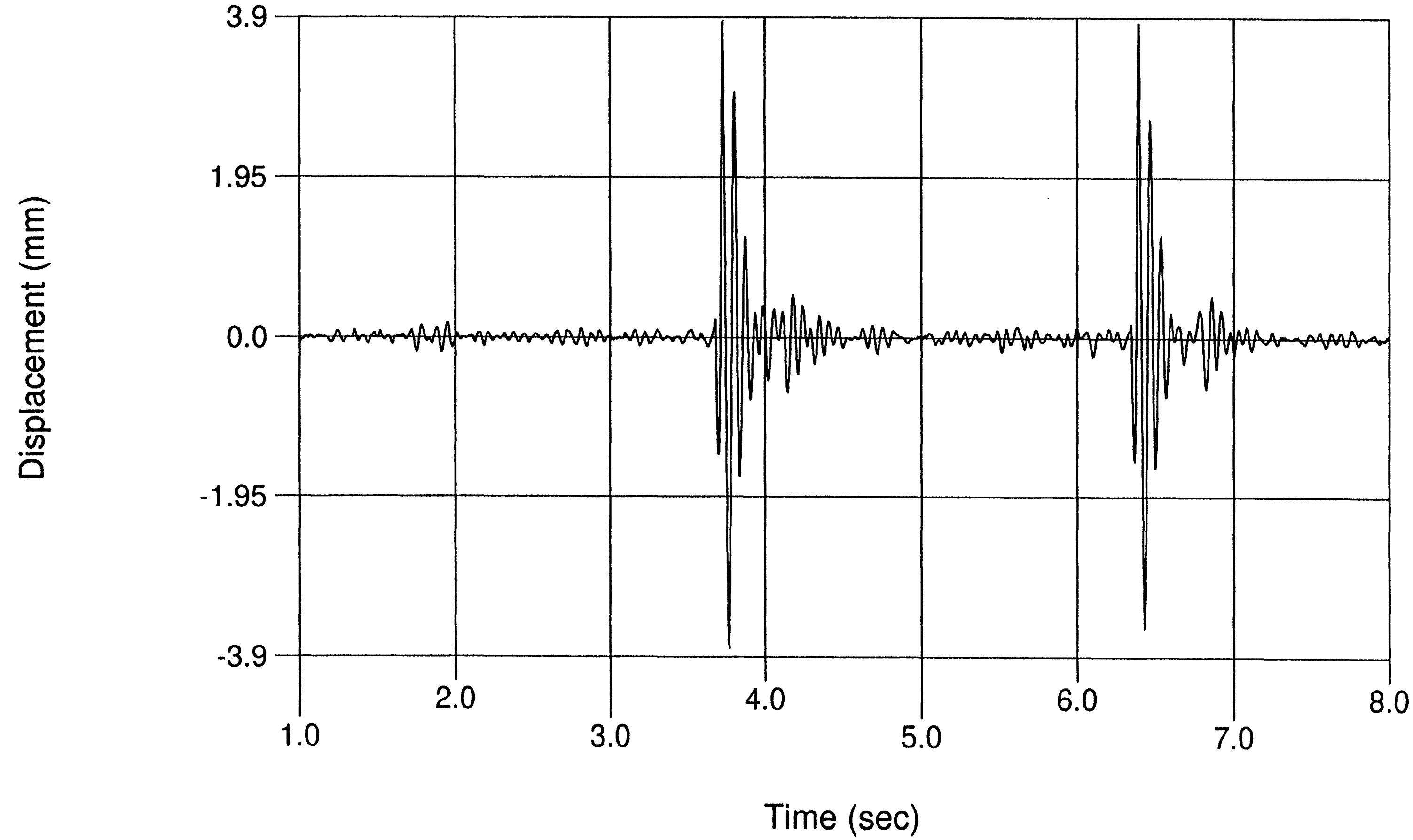


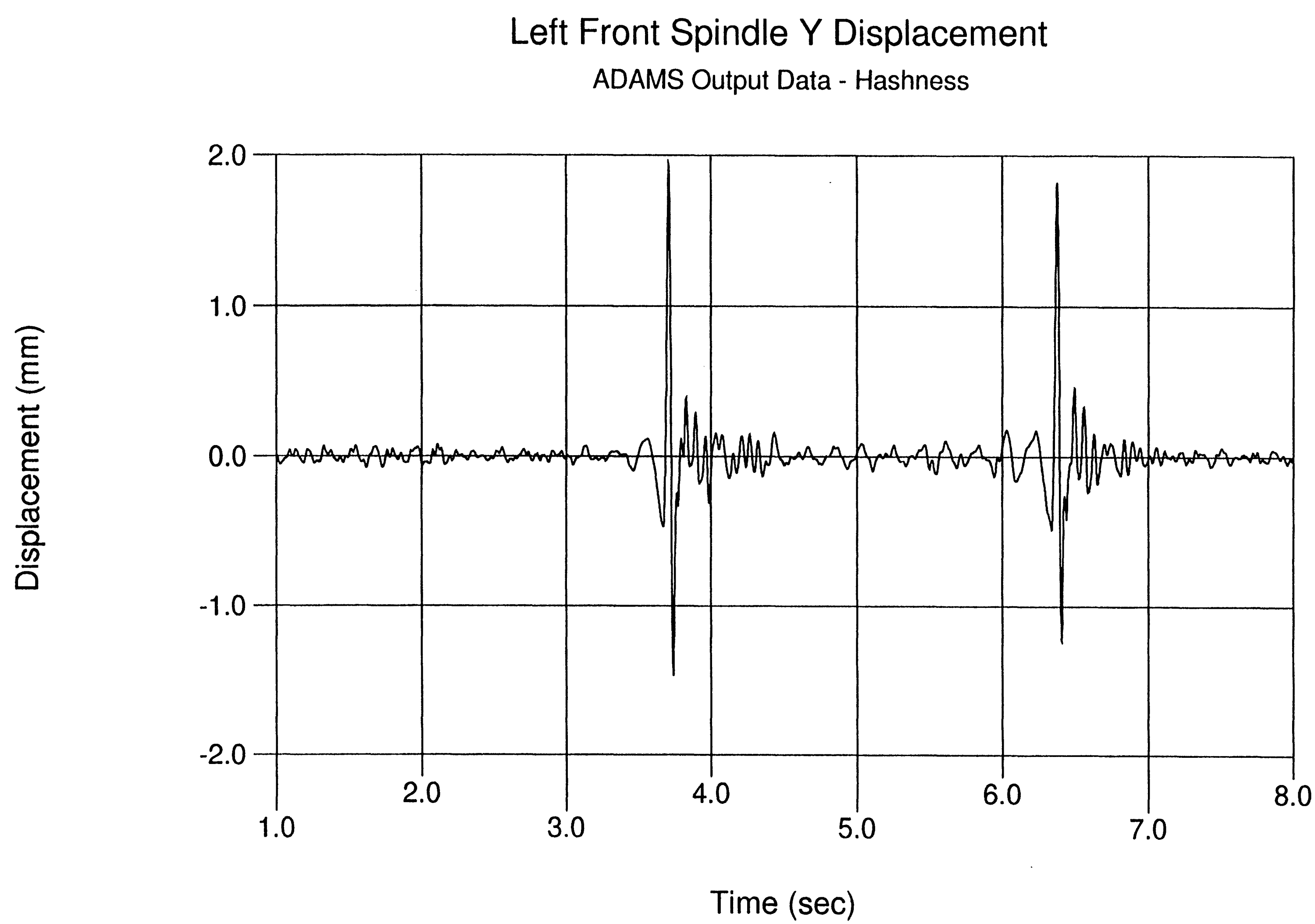

Left Front Strut Z Force
Power Spectrum - Frequency Dependent Bushing
Force (N)
20.0
15.0
10.0
5.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
Frequency (hz)

APPENDIX C: Harshness Case Study Results

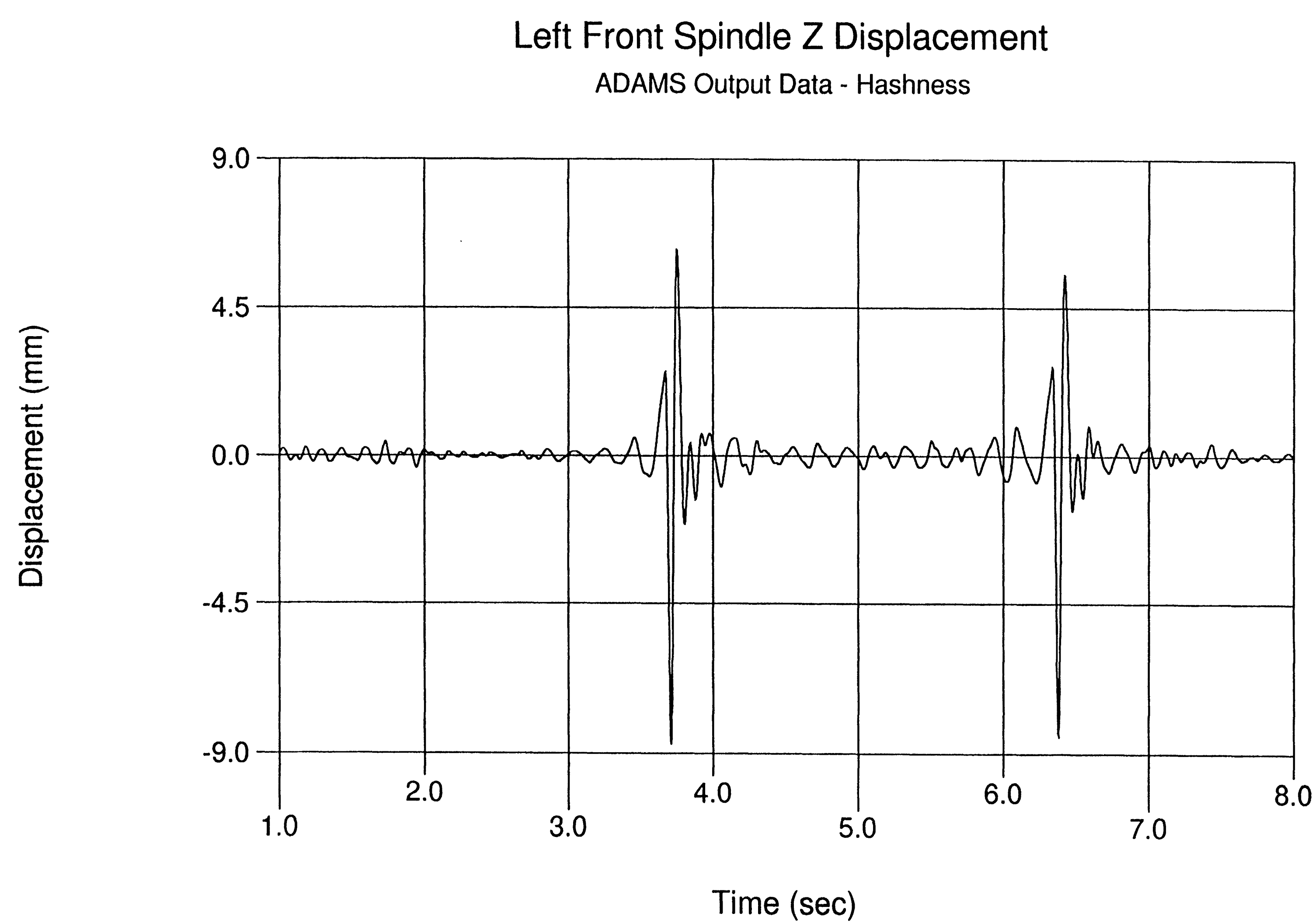
Left Front Spindle X Displacement

ADAMS Output Data - Hashness

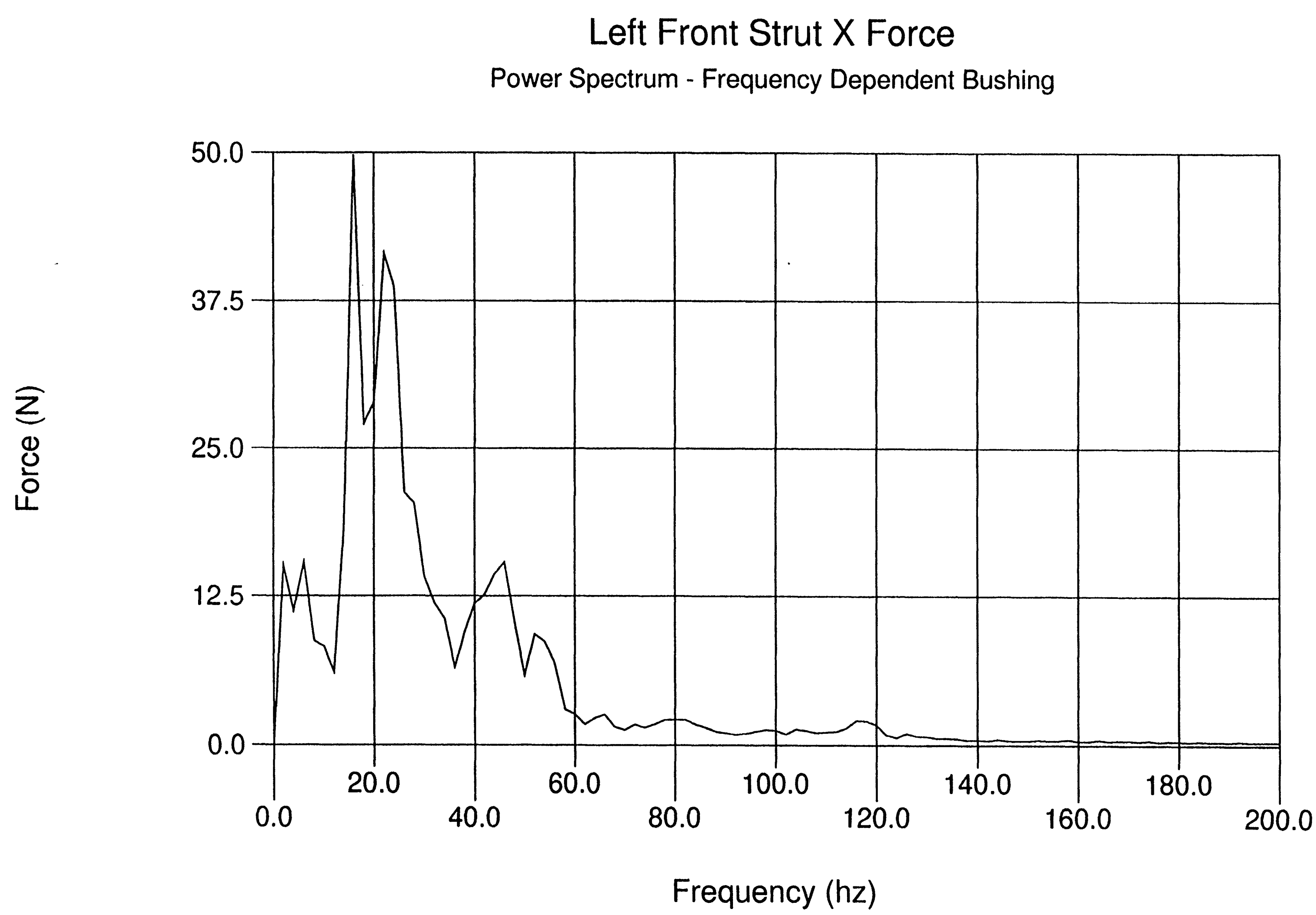




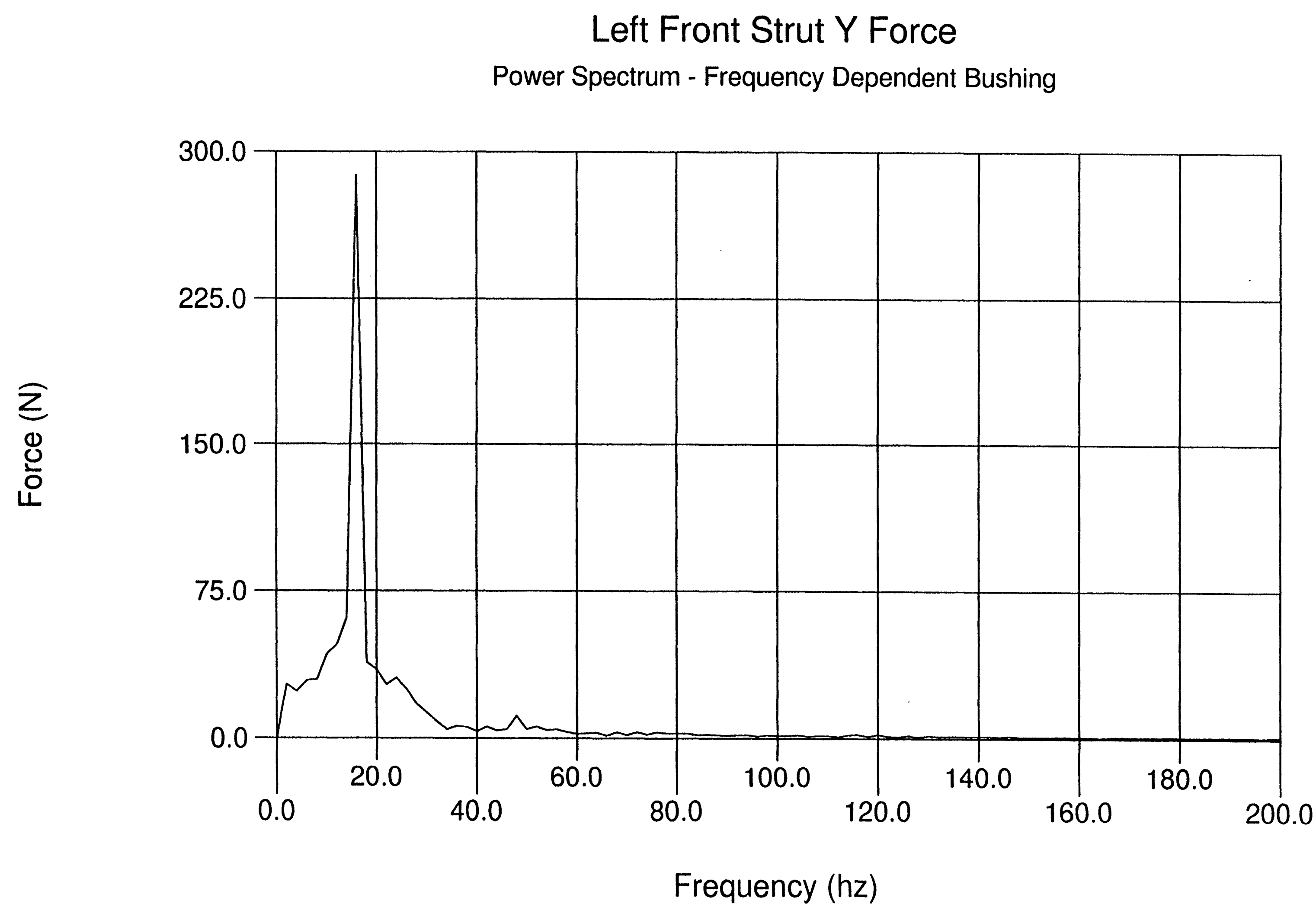
Left Front Spindle Y Displacement
ADAMS Output Data - Hashness
Displacement (mm)
2.0
1.0
0.0
-1.0
-2.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Time (sec)



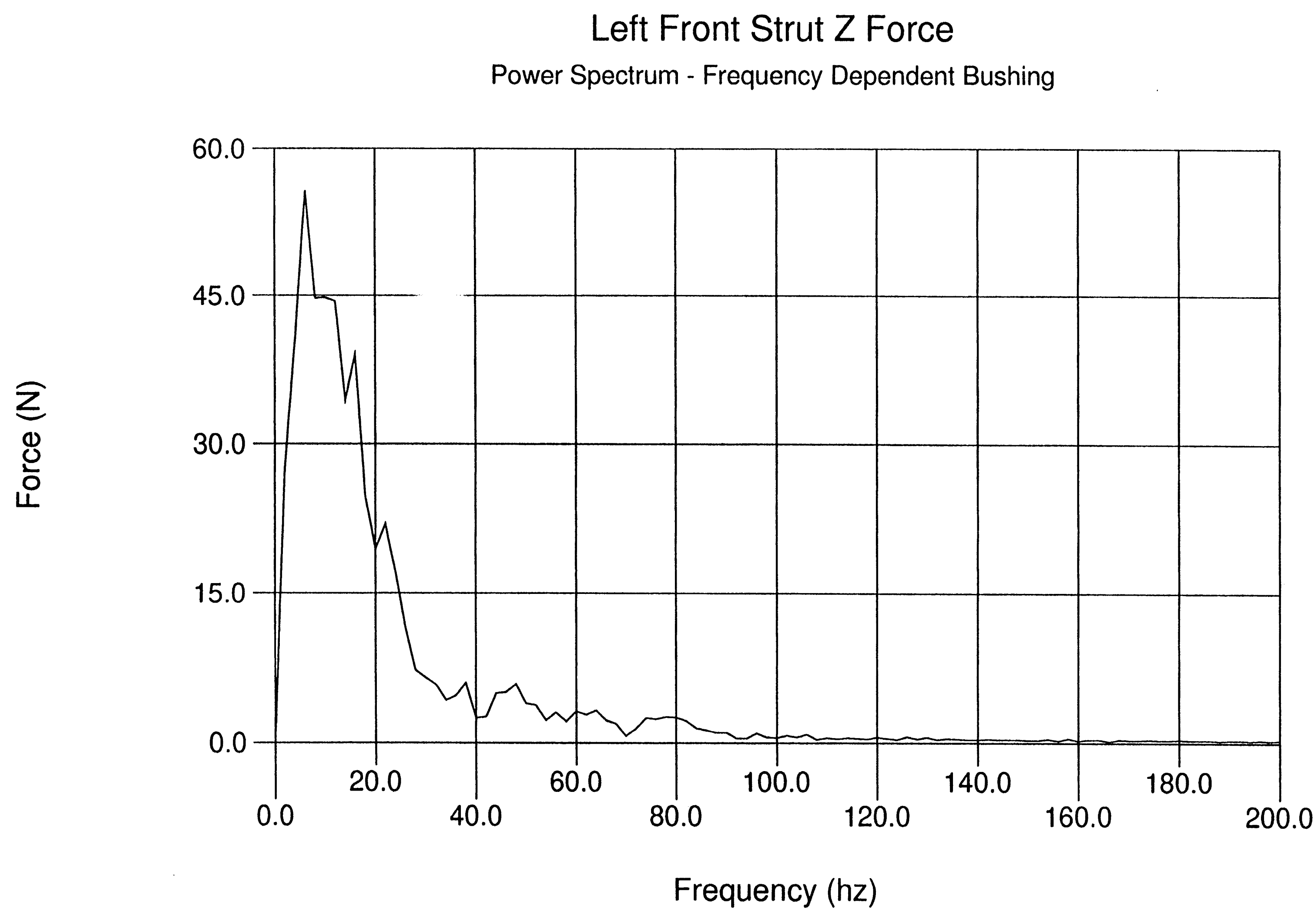
Left Front Spindle Z Displacement
ADAMS Output Data - Hashness
Displacement (mm)
9.0
4.5
0.0
-4.5
-9.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Time (sec)



Left Front Strut X Force
Power Spectrum - Frequency Dependent Bushing
50.0
37.5
25.0
12.5
0.0
Force (N)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
Frequency (hz)



Left Front Strut Y Force
Power Spectrum - Frequency Dependent Bushing
Force (N)
300.0
225.0
150.0
75.0
0.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
Frequency (hz)


Left Front Strut Z Force
Power Spectrum - Frequency Dependent Bushing
Force (N)
60.0
45.0
30.0
15.0
0.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
Frequency (hz)