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The Vibration Virtual Environment for Test Optimization (VETO)

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A new test simulation tool is being developed to support vibration test design and to evaluate the overall testability of a component or system. This environment, the Vibration Virtual Environment for Test Optimization (VETO), is utilized to optimally place vibration control and response transducers and to investigate the selection of test parameters needed in the design and performance of a vibration experiment. The engineer can investigate the effects of different control parameters prior to performing an actual vibration test. Additionally, new and existing fixture designs can be evaluated through the development of analytical or experimental models that can be integrated into the simulation environment. This test design environment also provides the engineer with the ability to combine analytically or experimentally derived models of the vibration test hardware, instrumentation and equipment into a simulation model that represents the vibration testing capability. Hardware-in-the-loop simulations can be conducted using this model to examine multiple facets of the test design. This paper presents a new tool that will assist test engineers in maximizing the value of vibration tests through the use of hardware-in-the-loop simulations.

INTRODUCTION

A test simulation and optimization tool which combines aspects of analysis and test to support a new product design and development concept is presented. This concept implements well defined tests early in the design cycle enabling the realization of highly reliable components and systems. The purpose of developing the VETO simulation environment [1] is to provide engineers with an essential tool needed to support this design approach. The specific research activity that will be discussed in this paper is the development and implementation of a vibration simulation environment. This simulation tool will help modify the conventional testing paradigm which normally tests a product only at the end of development, after hardware manufacturing decisions have been made [2].

The Vibration VETO is a new test simulation tool which reduces test iterations, producing better vibration tests through optimal test design. Communication between testing and analysis engineers is enhanced early in the design cycle through the use of this simulation environment. A goal in developing this tool is to provide test and analysis organizations with a capability of

simulating a vibration test within the computer using analytical or experimental models to achieve a better, faster and cheaper product. These models of the test instrumentation, equipment, and hardware can be combined with actual vibration test hardware (both vibration control and data acquisition systems) to provide a hardware-in-the-loop (HWIL) simulation of the vibration test, Figure 1. These HWIL simulations can be performed rapidly and can help identify and evaluate vibration test parameters before running the actual test.

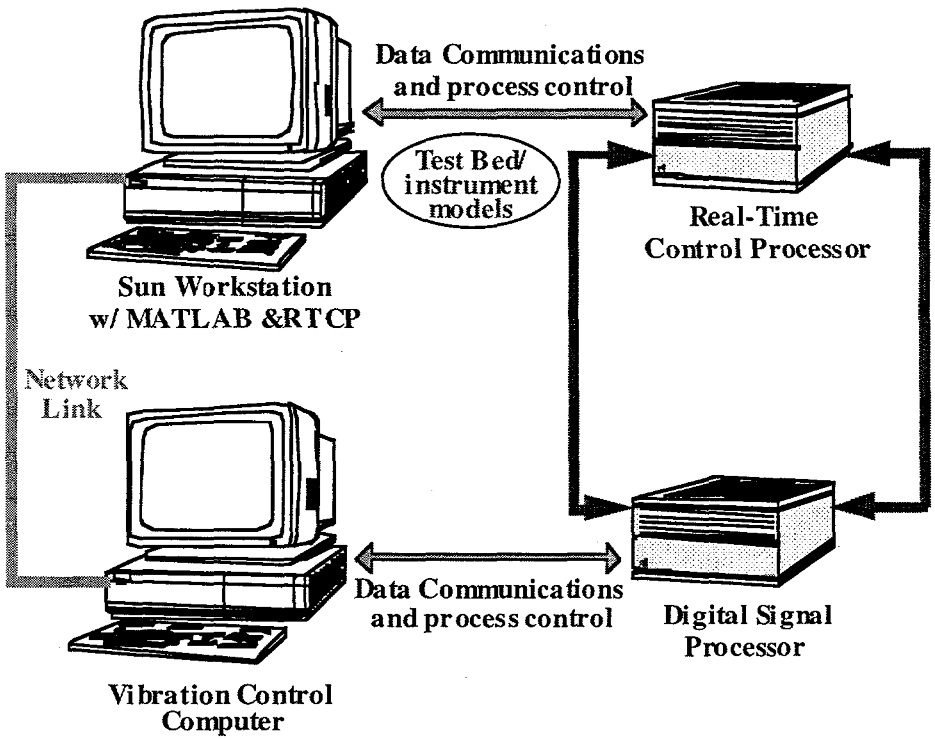

Figure 1. Vibration VETO Concept

Existing software and analysis tools are used wherever possible to provide the necessary functionality and flexibility for these HWIL simulations. Because the studies are performed within the computer, the test engineer can evaluate the overall testability of the component or system before actual placing the test hardware onto the vibration shaker. The benefits of using a vibration test simulation tool can be very extensive and can help limit unnecessary vibration inputs to items such as flight hardware and expensive one-of-a-kind systems. Additionally, this tool will provide the engineers with a mechanism for simulating vibration response of a component or system and maximizing the value and information that can be gathered from a vibration test.

The Vibration VETO environment is being constructed to support both production and development vibration testing. Thus, two distinct simulation approaches are being developed to provide an environment that addresses the different requirements in these particular vibration testing areas. The first approach is a vibration simulation environment in which the engineer has access to prototype hardware for the development of an experimentally-based model. This simulation model is developed using measured data from a low level vibration excitation and system identification tools [3]. The model is then downloaded onto a real-time control processor [4] in preparation for the HWIL simulation. The second approach is analytically-based and requires the use of a numerical model of the vibration test hardware which is combined with instrumentation and equipment models to support the test design. Furthermore, this simulation model is downloaded onto a real-time control processor for supporting the vibration HWIL simulations. More details about these two approaches will be discussed in the following sections of the paper.

For both of these vibration virtual environment approaches, the database and user interface functions are performed in the Vetomain module, Figure 2. This main interface provides the

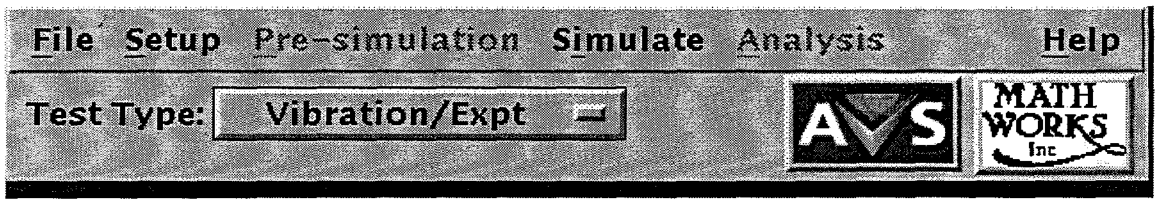

Figure 2. Vetomain Graphical Interface

necessary tools for developing a desired simulation model (either analytically or experimentally based) and then linking that model to the real-time processor. Vetomain is used to set up the vibration control and data acquisition systems needed in the HWIL simulations. This interface will allow the user to load analytical models and previously defined virtual test files into the VETO environment.

EXPERIMENTAL APPROACH

The experimental approach for the vibration test simulation requires access to test hardware for the development of an experimental model used in the simulation. Often, the test engineer has access to a mass mock-up of a particular component that can be used to evaluate the overall testability and to observe the effects of different control parameters on the vibration test. Futhermore, the recent development of numerous rapid prototyping techniques [5] makes access to physical hardware for this experimental approach more attainable. Another useful advantage of this approach is that often the numerical model of a component is not available making a model-based simulation infeasible. Using this experimental approach, the test engineer can design a vibration test and perform numerous test simulations without subjecting the actual test hardware to the full level vibration inputs. Full level component responses can be predicted using experimental models in the HWIL simulations and vibration test limitations, such as power amplifier current limits for shaker shock or vibration testing, can also be identified using this simulation environment. This experimental approach could also be used in evaluating fixture designs.

The first step in the experimental vibration VETO is the setup and initialization of the vibration control and data acquisition systems that will be used in the HWIL simulations. This setup procedure is the same procedure as preparing for a physical test. The prototype hardware is fixtured and placed on the vibration table in order to make the dynamic response measurements used in developing a system simulation model. The number of control transducers, the location of the transducers and the control strategy are selected for the vibration test. The use of multiple control transducers will allow the engineer to investigate which transducer yields the best system response. Also, the prototype test hardware is instrumented with transducers at locations where the response of the component is desired.

The next step is to excite the prototype hardware with a low level broadband random input. The responses from all the transducers are measured and frequency response functions (FRFs) are calculated. These FRFs are referenced to the computer drive signal that is output to the power amplifier. In addition to the response and control transducer measurements, the instantaneous current and voltage from the power amplifier are also measured and used to identify vibration test system limitations. These power amplifier measurements can be used to develop a full level current envelope for force limit testing.

The FRFs that are measured during the low level excitation are converted into a universal file format [6]. These files are read using a universal file translator and are loaded into MATLAB and some initial data processing of the FRFs is performed before a system simulation model can be developed. The FRFs must be transformed into representative impulse response functions for use in the system identification code. The Eigensystem Realization Algorithm with Data Correlation (ERA/DC) is the time-domain system identification tool used to generate a discrete state-space simulation model of the vibration environment. This state-space model can be used in the vibration HWIL simulations.

With the use of a graphical interface, the state-space simulation model of the vibration test is downloaded onto a real-time control processor. With the simulation model residing on the processor, the vibration control and data acquisition systems are disconnected from the power amplifier/shaker system and are connected to the processor in order to perform the vibration HWIL simulations. The particular processor used in our simulation environment was developed in-house and has the capability of handling 16 inputs and 16 outputs with a total of 128 states. The sampling rate of the processor is based on the number of states, inputs and outputs in the derived simulation model. Different input levels can be evaluated and responses measured. Based on the results of the HWIL simulation, the test engineer may determine that control parameters as well as response and control transducer locations need to be adjusted or changed.

EXPERIMENTAL APPLICATION

A weapon component was selected as the test case used to demonstrate the experimental HWIL approach. Figure 3 shows a picture of the actual component mounted to a vibration shaker table. A control accelerometer was located at the base of the component on the test fixture and six response accelerometers were placed on the component in order to measure the response behavior. Our goal in conducting this experimental application was to develop a model of the vibration test setup for this particular weapon component and to use this model in a HWIL simulation to help make vibration test design decisions. By exciting the weapon hardware with a nominal low level random input, a system simulation model was developed and used to support a HWIL simulation. Using this simulation model, vibration test studies were performed by applying component level specifications (both shock and vibration) to the model through the HWIL environment.

The simulation model was generated for the entire external load of the test setup which included all aspects of the vibration environment (the shaker/amplifier, interface block, fixturing, device under test, transducers and signal conditioning elements) from the voltage drive output of

Figure 3: Weapon Component on Shaker Table

the vibration control system through the response at the data acquisition box. FRFs referenced to the computer drive signal were calculated for all seven accelerometers and the amplifier current and voltage measurements. These nine FRFs were then translated into a universal file format and downloaded via a network link to MATLAB where the system identification was performed. Figure 4 shows a comparison of an original measured response FRF with a synthesized FRF

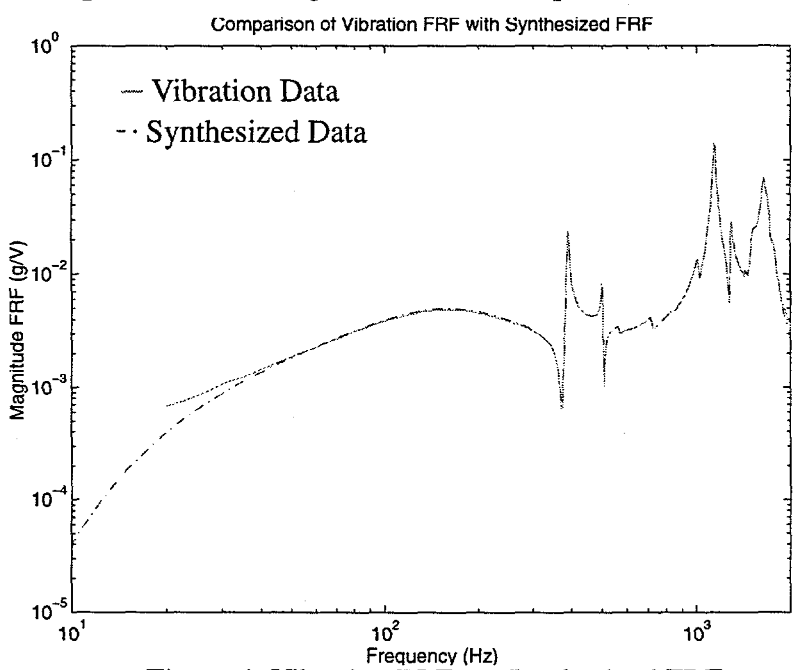

Figure 4: Vibration FRF vs. Synthesized FRF

generated from the system identification process. The ERA code produced a very good representation of the original data using 48 states. Only the low frequency responses, less than 40 Hz, showed any significant deviation in the comparison.

The output of the ERA code was a state-space model of the external load. This model was downloaded onto the real-time control processor and the processor was physically linked to the vibration control and data acquisition systems. Once the model was prepared for the HWIL simulation, initial simulations were performed at the low level inputs used in generating the model to assess model integrity. By comparing the simulation outputs to the original vibration data, the amplitudes of the simulation FRFs were confirmed, Figure 5.

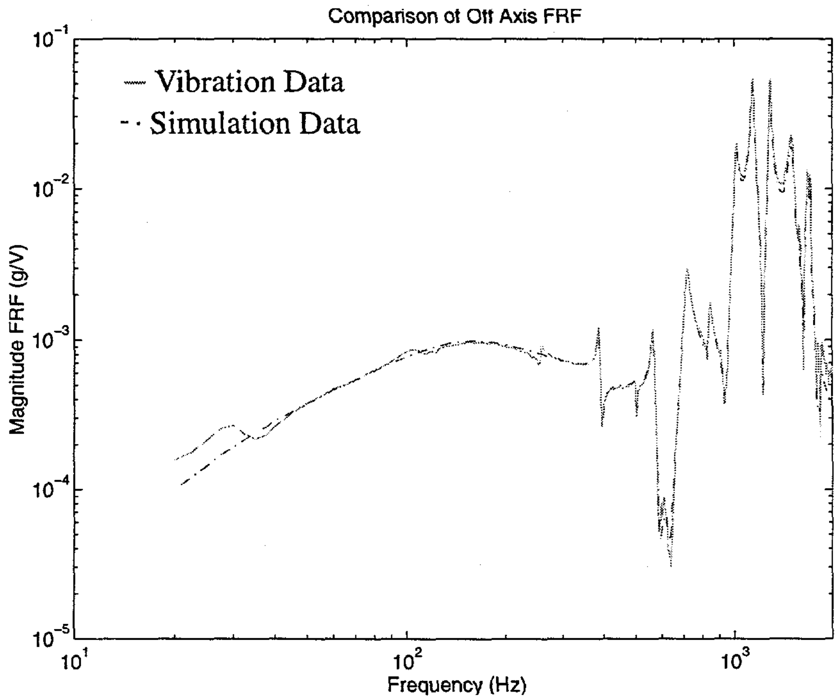

Figure 5: Comparison of Low Level FRF Data

After confirming the integrity of the simulation model on the control computer, the next step was to introduce a shaped component level vibration specification (at 8.7 grms) as input into the model. This environment was selected as a typical vibration qualification level. The output of this simulation was measured and analyzed with the vibration control/data acquisition system. A vibration test was conducted using this same vibration specification with the results of this physcial vibration test being compared to the HWIL simulation, Figure 6. This particular simulation application shows the advantage of using the vibration HWIL simulations to be able to predict component behavior at required vibration test levels. However, it should be noted that one of the limitations to this simulation approach at this time is that the model is linear and will not accurately predict non-linear response behavior in the component as the test levels are increased into a non-linear regime.

An additional study was conducted by selecting another transducer location (an existing accelerometer on the forward dome of the component) as the control point for the 8.7 grms random vibration input. Using the same simulation model, a HWIL simulation was performed for this configuration. Also, a test was completed with this location selected as the control point and the comparison of the test and simulation drive spectra is shown in Figure 7. This comparison of

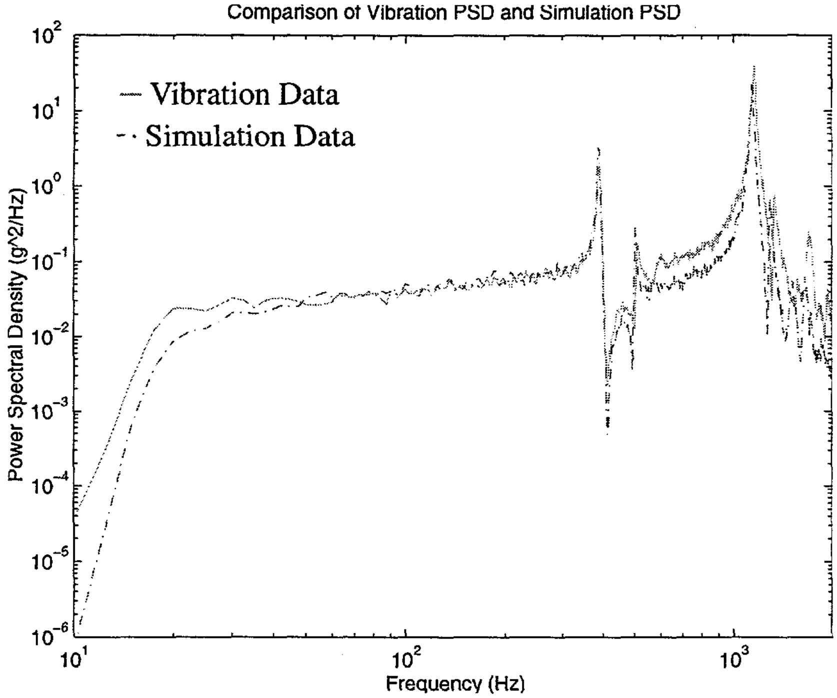

Figure 6: Comparison of Vibration Test PSD and Simulation PSD

the drive spectra indicates that the location on the forward dome is not an optimal location for controlling the test. The deep notches in the spectra are frequencies at which the control system has difficulty removing enough energy to match the desired reference spectrum on the forward dome. These results show the strength of this simulation and optimization environment that allows the engineer the ability to develop a model that includes multiple potential input locations to determine which location is the best for controlling the test.

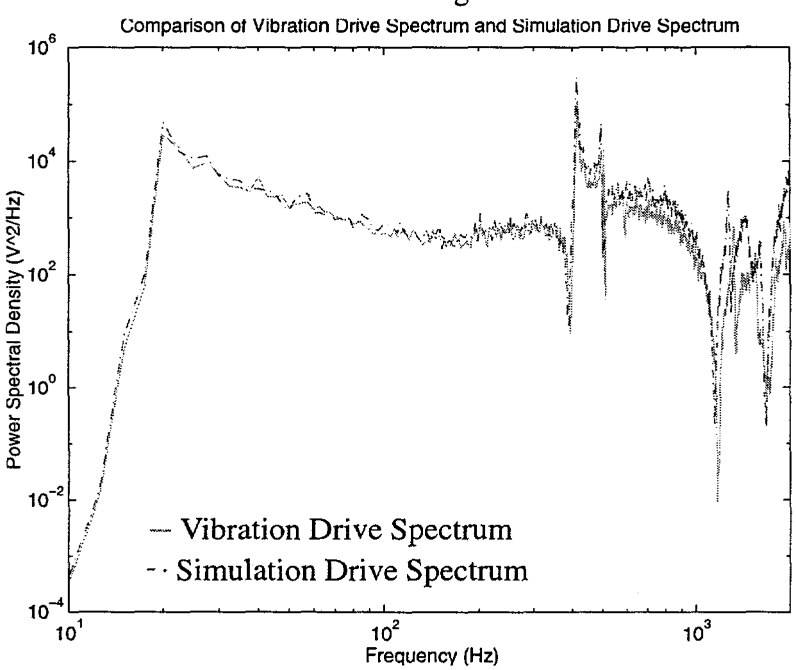

Figure 7: Comparison of Vibration Drive and Simulation Drive Spectrums

Finally, a component level shaker shock (approximately 40 g's) was used to excite the model in order to predict the component response to this transient input. Using the HWIL simulation environment, the test engineer was able to observe the power amplifier current and voltage requirements needed to perform the desired shock simulation. This information was then used to help determine if the requested shock level could be attained on the vibration shaker table. The results of the amplifier current response from the shock simulation and actual shock test are shown in Figure 8.

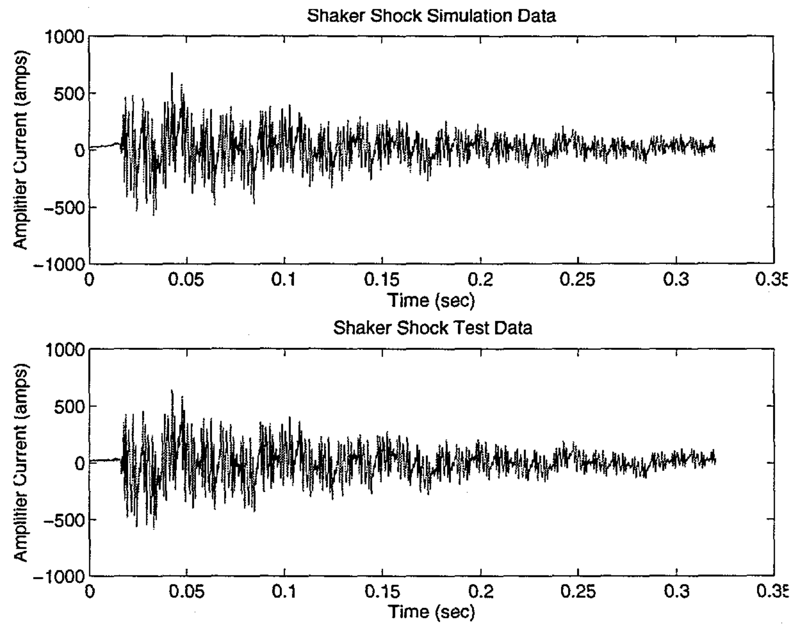

Figure 8: Comparison of Amplifier Current for 40 g Shaker Shock

FINITE ELEMENT ANALYSIS APPROACH

This research work has also focused on another simulation approach. This particular approach relies on the use of computational models to generate a vibration test simulation model when prototype hardware is not available. The Finite Element Analysis (FEA) approach has a number of similarities to the Modal VETO that was developed for designing and simulating modal tests. One of the major similarities is the use of a visualization software environment (AVS) to allow the user to interact with the FE models that have been developed. Computational models of the external load (the shaker/amplifier, interface block, fixturing and device under test) will be used to support this vibration test design. The engineer will be able to directly select desired control and response locations by interfacing with the analytical model in the visualization environment. Using the requested control and response locations and the finite element analysis response data, a state-space model is constructed for use in the HWIL simulation. This state-space model will be combined with instrumentation models (accelerometers and signal conditioning elements) and then be downloaded onto a real-time control processor for the HWIL simulations. This downloading process is similar to the one described in the experimental approach.

This particular test simulation approach is currently under development. There are a number of analysis and experimental modeling activities that are being conducted to support this FEA simulation environment. Computational models of the external load are in the development stages for the particular weapon component described in the experimental approach section. Once these models have been completed and combined into a single system computational model, a comprehensive finite element analysis will be conducted on the model. Figure 9 shows the current state

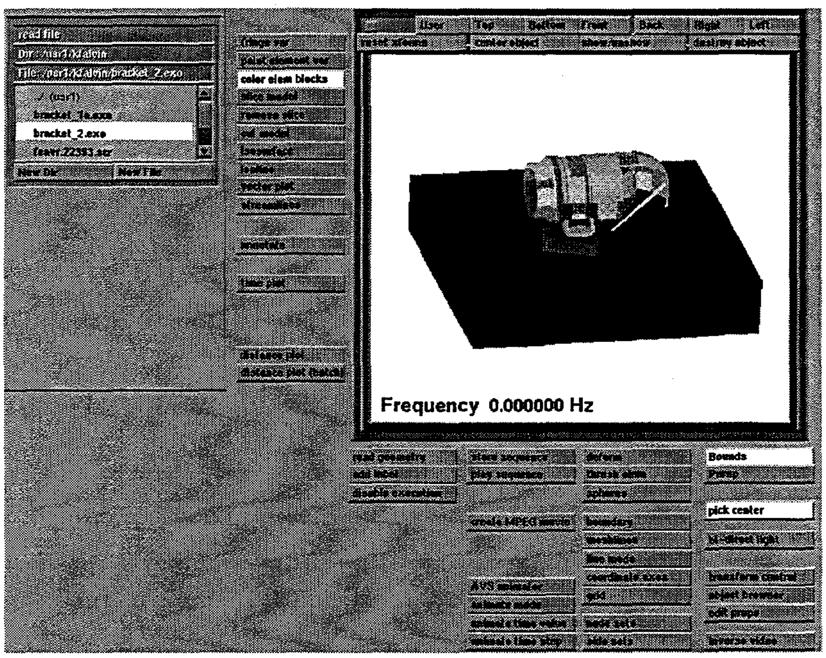

Figure 9: Analysis Models of Weapon Component in VETO

of this model in the VETO visualization environment. A detailed analysis of this particular model representation has not been completed at this time.

Current experimental activities that are being conducted to support this FEA approach are related to the development of a process for determining the shaker force using the power amplifier current and voltage measurements [7,8, 9]. These efforts are focused on calculating the interface forces between the shaker armature and the block fixtures in order to provide an appropriate force input into the analysis model for the simulation. In addition, these calculated forces for a particular shaker system can also be used to estimate the driving point impedance of the system for comparison and validation of the finite element model. Ultimately, the estimation of these interface forces in the simulation environment will be applied in force controlled or force limited vibration tests.

CONCLUSIONS

An important goal in developing the Vibration VETO environment is to provide the test engineers with a tool that enables the design of vibration and shaker shock tests using models of the test setup. This paper has demonstrated an experimental approach to create and use these models in HWIL simulations to make comparisons between simulations and data from actual shaker tests. The benefits of using this simulation environment can easily be observed. By adjusting the simulation input levels, the test engineer is able to perform various vibration test simulations to observe the changes in component response based on a linear model. Additionally, the engineer uses this tool to identify an optimal control location for the vibration test. Finally, the analysis of the amplifier current and voltage measurements is used as a means to determine if the full test level is possible and allows the test engineer to evaluate different test methods. All of these simulation capabilities require the use of the test simulation model and minimize unnecessary vibration test inputs to a component or system.

ACKNOWLEDGEMENT

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