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AUXILIARY TURBINE GENERATOR SET ISOLATION SYSTEM DESIGN FOR US NAVAL VESSEL

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ABSTRACT

The RR4500 Auxiliary Turbine Generator (ATG) incorporates an isolation system addressing four main design requirement environments. These environments include high-impact shock, structureborne vibration, sea state motion, and installation/integration into the machinery space. Multiple design iterations were performed, beginning with a simplified system representation and expanding to full system finite element models. Specific resilient isolation mounts were selected to satisfy the competing criteria from the different requirement sets. Design resolutions passed specific requirements down to the component level and were addressed during detail design. Structures, system components, and flexible ship connections were adapted to meet the requirements needed by the isolation system. Testing of the system indicates good correlation between system predictions and actual performance.

INTRODUCTION

The RR4500 ATG supplies electrical power for the US Navy. Each RR4500 ATG is a module that includes a model MT5S Naval Marine Gas Turbine, reduction gearbox assembly, Electric Start System (ESS), generator, Automatic Voltage Regulator (AVR), and Full Authority Digital Controller (FADC). All are mounted on a common base (referred to as the sub-base) with the associated gas turbine controls and monitoring equipment.

The US Navy required a compact design and placed stringent shock and vibration requirements on the ATG system. A complex design effort was performed to address the extremely challenging vibration requirements while maintaining a system survivable under adverse sea state and shock conditions. This system design required the use of developmental isolation mounts and a highly customized isolation system. Following the design effort, diagnostic and acceptance tests were performed to measure compliance to ship requirements.

KEY SYSTEM REQUIREMENTS

Requirements for the ATG system were flowed down from the shipbuilder procurement specification, program Design, Build and Process Specifications (DBPS), and the American Bureau of Shipping (ABS) Naval Vessel Rules (NVR).

The procurement specification controlled system requirements that immediately affected the isolation system design (e.g. weight, envelope, vibration levels). The DBPS and ABS NVR provided further criteria for evaluating sea motion conditions and specifics for conducting the structureborne vibration and shock testing and analysis.

The main design criteria impacting the isolation system are listed below:

- System maximum weight
- System width and height
- Structureborne vibration testing per MIL-STD-740-2
- Structureborne vibration limits
- MIL-STD-901D shock requirements
- Maintain operation under sea state conditions

SYSTEM OVERVIEW

The top technical risk in the development of the RR4500 ATG was meeting the structureborne noise requirement. This presented a significant challenge while maintaining compliance to all other project requirements.

The ATG isolation system is comprised of two layers of resilient mounts separated by an intermediate mass (raft) layer. After optimizing the design, a two-part raft layer was chosen. The main raft is larger and heavier as it supports the bulk of the system weight. The majority of the system weight is contained within the electrical generator. The second raft is smaller and lighter than the main raft, and it supports the auxiliary systems and the gas turbine.

The lower layer of isolation mounts are US Navy standard mounts paired with auxiliary snubber cones to provide motion control and shock protection of the mount. Internal snubbing devices prevent excess motion in the tensile direction. This mount layer was chosen specifically for vibration isolation characteristics and provides little protection under shock conditions.

The upper layer of resilient mounting consists of a developmental mount produced for this design. This is a Y-shaped mount and was chosen for specific shock and vibration characteristics.

Specific positioning of mounts and mount orientation were chosen to establish the required isolation system characteristics. The genset aspect ratio gives it a dominating height over the relatively small width. This characteristic translated sub-base motion to critical interface points at the top of the system enclosure. The system ventilation, gas turbine intake, and gas turbine exhaust interfaces connect on top of the genset enclosure. These components are critical to the survivability and operation of the unit under the required environmental conditions of shock and sea state motion.

Figure 1 illustrates the RR4500 ATG in an ISO view with the isolation system shown in color.

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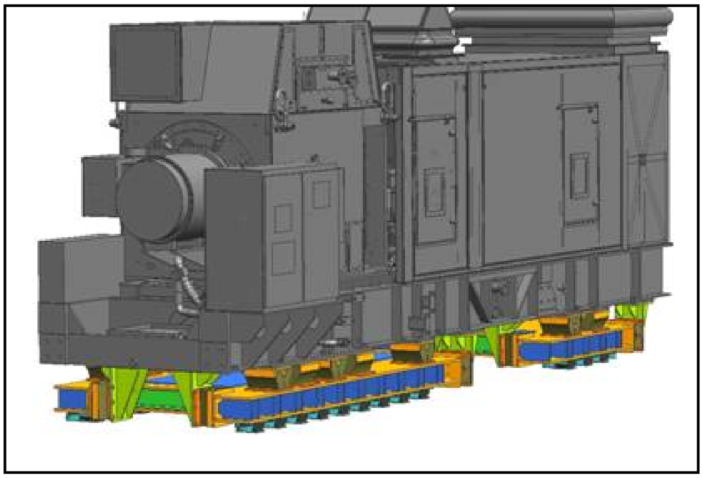

Figure 1: RR4500 ATG System Overview

INITIAL SYSTEM DESIGN AND ANALYSIS

The primary function of the isolation system is to minimize the transmissibility of energy sources between the ATG and the Ship's foundation. This was accomplished by incorporating a mass layer, referred to as rafts, between the turbine/generator package and the foundation. The dynamic impedance of the rafts in the frequency ranges of the ATG energy sources creates the isolation between the ATG and the foundation.

As with any design undertaking, other competing system requirements were addressed in defining a solution that was actually in the design space. Figure 2 provides a schematic of the design process used to address other three functional constraints on the system.

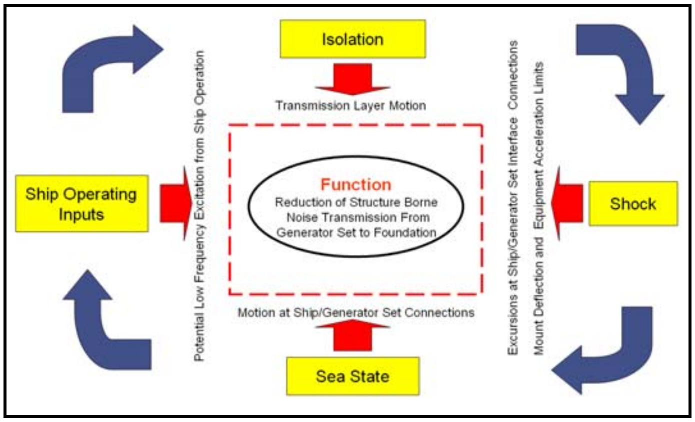

Figure 2: Functional Design Constraints

Dynamic Impedance

The dynamic impedance is created by accounting for all of the rigid body mass and inertia participation of the rafts in a frequency range below that of the system's energy input. The impedance is created when the raft participation is out of phase with the excitation sources. With the rafts designed to act as rigid bodies in the lower frequency range, the higher frequency elastic modes are modulated on the rigid body mass. Due to the relative complexity of elastic modes, the participation factors from broadband excitation tend to be significantly lower compared to the rigid body modes.

To create the rigid body raft modes requires two layers of elastomeric mounts, one mount layer between the ship foundation and raft and another mount layer between the raft and ATG unit. This arrangement creates two distinct low frequency regimes of rigid mass participation. The first regime is the rigid body motion of the ATG and rafts in phase with each other. All six (6) degrees of freedom (DOF), three translational and three rotational, are addressed in this frequency range. In the second regime of rigid body mass participation, the ATG acts essentially as a node in the system. In this frequency range, the only active mass is the raft. Once again all six degrees of freedom of the participating mass are accounted for.

Initial Isolation Design

The initial sizing of the dual layered mount design was performed employing a simple two (2) DOF system. Figure 3 shows the various mount scenarios that were evaluated for the preliminary design review with frequency response functions (FRF) driven from the generator set. The FRFs in Figure 3 are in terms of receptance (in/lb).

Various mount scenarios were compared to the baseline receptance, the blue line, to obtain the relative improvement in transmission reduction between the generator set and the foundation.

The yellow FRF was an evaluation of the transmissibility between the generator set and foundation with a legacy shock mount and Navy mount combined in series without an intermediate raft mass. Since no intermediate mass is in the system, the response of the transmission path follows the mass line of the baseline. No improvement in dynamic impedance is created even though the fundamental frequency of the system was lowered.

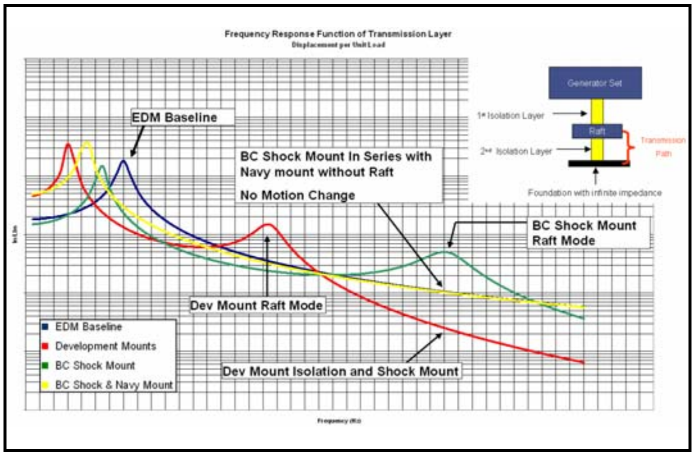

Figure 3: Raft Receptance

The green FRF is the transmission path created using two layers of legacy shock mounts. The dynamic stiffness of these mounts was such that the raft resonance mode was aligned with the generator imbalance frequency. This would have facilitated the transmission of the energy from the generator to the foundation.

The red FRF is the scenario which employed the developmental vibration and shock mount in both mount layers. With this design the raft mode was well below the generator imbalance noise source, and the mass line of the raft created an acceptable decrease in transmissibility from the generator to the foundation.

Using these simple two (2) DOF system models provided an efficient means of screening several mount and raft mass options to indentify one that was within in the design trade space.

Initial Shock Design

This preliminary isolation mount and raft mass design was then evaluated for shock performance using a two (2) DOF model. Due to the absence of production shock input data, an estimated half sine wave input was employed in the preliminary evaluation. This preliminary input had its basis in an international shock specification. In the final design stage, a production level time history shock input was supplied that captured not only the initial shock wave but also the corresponding shock bubble collapse.

Employing the developmental shock and vibration mounts for both mount layers, the maximum limit for the ATG met under the preliminary shock input. The mount deflection and exhaust flex joint limits, however, were exceeded. This condition ultimately was one of the driving factors that moved the design towards employing Navy mounts between the foundation and rafts and a developmental mount between the rafts and ATG sub-base. The Navy mount incorporates internal snubbers which limit the system's relative displacement under shock.

Sea State Motion:

The other constraint that directed the design towards employing Navy mounts in the lower layer was the relative motion of the system to the foundation under varying sea state conditions. The two layered mount, arranged in series, created a relatively soft composite mount system. The compliance of the two-layered developmental mount design created a condition that produced excessive relative motion at the flexible intake, ventilation, and exhaust joint interfaces due to sea state motion especially in the lateral direction.

Roll motion exacerbated the excursions at the flexible joint between the enclosure and air inlets. Employing lateral limiters at the ATG sub-base was not significantly helpful in limiting the motion at the flex joint locations, since this behavior was primarily controlled by the effective vertical mount stiffness. The internal snubbers in the Navy mount provided the feature to limit the deflection of the lower mount layer to address this behavior under high sea state conditions.

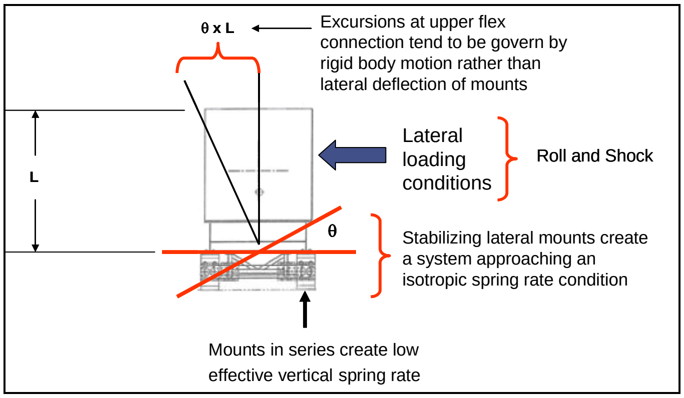

Figure 4: Motion Calculation

Number of Isolation Rafts

The mass distribution of the raft was the final decision to be made in the preliminary design effort. The key feature of the raft or rafts was to account for all the mass and inertia participation before any elastic raft modes occurred. This would ensure that the elastic modes would be modulated on the mass line of the rafts and thus minimize the receptance of their elastic modes at higher frequencies.

This design decision was guided by a three-dimensional finite element analysis (FEA) model of the raft employing a lumped mass/inertia element for the ATG. From this study it was apparent that a single raft could not be designed such that no elastic modes occurred before all the rigid body mass and inertia was accounted for. A two raft design was developed that provided the desired low frequency rigid body participation. The design intent was to account for all rigid body raft modes 10Hz below the generator noise source frequency. Once the rafts were sized, a FEA model of the system with an elastic sub-base was developed to further verify the low frequency behavior of the rafts.

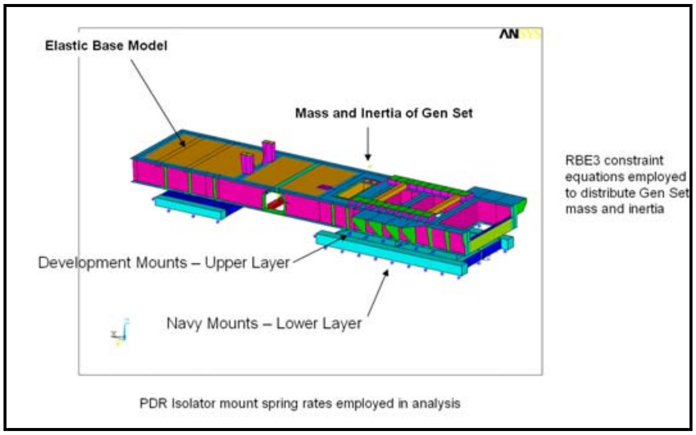

Figure 5: Dual Raft Design

All the rigid body modes were at least nine (9) Hz below the generator noise source frequency with the configuration in Figure 5. There were six (6) system modes and six (6) modes for each raft totaling 18 rigid body modes. As the definition of the system evolved, the static mount loading for the aft raft drove the design toward an additional set of Navy mounts. Due to the discrete nature of the mounts (e.g., half mounts are not permissible) this created an underutilized condition of three quarters of the aft raft Navy mounts. This underutilization increased the highest rigid body aft raft mode to within 5Hz of the generator noise source frequency.

STRUCTUREBORNE VIBRATION ANALYSIS

Final FEA Structureborne Noise Model

The final structureborne vibration analysis incorporated the use of a detailed FEA model of the system for evaluation of energy inputs below 250 Hz. Forced response analyses were employed at frequencies of known ATG energy inputs.

The model was generated employing both shell and solid elements for the rafts, sub-base, enclosure, inlet plenum, and exhaust duct. The generator and gas turbine was modeled with mass/inertia elements. Workless constraint equations from the center of gravity (CG) of these components were employed to define the bearing locations of their rotor systems so that the line of action of rotor imbalance would be properly incorporated in the forced response analysis.

Damping

The mounts were modeled with linear spring elements which incorporated material damping with a constant damping ratio. Material damping in the mount was employed rather than a dashpot, due to the latter creating an over-damped condition for frequencies higher than the fundamental raft modes. A constant damping ratio was used for the sub-base weldment and the enclosure.

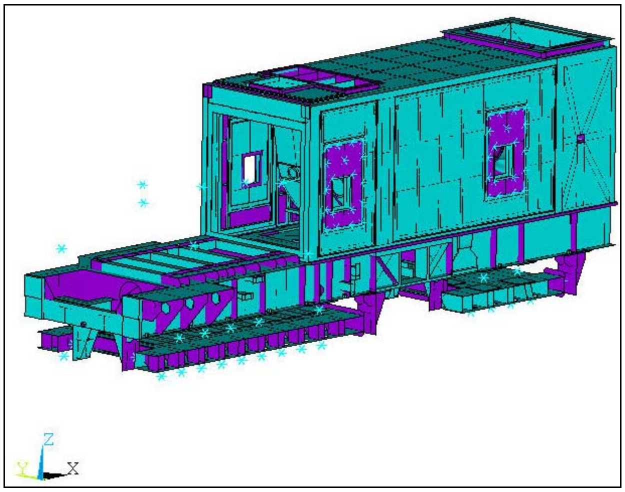

Figure 6: Final Structureborne Vibration Model

Force Response Analysis

Force response analyses at driving frequencies associated with the generator, gearbox and turbine were executed and the displacement response at the Navy mounts obtained as output. The motion at the mounts was converted into acceleration levels, power summed and powered averaged and compared to the specification limit.

Final Mount Locations

In addition to evaluating the energy transmissions from ATG drive components to the Navy mounts; this model was also employed to finalize the mount locations of the isolators. Since the support system is statically indeterminate, considering the elasticity of the sub base and rafts was required for the final evaluation of the number and location of the mounts.

The design goal of maintaining a static load of +/-10% of the nominal load rating for the Navy mounts compromised the design intent of accounting for all the rigid body modes of the rafts 10Hz below the generator noise source frequency. An additional set of mounts were added to the aft raft to meet the static goal.

SHOCK ANALYSIS

The RR4500 ATG has the system requirement to survive the high-impact shock test for shipboard machinery, per MIL-S-901D. The unit must continue operation without any detrimental effects causing an unstable condition or safety hazard.

The initial proposed method for shock analysis was the Dynamic Design Analysis Method (DDAM), utilizing an ANSYS FEA. The contractual requirement existed for a high-impact barge test to be completed upon execution of the contract option. The DDAM FEA was intended to provide design guidance in constructing a survivable system.

It soon became evident that the DDAM process held limitations when attempting to represent non-linear components such as the resilient mounts in the isolation system. This is normally solved by fixing, or grounding, the non-linear mounts on a single layer isolation system. This solution would have presented a highly conservative result when applied to a dual-layer isolation system. Instead, a linear stiffness value was chosen for the upper mounts. This value was the result of multiple iterative analysis runs whereby the results were used to back-calculate the linear stiffness value. This value from the results was then compared to the initial applied value until they both reached relative agreement. The DDAM analysis was then performed using the final assumed stiffness value.

Transient Shock Model

The amount of system motion due to the shock event was a critical parameter. This motion was anticipated to be quite large due to the aspect ratio of the system and the two layers of resilient mounting. The risk of obtaining deflection values that were too conservative by using the DDAM approach was too high, and a transient, time-domain analysis approach was taken.

The objective of the time domain analysis was to evaluate the peak transient loads carried by the mounts, maximum mount deflections and peak component accelerations during the shock event.

The transient shock model employed non-linear springs for the Navy mount snubbers with a 1.4 factor applied to the dynamic spring rates of the upper layer developmental mounts. The sub-base and rafts were modeled with shell elements with the generator, turbine and enclosure represented by mass/inertia elements. The load path between these system components and the sub base were created using rigid body constraint equations. Material damping was employed for the rafts and sub base. Viscous damping was used for the mounts with the damping value based on the primary response frequency of the system.

Input Data and Modeling Technique

Considerable time and effort was expended to obtain the program acceptable barge input functions, and the correct characteristics to represent the resilient mount. Since the top layer mount was developmental, initial analysis runs were performed with estimated data. The lower layer of Navy mounts was characterized and utilized an acceptable non-linear response curve. Another advantage the transient model provided was the ability to understand the system reaction to the shock bubble collapse that occurs after the initial shock pulse. This event provided the largest deflections on the system and shock accelerations to the components. Figure 7 illustrates the construction of the ANSYS FEA transient model, showing both isolation mount layers, lumped mass CGs, and massless interface connection points for measuring deflections.

The technique employed to impose the transient motion on the system is typically referred to as a "large foundation approach". A mass/inertia element, which is several orders of magnitude greater than the system itself, was connected to the Navy mounts on the foundation side using constraint equations. Forces were then applied to the foundation mass to produce the acceleration time history of the production level shock event. The production level shock data included the shock bubble collapse that occurs after the initial shock wave and was the limiting event in the simulation.

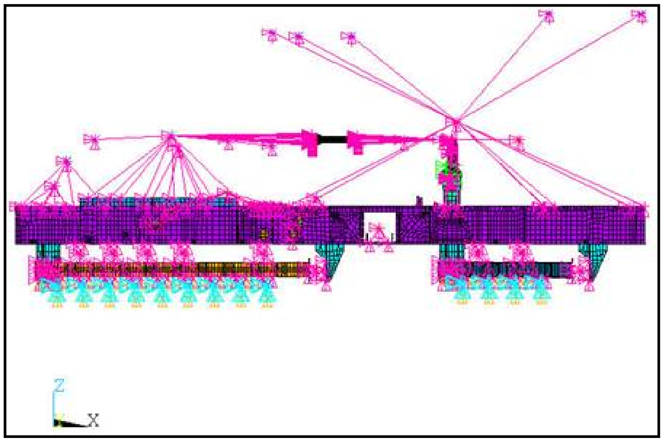

Figure 7: Transient ANSYS FEA Model

Output from Transient Shock Simulation

Three primary outputs were obtained from the time domain simulation. They were the mount deflections, mount loads and ATG component accelerations. The compression and elongation of the mounts along with the loads were extracted and compared with the allowable levels defined by the mount manufacturer. The displacements at the CG of the ATG components, such as the generator and turbine, were also obtained and the second derivative with respect to time taken to calculate the accelerations. Motion parameters such as relative motion of the upper and lower mount layers and full boundary system motion at the top interfaces were reported and compared against what was allowed for the specific pieces of equipment.

DDAM Model

The other shock analysis performed was executed in the frequency domain using the U.S. Navy's spectrum based approach. The model employed in this analysis was more characteristic of the structureborne model shown in Figure 6. The increased detail was due to the analysis being in the frequency domain rather than time domain, and also due to its purpose of evaluating load path connections in more detail.

The sub-base and load path connections of the generator, turbine, and exhaust duct were primary areas of evaluation. The Naval Research Laboratory mode participation summation method was used to combine the contribution of the system modes across the input spectrum. The loads and effective stresses carried in service-critical load paths were then evaluated against design allowables. Based on the results of this spectrum analysis, the capacity of several load path features in the sub-base were increased.

Component accelerations were obtained through both transient and DDAM methods. The transient analysis illustrated component accelerations that were approximately 50% higher than the DDAM results. Both analysis results illustrated acceptable acceleration levels to the components and were deemed acceptable.

SHIP MOTION ANALYSIS

A modified version of the transient shock model was employed to evaluate the system motion under sea state conditions. The ship motion analyses had two primary objectives. The first objective was to establish the gap setting required for the Navy mount snubbers. These gap settings are optimized to allow the vibration mount to provide isolation, reducing overall system excursions. The second objective of the analysis was to determine the maximum flex joint excursions under maximum Sea State with the optimized Navy snubber gap setting.

The snubber gap settings were determined by applying the sea state acceleration fields in the vertical, longitudinal and athwartship directions and evaluating the relative displacements within the Navy mounts. The combination of all three directions for both high and low motion conditions created eight loading scenarios. The maximum relative displacements from these eight runs were then transformed into a local coordinate system aligned with the conical snubber seat to determine the require gap. Figure 8 provides a schematic of the conical snubber surface engagement.

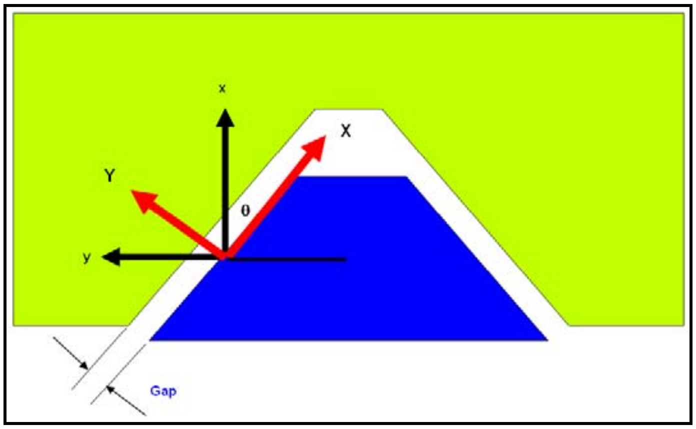

Figure 8: Snubber Schematic

The next task was to evaluate relative motion in the inlet and exhaust flex joints under maximum sea state conditions. A spring/gap model was created that replicated force/displacement behavior of the Navy mount. The Navy mount model for the sea state evaluation was created from a combination of linear, non-linear springs and gap elements. The standard Navy force/displacement curves for the Navy mount are based on a specific snubber gap. The model was developed to replicate the force/displacement curve with this gap setting. Figure 9 provides an example of the mount model performance.

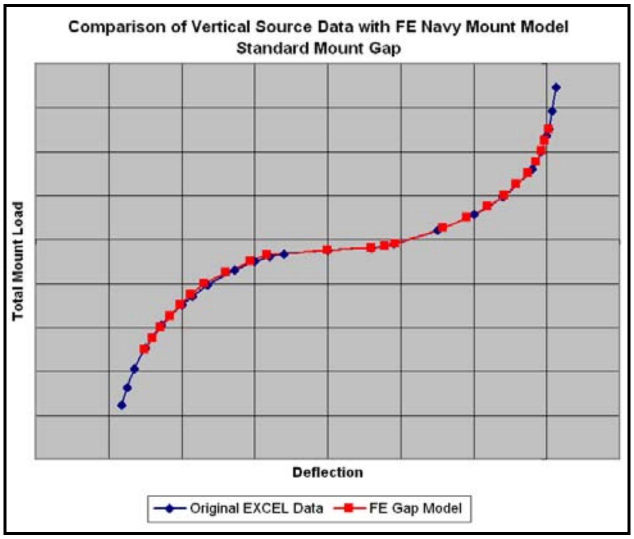

Figure 9: Finite Element (FE) Mount Navy Mount Model

This mount model allowed the modification of the internal snubber gap so that the relative motion of the ATG unit could be evaluated under maximum sea state conditions with the adjusted gap. Figure 10 provides the force displacement behavior of the mount with the optimized gap.

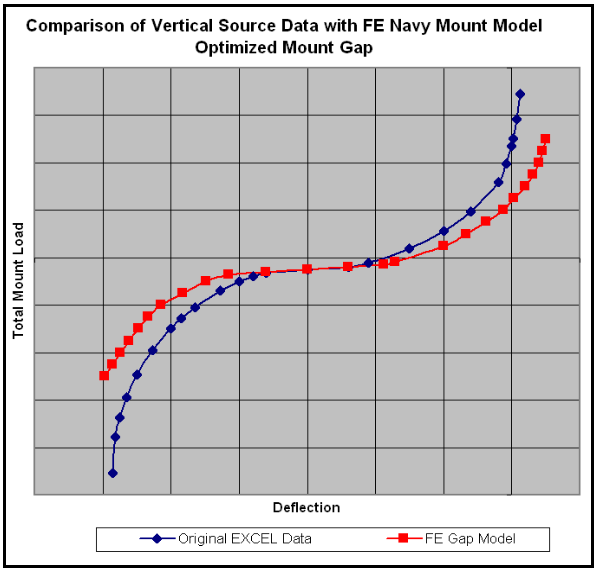

Figure 10: Navy Mount Model with Adjusted Snubber Gap

The last technique employed was the use of large deflection and death/birth elements in the maximum sea state analysis. This enabled the simulation of the mount to take its deflected position and have the snubber gaps set appropriately.

Once again the three loading directions for both a high and low sea state conditions created eight possible loading conditions. All eight loading conditions were analyzed and the developmental mount and Navy mount loads extracted along with the relative flex joint displacements.

SYSTEM MAINTAINABILITY AND INSTALLATION

Throughout the design phases, maintainability and installation requirements were evaluated. Physical access was required to install both layers of resilient mounts, along with their accompanying snubbers and shim components. A manufacturing assembly walk-through was conducted to ensure the system could be assembled properly at the factory and for on-board replacement.

Studies were conducted to ensure all bolts could be accessed for installation. This activity drove the final placement of many of the raft vertical gusset supports as seen in Figure 11.

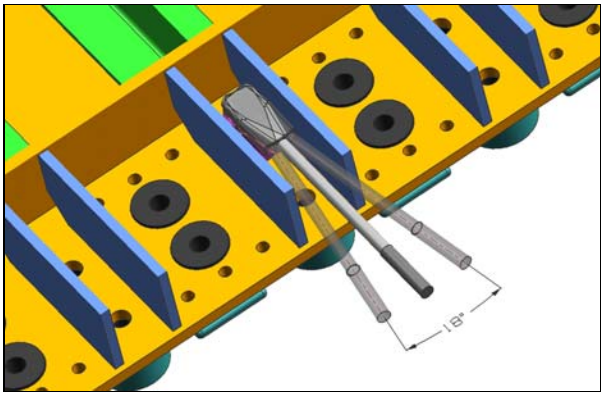

Figure 11: Installation Assessment

The required envelope of the two rafts drove several man-access holes designed into the sub-base cross-beams. These access holes provide access to the underside of the generator. The horizontal separation between the two rafts provides access to the system oil cooler and rear below-base access.

Several ship installation constraints were placed upon the isolation system design. Early in the design, proposals for motion bracing (sway bars) were made. Due to machinery room space constraints and lack of available supporting structure, this proposal proved impractical. This forced increased motion requirements to be handled at the flexible connections on top of the unit.

Ship foundation designers defined mount placement requirements early in the program. The bottom layer of mounts was to be arranged in two parallel rows, along the length of the unit (e.g. no mounts located on cross members). The footprint location of these mounts was frozen at the system preliminary design review. This design definition provided further constraint on the placement of the upper mount layer to account for shifts in system CG as the design was finalized.

SYSTEM TESTING

The system required vibration testing at the factory through the conduct of First Article Testing. The structureborne noise vibration testing was performed per MIL-STD-740-2. Some test cell constraints prevented full demonstration of the system under the actual ship installed conditions. Electrical load simulation was performed using load banks that did not provide the electrical harmonic vibration impact to the system.

The test results from the system are in processed at the time this paper is being published. Diagnostic tests were conducted on the unit to provide baseline information and to validate prior analysis. System raft modes aligned well with the analysis predicted system performance. Documentation of results against system requirements and as validation to design analysis is underway.

Equipment shock testing is scheduled to be performed on a later unit, at the Navy's discretion. This test will require a barge mounted MIL-STD-901D test to be performed.

The RR4500 ATG testing to date has exhibited a high level of predictability from the analysis tools used in design. With the results of a future barge shock test pending, the design team is satisfied with the performance of the isolation system that resulted from multiple constraining requirements.

ACKNOWLEDGMENTS

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