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STRUCTURAL DYNAMICS TEST SIMULATION AND OPTIMIZATION FOR AEROSPACE COMPONENTS

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ABSTRACT:

This paper initially describes an innovative approach to product realization called Knowledge Based Testing (KBT). This research program integrates test simulation and optimization software, rapid fabrication techniques and computational model validation to support a new experimentally-based design concept. This design concept implements well defined tests earlier in the design cycle enabling the realization of highly reliable aerospace components. A test simulation and optimization software environment provides engineers with an essential tool needed to support this KBT approach.

This software environment, called the Virtual Environment for Test Optimization (VETO), integrates analysis and test based models to support optimal structural dynamic test design. A goal in developing this software tool is to provide test and analysis engineers with a capability of mathematically simulating the complete structural dynamics test environment within a computer. A developed computational model of an aerospace component can be combined with analytical and/or experimentally derived models of typical structural dynamic test instrumentation within the VETO to determine an optimal test design. The VETO provides the user with a unique analysis and visualization environment to evaluate new and existing test methods in addition to simulating specific experiments designed to maximize test based information needed to validate computational models. The results of both a modal and a vibration test design are presented for a reentry vehicle and a space truss structure.

INTRODUCTION:

This paper presents the Knowledge Based Testing (KBT) concept which incorporates aspects of design, analysis, and test with rapid prototyping to optimize test based product information from an experiment. The purpose of developing a KBT program is to utilize testing earlier in the design cycle. There are a number of research activities that will be discussed in this paper that help modify the conventional testing paradigm that normally tests a product at the end of development.

One of these research areas being developed is the Virtual Environment for Test Optimization, VETO[1]. This innovative test/analysis tool reduces test instrumentation iterations, producing better tests through optimal test design. Communication between test and analysis engineers is enhanced early in the design cycle. Traditionally, the role of testing in the product realization process is limited to the end of the design cycle, after hardware manufacturing decisions have been made. As a result, data analysis and test requirements for a component are only considered when the hardware is scheduled for testing. Thus, the full benefit of the analysis in guiding the test is not realized. A goal in developing this software tool is to provide test and analysis organizations with a capability of mathematically simulating the complete test environment within a computer. Derived models of test equipment, instrumentation and hardware, called virtual instruments, can be combined within VETO to provide the user with a unique analysis and visualization capability to evaluate new and existing test methods. By providing engineers with a tool that allows them to optimize an experimental design within a computer environment, pre-test analysis can be performed using analytical models to rapidly evaluate components before manufacturing has occurred. The benefits of using this type of experimental design tool can be very extensive. The user can evaluate the use of different types of test instrumentation and equipment as well as investigating new testing techniques for system identification used to experimentally validate analytical models.

A second research activity has focused on using the recently developed stereolithography process[2,3] to reduce the time between concept and product realization by evaluating plastic models to predict the structural behavior of actual metal parts. This

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stereolithography process has provided the means of economically generating very exact plastic prototype parts from three dimensional solid models. This process rapidly produces prototype plastic parts with astounding accuracy including bolt holes, countersinks, fillets, cutouts, etc. These stereolithography plastic prototypes include all the detail and are nearly perfect replicas of the actual parts. They afford detail that cannot be included in finite element models without extremely expensive high order meshes of very small features which may be important to the structural performance of the design.

These prototypes are currently used primarily to verify geometries, for interference checks, and for product visualization. The ability to perform mechanical tests on these plastic prototypes and infer actual metal part structural performance could significantly reduce design cycle times. Mechanical tests of interest include static loading, modal testing and vibration testing. These rapid prototype test results could also be used to validate analytical models early in the design process to provide predictive models for effective design iterations and tradeoff studies. These very exact plastic prototypes offer a new realm of opportunity for the use of plastic models to predict the structural performance of actual metal parts.

A third area of ongoing research related to the KBT program is in computational model validation[4]. Improved finite element modeling techniques and the ever decreasing cost of computing have been a major contributor to the increased capability of computationally-based engineering simulations. The current trend toward increased reliance on simulations for design and performance evaluation is pervasive throughout the industry. However, within the KBT program it is also recognized that there is a need for increasingly sophisticated testing and physical simulation that is essential to the development and validation of engineering models. Thus, by combining the use of the VETO, to optimally design an experiment, with the use of rapid prototyping techniques for generating component parts, the processes of model updating and validation becomes much more efficient. These tools are critical to providing test based information needed to produce confidence in the predictive capabilities of computational models of aerospace components.

KNOWLEDGE BASED TESTING (KBT) OVERVIEW:

As was mentioned in the previous section, the goal of the KBT program is to position testing earlier in the design cycle. This new vision or role for testing is partly motivated by increased modeling capabilities as well as the recent increase in computational power. In this vision, the definition of testing will not simply mean to provide the "admiral's tests" but will be used as an underlying tool that is essential to model development and validation. A view of the KBT concept is shown in Figure 1. This bubble chart depicts the important interactions between design (starting with requirements and specifications), analysis and test used to support rapid product realization.

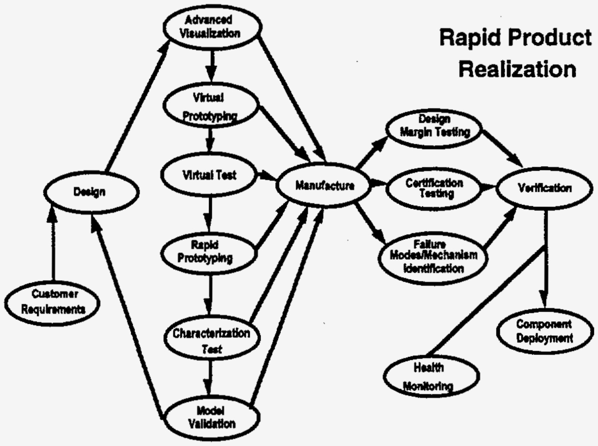

Figure 1. Knowledge Based Testing Chart

The initial step in the KBT program is the generation of a computer aided design model which represents the geometry of the component or component housing to be tested. This model is generally driven by certain requirements and specifications. This geometric model is then used to assist component visualization, to generate a computational model used for dynamic analysis, and to produce a rapid prototype component through a stereolithography or "fastcast" process[*][5]. The developed computational model of the component is then combined with analytical and/or experimentally derived models of the test instrumentation within the VETO software to determine an optimal test design. The VETO is then used to simulate the structural dynamics experiment in order to maximize the test based information gathered from the experiment. The next step in the KBT process is the performance of the experimental test or characterization test using the rapid prototype component given the VETO test design. The results of this experiment are then used to update and validate the computational model.

This systematic approach to rapid prototype evaluation integrated with optimal test design software is an

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[*] Fastcast uses a stereolithography or laser sintered part as a mold for an automatic metal casting system.

important part of the KBT concept that helps bridge the gap between the old testing paradigm and this new testing vision. Design and analysis methods are integrated to support test simulations. These computationally-based simulations provide predictions of component or system response to testing environments and the results of these simulations are then used to guide an actual characterization test. By completing the test design within the virtual environment, the user can effectively evaluate what test information is needed from the experiment to update and validate the computational model. After this validation process is complete and some level of confidence is established in the computational model, further optimization and simulation studies can be performed using the model before any manufacturing or building of the component is done. It should be noted that the KBT concept also includes aspects of testing necessary for product verification. The KBT definition of product verification includes certification testing, design margin testing[6] and failure mode/ mechanism identification testing. Long term monitoring of component performance is the final type of KBT which involves health monitoring[7].

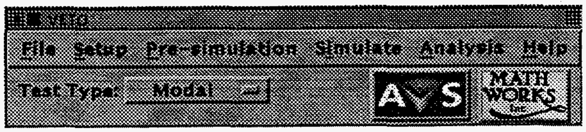
ROLE OF STRUCTURAL DYNAMIC TEST SIMULATION AND OPTIMIZATION IN KBT:

The VETO software environment currently integrates analysis and test based models to support optimal structural dynamic test design. The structural dynamics testing environment was selected as the initial VETO environment for investigation into areas of design/ analysis/test interfaces, visualization, versatility and repeatability. This initial VETO effort has focused on assisting engineers to maximize the value and information gathered from these tests.

A major objective of the VETO software development effort is flexibility. Because the virtual environment is a prototype software system, a primary concern for its design is that the code be easy to develop. To minimize this effort, existing software tools are used wherever possible, provided that the necessary functionality and flexibility are available. Another significant design objective is to provide a final software system that can be used by a variety of individuals who have not been involved in its development. As is described below, VETO integrates several commercial tools to meet these objectives.

Currently, the VETO software tool has been developed to support a modal virtual test environment while development of a vibration virtual environment is under development. Many of the tools needed to support simulations of these two structural dynamic test capabilities are similar, however, because of the various differences in these technologies, two distinct simulation approaches have been developed. The first approach, which was formulated to support modal test optimization, provided the user with an environment where numerical integration is performed on a system of state space models which described the modal test configuration. This method served very well in the support of simulations which did not include closed loop control. However, in our second approach an effort is being made to address simulations that do include control aspects, namely vibration tests. The vibration virtual environment will include hardware-in-the-loop (both control and data acquisition elements) in addition to instrument and equipment models to support the simulation. Further details on these approaches are described below.

For both of the structural dynamic testing environments, the database, integration, utility and user interface functions are performed in the Vetomain module, Figure 2. This main interface provides the communication links between the two commercial software packages: AVS which is used for visualization and MATLAB which is used to perform modeling and time integration. The "File" option of the vetomain menu bar allows users to load finite element (FE) models and previously defined virtual test files into the VETO software. The setup for the test simulation is performed using Vetomain to construct parametric models of the instruments, and to formulate interconnections between the models. The user is able to interact with the virtual instrument to provide and view information on the devices needed in the simulation. This user interaction includes the selection of the number of desired response locations, the location of input excitation and the type of instruments needed to support the simulation. This interface module also provides numerous tools to assist the engineer in setting up and understanding how the various virtual instruments interact together to support a specific structural dynamic test simulation. These tools will help guide the engineer in the design of tests that will accurately identify all the desired modes of the structure, select the appropriate test instrumentation as well as identify the proper excitation levels for the test.



Test Type: Modal

Figure 2. Vetomain Graphical Interface

MODAL TEST SIMULATIONS AND OPTIMIZATION:

The SIMULINK Dynamic System Simulation Software provided by MATLAB is used as the environment to assemble and ultimately integrate mathematical models of the modal test system. This same software controls the simulation processing. Dynamic response equations are integrated by SIMULINK to provide system output time histories. Within the VETO software, inputs such as type of device and interconnection of instrumentation models are combined to facilitate the rapid connection of various models (including models of test instrumentation, equipment and hardware) which comprise a given modal testing process. In order to achieve rapid set up of this virtual environment, models representing the instrumentation and test equipment need to be developed. These models consist of mathematical descriptions of the dynamic response of the instruments derived either theoretically or experimentally. Most of the instruments modeled to date have been modeled in the discrete state space domain. A number of system identification tools were used in MATLAB to generate the mathematical models. Development was based on an experimental frequency response function of the instrument or equipment.

The models of the different types of instruments and equipment (transducers, amplifiers, filters, etc.) needed to represent a complete modal testing environment are located in a SIMULINK Virtual Test Equipment Library (VTELib). When preparing for a test simulation, the selection of the desired test instrumentation from the Vetomain is performed with the assistance of a MATLAB code which searches the VTELib for available instrument models. Optimal experimental design and simulation of the complete test environment is further facilitated by the VETO's ability to include models of external inputs and electronic instrumentation noise. In addition, complex instrumentation models, such as the data acquisition system (Front End), are constructed by combining multiple submodels to simulate the dynamic response behavior of the hardware.

As these models are added to the new simulation system, interconnecting lines are placed between the block models within SIMULINK. These lines represent the flow of signals in the actual modal test system and are specified using the "wire" instrument in Vetomain. Using these interconnecting lines, the input signals from the actuator devices (e.g. impact hammers) are fed to both the device under test (DUT) model for simulation of system excitation and to the "Front End" device for simulation of data acquisition. This DUT model is directly generated using the FE modal data given the user desired input and sensor locations for the simulation. The "Front End" device also receives the signals from the sensors that have been attached to the DUT to simulate structural system response to the actuator input. Both the simulated actuator and sensor signals are linked through amplifier and filtering blocks to represent preconditioning of the signals.

The process of simulation begins when the user selects "Run" from the "Simulate" option on Vetomain. The data files which define the dynamics of the desired instrumentation are loaded into the test simulation system and the "Simulation Monitor" is created and displayed. This monitor allows the user to observe the estimated system response based on the numerical integration. The Simulation Monitor represents the data acquisition environment commonly used to gather data in a physical test and is a graphical interface through which the user interacts with the modal test simulation system. After collecting the desired amount of simulated data, the user can activate a window providing an interface to analysis routines for computing measures such as frequency response functions, power spectral densities and coherence based on the simulated data.

MODAL TEST APPLICATION:

An aerospace component was selected as a test case for application in the VETO environment. The VETO software simulation tool was used to design an optimal experiment for this mock reentry vehicle, Figure 3. The goal of performing this test design optimization was to observe the vibration modes of interest and to study the interaction of the support flanges with the reentry vehicle housing. The initial steps in the test design

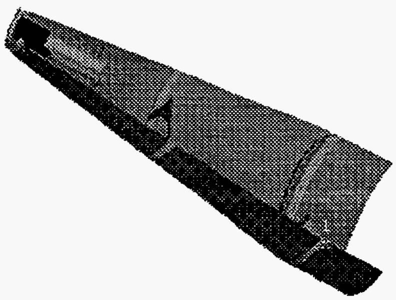


Figure 3. Mock Re-entry Vehicle Model

were to select an appropriate set of instrumentation (including sensors and actuators) needed to perform a modal experiment within the VETO environment and to simulate responses on the aerospace component. A symmetric finite element model of the structure was loaded into the VETO environment for use in the modal test simulation. The test design was performed over a frequency band, up to 250 Hz, which included fifteen vibration modes of the reentry vehicle.

The outcome of the VETO test design "Setup" was to excite the structure using an impact hammer and to measure acceleration responses on the reentry vehicle at 40 different locations in order to characterize the dynamic behavior of the component. Approximately half of the response locations were automatically selected using an analysis code to optimize the sensor locations. Some care was taken in utilizing this code to ensure that redundant or closely spaced response locations on the structure were not used in the simulation. Other instrumentation such as the signal conditioning amplifiers and the data acquisition system were also set up with the use of Vetomain in preparation for the test simulation. Data acquisition parameters for sampling, averaging and acquiring the desired analysis measurements were also selected for use in the post-simulation analysis.

A number of "Pre-simulation" tools were used to determine the completeness of the test design. First, the effects of mass loading the component were calculated given the test design sensor set. Small accelerometers, Endevco 2250s, were selected in the test design in order to minimize the mass loading effects that might occur during the experimentation. This analysis predicted that very small changes in the frequencies of vibration (approximately 0.1%) would be experienced if an experimental test was conducted based on the selection of small accelerometers in the test design. Second, a normal mode indicator function and a driving point frequency response function were viewed before conducting the test simulation in order to assess whether the selected sensor and actuator (selected impact location) set would accurately identify all the desired modes of interest on the aerospace component, Figures 4 and 5. By using the normal mode indicator function, it was determined that a single input location at the nose of the reentry vehicle would not excite al of the modes of the structure. Therefore, additional excitation locations would need to be included in the test setup so that all the modes of vibration of the reentry vehicle could be observed. Finally, the Modal Assurance Criterion (MAC) was calculated for the test design to determine if the modes of vibration of the structure could easily be distinguished from one another given the selected sensor set. Small values on the off-diagonal terms of this MAC matrix, Figure 6, indicate the relative independence of the modes of vibration, thus facilitating correlation with analysis.

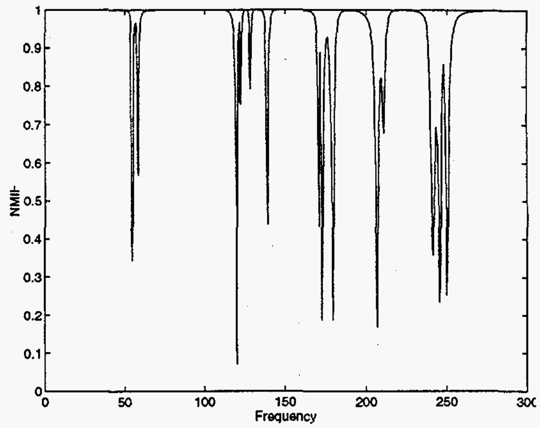


Figure 4. Normal Mode Indicator Function

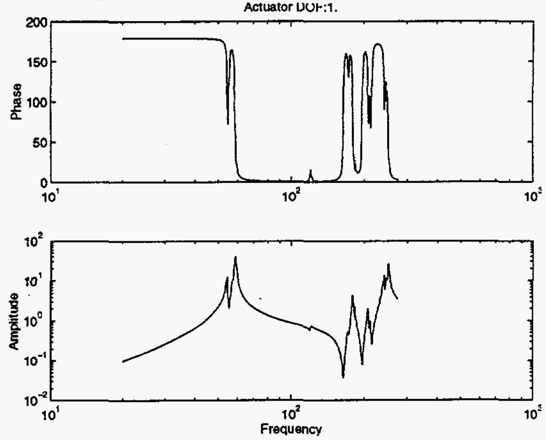


Figure 5. Driving Point Frequency Response Function

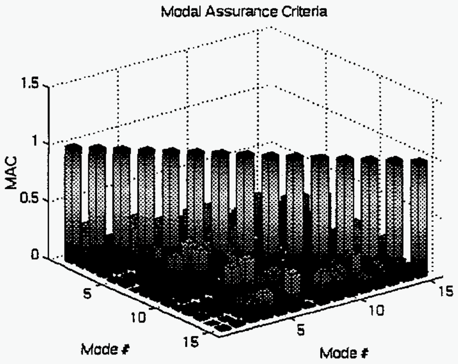


Figure 6. Modal Assurance Criterion

With the complete test design within the VETO environment, a SIMULINK block model of the test environment is automatically generated to support the simulation of the modal test. Figure 7 shows a partial

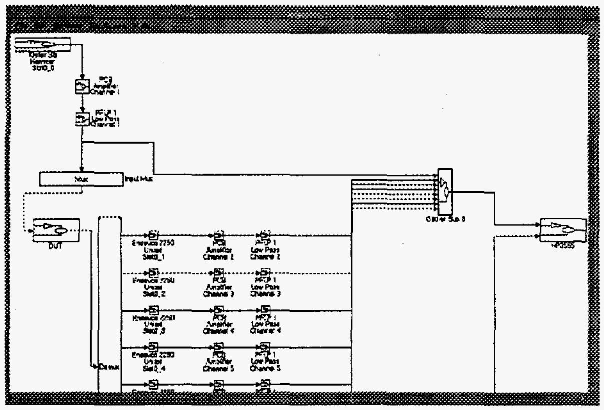


Figure 7. Modal Test Simulation Block Model

block model of the SIMULINK environment.

The next step in the modal test simulation is the numerical integration of the mathematical models within SIMULINK to estimate the system responses. Using the Simulation Monitor, these responses are observed for each set or frame of data to be collected, Figure 8. Once the data are gathered to support the desired measurement set, the test simulation within SIMULINK is concluded. A window which provides an interface to the post-simulation analysis routines is then used to download the data for measurement analysis. A number of analysis routines for computing desired measures such as frequency response functions, power spectral densities and coherences are available. The simulated data, which are based on the FE dynamic analysis, were used to generate frequency response functions, Figure 9.

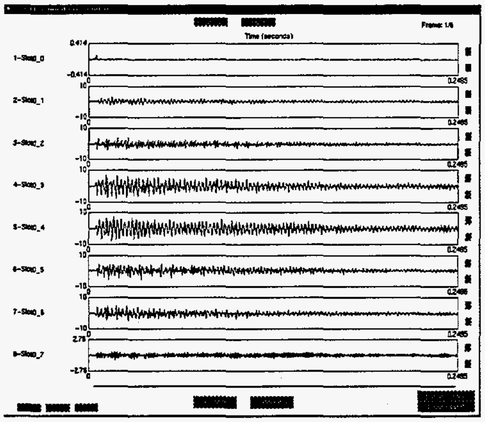


Figure 8. Simulation Monitor

VIBRATION TEST SIMULATION AND OPTIMIZATION:

As was mentioned earlier, the vibration virtual environment is currently under development. Some of the issues that must be addressed in this particular simulation environment that are not included in the modal virtual environment are: closed loop vibration control, detailed shaker/amplifier models and shaker/ fixture/component interaction. Because of these issues as well as others, it was determined that a new simulation approach would be developed using some of the existing hardware that directly support vibration tests. These simulations, called hardware-in-the-loop simulations, would provide the user with the ability to combine actual vibration test hardware (such as vibration control and data acquisition systems) with instrumentation models to support vibration test design. Models of the external load (the shaker/ amplifier, interface block, fixturing, device under test, accelerometers and signal conditioning elements) will be combined into a single state space model using MATLAB routines and then downloaded onto a real-time control processor. With the simulation model of the external load residing on the processor, the physical hardware is then connected to the processor for performing the vibration test simulation. 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 size or number of states of the model. Figure 10 shows a simple representation of this hardware-in-the-loop simulation environment.

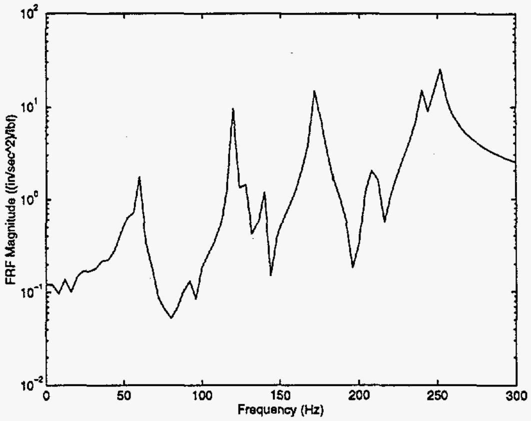


Figure 9. Measured FRF using Simulated Data

The virtual vibration environment will allow the user to evaluate the overall testability of a component or system. The test engineer will be able to observe the effects that different control parameters might have on the DUT without putting the physical hardware through an actual vibration test. An advantage of this environment is that it can help limit unnecessary vibration inputs to flight hardware. New and existing fixture designs can also be studied through the development of analytical models that can be integrated into this simulation environment. Testing

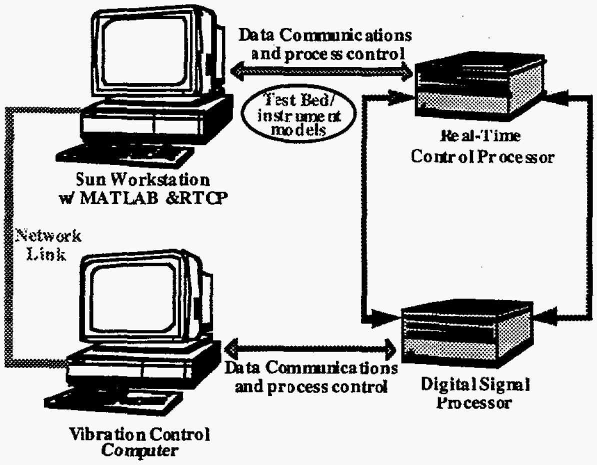


Figure 10. Vibration VETO Concept

methodologies such as the number of control transducers, the location of control transducers and the control strategy or method can also be investigated within the vibration environment. These developments will help assist analysis, design and test engineers in maximizing the value of each vibration test.

VIBRATION TEST APPLICATION:

A large gamma truss structure was selected as the test case for the vibration test simulation environment[8]. Figure 11 shows a picture of the actual truss hardware that was used to demonstrate the hardware-in-the-loop simulation concept. It should be noted that due to the ongoing development of the vibration virtual environment, not all of the instrumentation models (namely the shaker/amplifier model) were included in this demonstration of the vibration simulation capability. Our goal at this point is simply to show the hardware-in-the-loop simulation process.

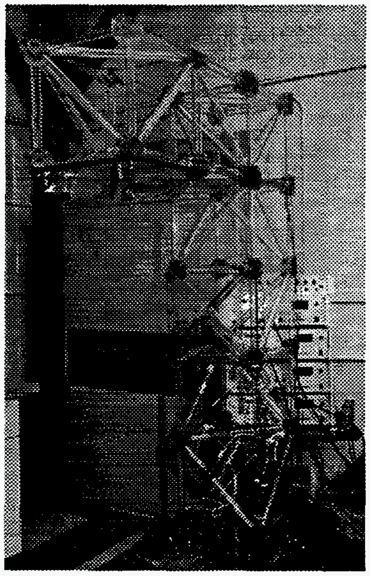


Figure 11. Gamma Truss

The truss structure was designed with integrated sensors and actuators to provide a testbed for studying structural controls applications. Through numerous control studies, experimental data had been gathered in the form of input/output models for the truss. For use in the vibration test simulation, an eight input/eight output experimental model was selected as the model that would represent the truss in the simulation. This state space model of the truss was combined with models of the sensors (accelerometers) and signal conditioning elements to form a single state space model of the vibration external load. This combined state space model was then downloaded onto the real-time control processor in order to support running the test simulation. An actual vibration test control and data acquisition system was then connected to the real-time processor for the simulation study.

A single vibration drive signal was generated from an arbitrary shaped random spectrum (up to 200 Hz) and then used in the simulation to excite the external load model on the processor. The first output or response channel from the processor was feed back into the vibration control computer as the control channel. The drive signal was updated in order to match this shaped random spectrum for the chosen control channel. This drive signal was notching at 44 Hz due to a lightly damped mode at that frequency. Figure 12 shows the drive spectrum for this vibration simulation. By utilizing this vibration test simulation environment, the engineer is able to select desired control parameters such as control Degrees of Freedom, frequency resolution and time constants to successfully control a specified vibration test, Figure 13. This simulation example shows the strong advantage of having an environment to setup and customize vibration tests.

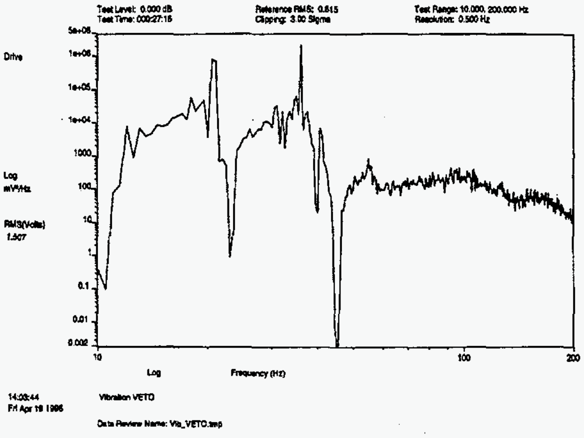


Figure 12. Vibration Drive Spectrum

Using this tool, test engineers can easily change parameters within the simulation to optimize vibration tests.

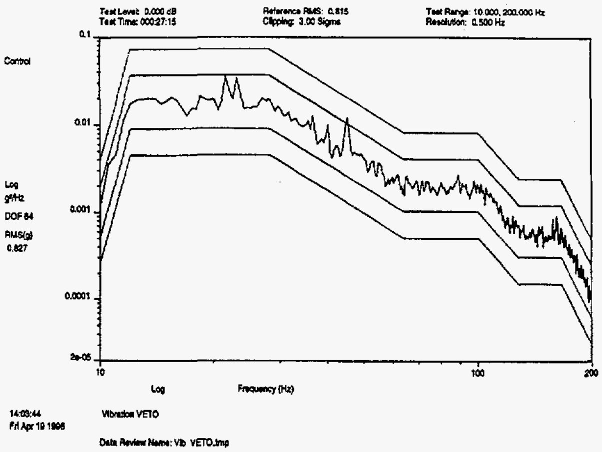


Figure 13. Vibration Control Spectrum

CONCLUSIONS:

An important goal in developing the KBT program is to provide an environment in which designers and analysts are given earlier access to test based information in order to make intelligent design decisions. There are a number of significant research activities ongoing that directly support this new testing vision. A test simulation and optimization software tool called VETO is one of these activities that helps position testing earlier in the design cycle. Using this simulation software and rapid prototype parts, characterization tests can be performed in order to generate test data needed to update and validate computational models.

Within the VETO software environment, engineers are able to investigate the testing of aerospace components, using computational models, prior to the existence of any hardware. A goal in developing this software tool is to provide test and analysis organizations with a capability of mathematically simulating the complete test environment within a computer. Applications of this test simulation environment have been shown for both modal and vibration capabilities essential to the development of aerospace components.

ACKNOWLEDGEMENT:

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REFERENCES:

[1] Klenke, S., Reese, G., Schoof, L. and Shierling, C., "Modal Test Optimization Using VETO (Virtual Environment for Test Optimization)", Sandia Report SAND95-2591, January 1996.

[2] Gregory, D. and Hansche, B., "Rapid Prototype and Test", Sandia Report, 1996.

[3] Jacobs, P., "Rapid Prototyping & Manufacturing Fundamentals of Stereolithography", McGraw, 1992.

[4] Dalton, E., Chambers, B., Bishnoi, K., Bateman, V., and Baca, T., "Test Validation of MANTA: A Code for the Practical Simulation of Shock in Complex Structures", Proceedings of the 65th Shock and Vibration Symposium, Vol. 1, San Diego, CA, October 1994, pp. 66-75.

[5] Zanner, F., and Maguire, M., "FASTCAST, A Program to Remove Uncertainty from Investment Casting", Modern Casting, 8/93.

[6] Baca, T., Bell, R., and Robbins, S., "Conservatism Implications of Shock Test Tailoring for Multiple Design Environments", Proceedings of the 58th Shock and Vibration Symposium, Vol. 1, October 1987, pp.29-47.

[7] James III, G., "Development of Structural Health Monitoring Techniques Using Dynamic Testing", Sandia Report SAND96-0810, April 1996.

[8] Lauffer, J., Allen, J., and Peterson, L., "Structural Dynamics Considerations for Structural Control", Proceedings of the 7th International Modal Analysis Conference, Vol II, February 1989, pp. 1079-1086.