The Application of Statistical Energy Analysis in The Design of Viscoelastic Passive Damping

by

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ABSTRACT

This paper presents the results of a study to determine the feasibility of using statistical energy analysis (SEA) methods for the design of viscoelastic passive damping treatments. The primary emphasis of the study was to determine the applicability of SEA methods for predicting the response of damped structures in the high frequency, high modal density regime where modal methods such as the modal strain energy technique become inappropriate because of model complexity or uncertainties in geometry. The other area of interest was the use of SEA augmented by modal strain energy methods as a type of substructuring technique for large, complex structures. To accomplish this investigation, the VAPEPS SEA code was used to model a component test article in several damped configurations and the results were compared to available test data to determine the validity of the analysis methods. The component test article was constructed during the Reliability for Satellite Equipment in Environmental Vibration (RELSAT) program as a developmental platform representative of satellite equipment support structures which are subjected to high-level vibroacoustic environments typical of launch vehicles.

INTRODUCTION

Recent advances in the field of viscoelastic passive damping have been numerous and cover a wide variety of disciplines. They were successfully used in the "Reliability for Satellite Equipment in Environmental Vibration (RELSAT)" program to demonstrate the use of viscoelastic passive damping to control the vibroacoustic response of satellite avionics equipment (reference 1). In particular, an analysis technique utilizing finite element modeling and the modal strain energy (MSE) method is now being used to analytically predict the effects of applying viscoelastic damping treatments to structures (reference 2). Since the technique is based on finite elements, it is possible to analyze a wide variety of structural configurations, however, the size of the model required to accurately predict damping rapidly increases with the size and complexity of the structure. For this reason, a study is currently in progress at Boeing Aerospace to determine the feasibility of using finite element modeling and MSE to analyze the design of damping treatments on the substructure-level and statistical energy analysis (SEA) to evaluate the resulting changes in the vibroacoustic responses on the system level. This paper presents the approach that is being used in the study and discusses some preliminary results.

BACKGROUND

The study described in this paper is an extension of work that was performed by Boeing Aerospace on the RELSAT program. The program was started approximately 6 years ago by the AFWAL Flight Dynamics Laboratory under the direction of Dr. Lynn Rogers and was completed last year. The RELSAT program was a study to investigate the use of viscoelastic passive damping technology to reduce the structural response of typical satellite systems to high-level acoustic noise.

The approach used was to (1) design passive damping treatments into an example satellite system and (2) perform acoustic and modal survey testing on the structure to verify their effectiveness. A pictorial view of the program methodology is shown in figure 1. The Boeing Aerospace Inertial Upper Stage (IUS), which is subjected to the severe launch vibroacoustic environments of the Space Shuttle and Titan launch vehicles, was selected as the baseline satellite system. System requirements were outlined, system disturbances were identified, and a set of goals for a redesigned damped dynamic test article were established. A sketch of the IUS is shown as the first illustration in figure 1. The harshest vibrational environment endured by the IUS occurs during launch when the acoustic noise in the Space Shuttle payload bay typically reaches levels of 145 db overall from 20 to 2000 Hz. The design of damping treatments for the IUS dynamic test vehicle

(DTV) was carried out in several stages using finite element techniques and the modal strain energy (MSE) method to analytically predict the effectiveness of the designs.

To conduct the design development phase in a cost effective manner, a smaller substructure representative of the IUS DTV equipment support section was designed and fabricated. A finite element model of the substructure is shown as the second illustration in figure 1. Several design, analysis, and test cycles were performed to evaluate a wide variety of damping concepts and to establish the validity of the analysis methods. The preliminary design development on this smaller substructure proved to be very valuable in choosing damping treatments for application to the full scale DTV.

The DTV was then analyzed by breaking it into several substructures representative of critical portions of the structure. Damping treatments were designed and optimized for these substructures and then applied to the full vehicle for testing. All of the damping treatments for the DTV were designed and optimized using finite element analysis and the MSE method to predict damping levels. Figure 2 shows the finite element models and lists the damping treatments designed with each one. The global model described the entire DTV in the test configuration including a simulated spacecraft payload structure. This model was used only to design a ring damping treatment for the global ring type modes of vibration. The model was much too coarse to design damping treatments for the local substructures. The other three substructure models represent critical isolated portions of the DTV and were used to design the remainder of the damping treatments. Detailed descriptions of the damping treatments and the design optimization process are contained in reference 3.

Figure 3 shows the DTV located in the Boeing Aerospace Environmental Test Laboratory acoustic cell for testing. The acoustic testing revealed that the structural response at all equipment locations were substantially reduced by the addition of the damping treatments. A summary of the RMS response of five critical IUS avionics components is given in figure 4. Overall response levels at the avionics equipment attachment points were typically reduced by 62%. Acceleration response power spectral density (PSD) envelopes for an encrypter located on the DTV equipment support deck are shown in figures 5 - 7 before and after the application of viscoelastic passive damping. This is typical of the types of reductions achieved. Analyses and tests were also performed to assess the impact of the damping treatments on IUS system-level requirements such as vehicle weight, outgassing, strength, and heat transfer.

Although the results of the acoustic tests of the DTV showed that significant decreases in the vibroacoustic responses were achieved through application of the viscoelastic passive damping treatments, a good test/analysis correlation of predicted and measured modal damping and vibration levels could not be obtained. Due to the large size and complexity of the finite element models which include the viscoelastic damping treatments, it was not economically feasible to run a dynamic analysis with an overall finite element structural model of the DTV. Ordinary substructuring techniques based on component mode synthesis would not significantly decrease the problem size because no simple boundaries exist between the various substructures, and a large number of component modes would have to be carried to adequately predict the local deformations in the substructures.

Through the RELSAT program, it was realized that the modal strain energy method is a powerful analysis tool for damping design that is limited primarily by the ability to model the damped structure with finite elements. Extremely large, detailed models must be developed which tend to be very costly in terms of computer time to run the models and manpower to interpret the results. Areas identified for further research included the refinement of substructuring techniques and the development of an economical method to determine system-level responses from substructure-level analyses. The application of statistical energy analysis (SEA) methods was identified as a technique which should be investigated to address this issue. It was felt that SEA could potentially be a good method to track the principal energy paths of acoustic and vibration disturbances, to identify the critical substructures for the application of damping, and to envelope the system-level responses in the high-frequency 200- to 2000-Hz range.

STATISTICAL ENERGY ANALYSIS (SEA)

SEA is an analytical method to predict vibration and acoustic responses of dynamic systems by treating the structural or acoustical mode shapes and frequencies as statistical parameters. The dynamic energy is used to describe the state of the system and simple power balance equations describe the interactions between the coupled subsystems that constitute the dynamic system. Reference 4 contains a comprehensive overview of the development and engineering applications of the SEA method. As described in the reference, the general steps required in SEA to develop a model and calculate responses are outlined in figure 8. The first three steps are the development of the SEA models of the subsystems and their interactions. These steps require engineering experience and judgement. The last three steps involve computational procedures that can be performed through implementation of one of several available general purpose SEA computer codes.

For this study, the Vibroacoustic Payload Environment Prediction System (VAPEPS) code was used to perform the SEA response predictions. The VAPEPS code development was sponsored by NASA and the Air Force Space Division. The development and maintenance of the code is currently being performed by the Jet Propulsion Laboratory (JPL). In addition to the SEA option, VAPEPS provides a database of vibration and acoustic data that can be used with empirical and semiempirical techniques for determining vibroacoustic responses and test environments.

The SEA model of the IUS DTV that was developed for this study is shown in figure 9. An illustration of the DTV acoustic test configuration is shown with the associated power flow diagram for the dynamic system. The diagram describes the acoustic and structural subsystems and their interconnections. This model was used to predict the acoustic environment internal to the IUS interstage structure and the vibration response of a battery located on the interstage structure.

Equivalent plates were used for the SEA model of the interstage structure. The equivalent plate calculations are presented in figure 10. Two approaches were used in the equivalent plate calculations. The first approach included stiffening effects of the interstage rings by determining an equivalent plate thickness. The second approach considered the rings as boundary conditions.

The predicted IUS interstage internal acoustic environment is shown in figure 11 for the two equivalent plate modeling approaches. Also shown is the acoustic sound pressure level (SPL) data obtained from microphones located in the interstage internal volume during the acoustic test of the IUS DTV. Although good correlation was obtained with both approaches, the spectral levels predicted by the first approach appear to correlate better with the test data. The predicted acceleration PSD for the vibration response of the interstage battery is shown in figure 12. The PSD of the vibration responses measured by accelerometers mounted on the battery during the acoustic tests are also shown for comparison. It can be seen that the SEA prediction correlates fairly well with the test data, however, the correlation between the predicted and measured vibration responses does not appear to be as good as that obtained for the acoustic responses. One cause for this is VAPEP's inability to account for non-structural mass in its coupling and damping calculations. Currently, VAPEPS only uses non-structural mass in the conversion from energy to mean response for the entire element. This may be one area where finite element methods can be used to effectively augment the response predictions for avionics equipment and include the localized effects of a lumped mass.

SUMMARY

In summary, although the results of this study are still very preliminary, it appears that SEA may provide the means to analytically establish avionics component vibration and acoustic environments. Although the method requires an experienced user to obtain accurate results, it provides a systematic means for determining vibroacoustic responses that will be particularly useful when performing vehicle design trade studies in which predicting the absolute magnitude of the responses may not be as important as predicting the differences produced by changes in the design trade parameters. The acoustic test data obtained during the RELSAT program will be useful to correlate with SEA predictions of the differences in vibroacoustic responses produced by varying levels of substructure damping. This will be the emphasis of future efforts for this study.

During the RELSAT program, viscoelastic passive damping treatments were designed for an extremely complex structure using finite element structural modeling techniques and the MSE damping prediction method. By isolating portions of the structure down to substructures, it was possible to cost effectively design damping treatments for an otherwise intractable structure. The significant reductions in the vibroacoustic responses observed during the acoustic testing of the IUS DTV verified the viscoelastic passive damping design and analysis methodology. The MSE method was shown to be a powerful analysis tool that is limited primarily by the computational cost required to model a large complex damped structure with finite elements. This study is investigating the application of SEA methods to address this issue of economically determining system level responses utilizing the information provided by substructure level analyses. The results to date of this study and of the RELSAT program have demonstrated the use of new damping design and analysis methods and conclusively shown that viscoelastic passive damping has the potential to yield a system level payoff in the form of lower vibroacoustic environments and increased reliability for future space systems if incorporated early in the design cycle.

REFERENCES

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3. Johnson, D.W., Ikegami, R., and Austin, E.M., "The Design and Analysis of Passive Damping for Aerospace Systems", Presented at AIAA 28th SDM Conference, Monterey, Ca., April 6-8, 1987.

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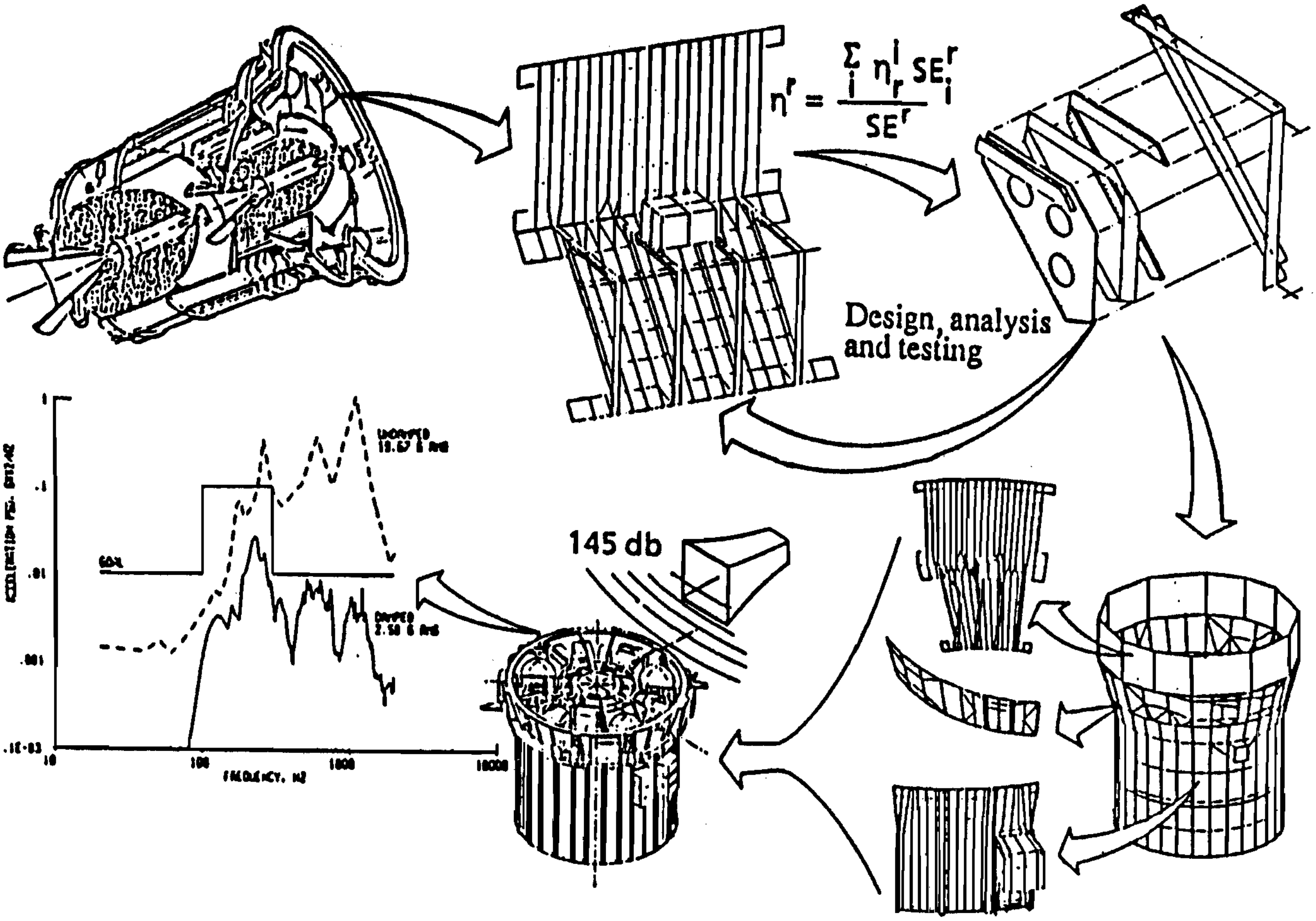


Figure 1. RELSAT Program Methodology

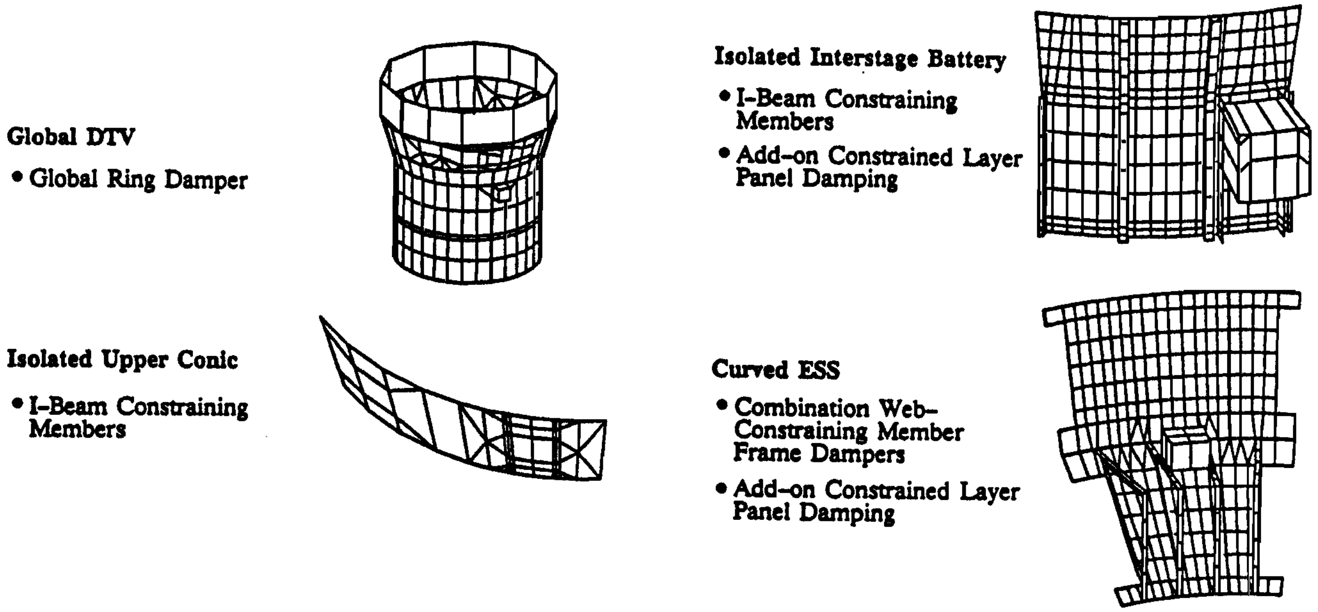


Figure 2. Summary of IUS DTV Finite Element Models and Damping Treatments

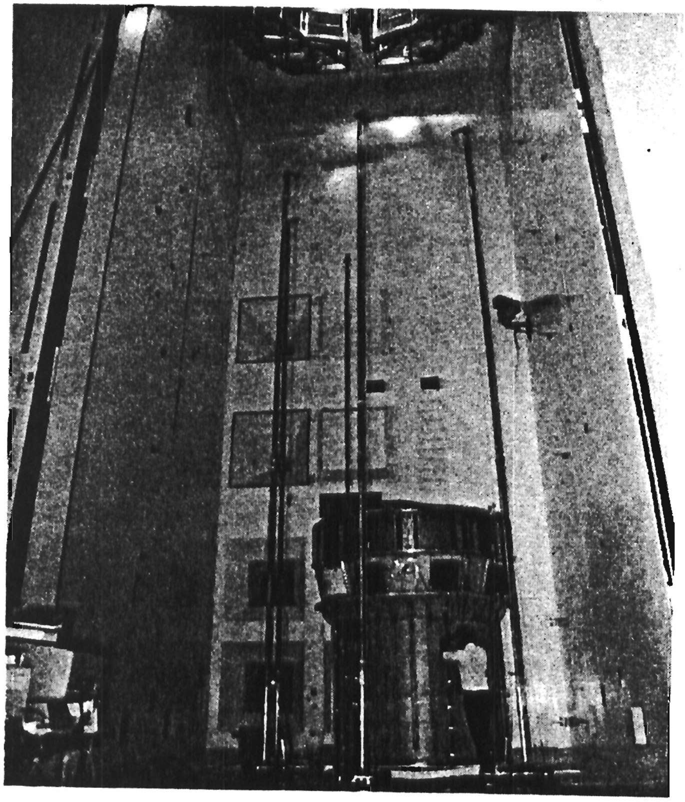


Figure 3. DTV Set Up for Acoustic Testing

Component	Direction	Undamped Response G RMS	Damped Response G RMS	Percent Reduction
Encrypter	Axial	21.83	6.47	70
	Radial	17.26	2.98	83
	Tangential	19.67	2.58	87
ESS Computer	Axial	16.27	2.40	85
	Radial	12.01	4.20	65
	Tangential	17.74	3.99	78
REM	Axial	15.78	9.75	38
	Radial	11.12	6.62	40
	Tangential	13.48	10.16	25
ESS Battery	Axial	11.84	3.81	68
	Radial	10.61	3.74	65
	Tangential	15.84	3.86	76
Interstage Battery	Axial	5.09	3.00	41
	Radial	8.63	5.51	36
	Tangential	10.08	2.83	72

Figure 4. Overall Response of Five Critical DTV Avionics Component s

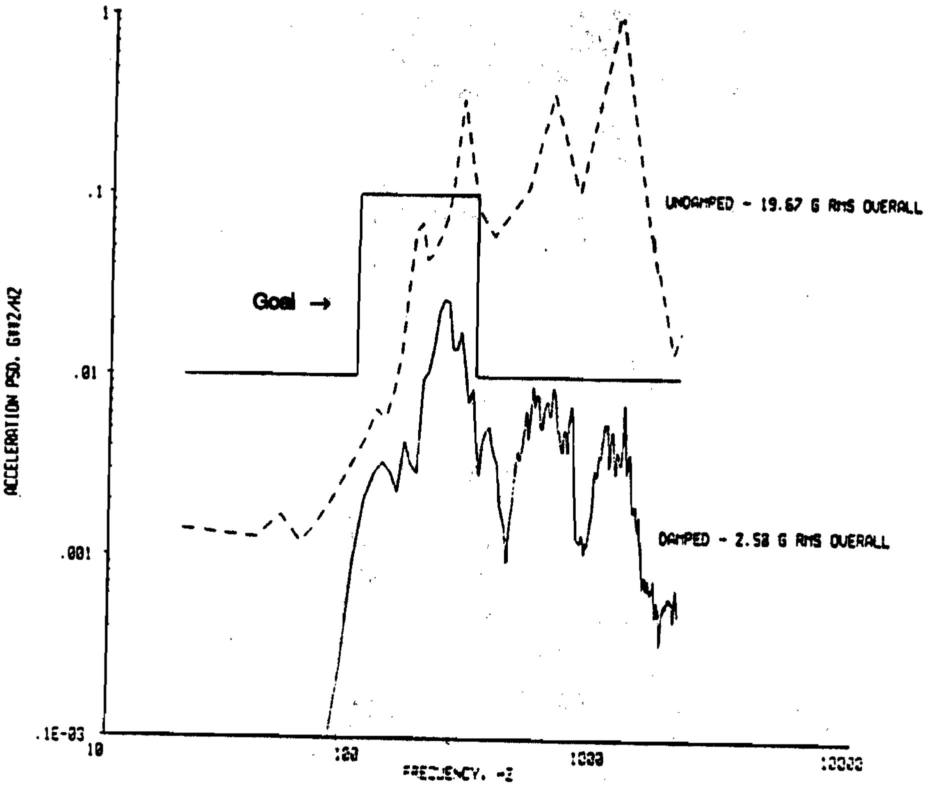


Figure 5. Envelopes of DTV Encrypter Tangential Response

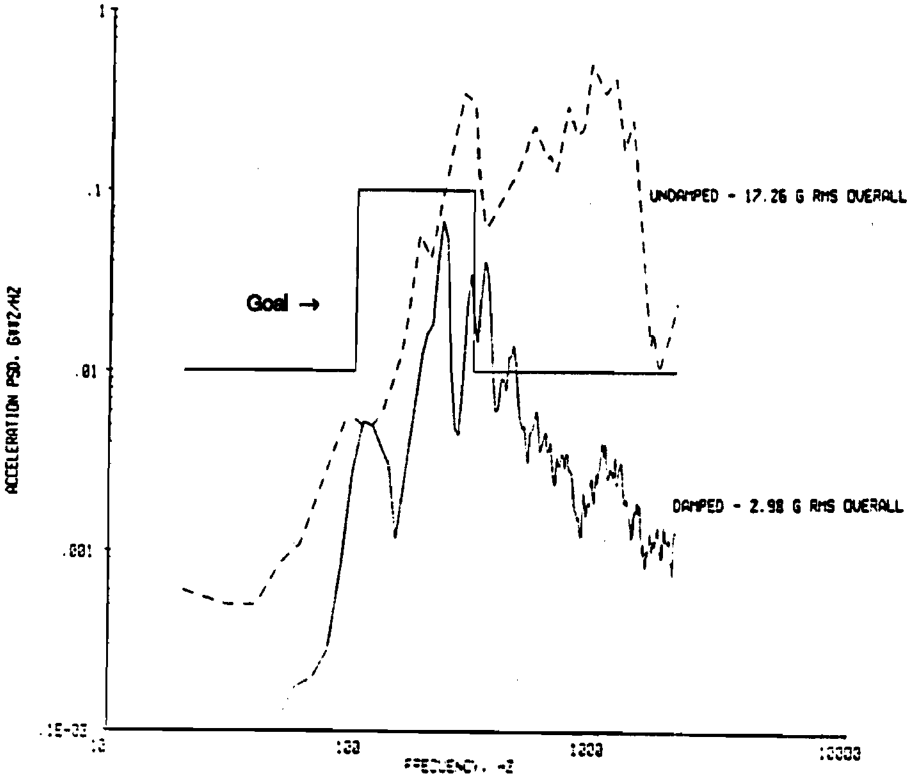


Figure 6. Envelopes of DTV Encrypter Radial Response

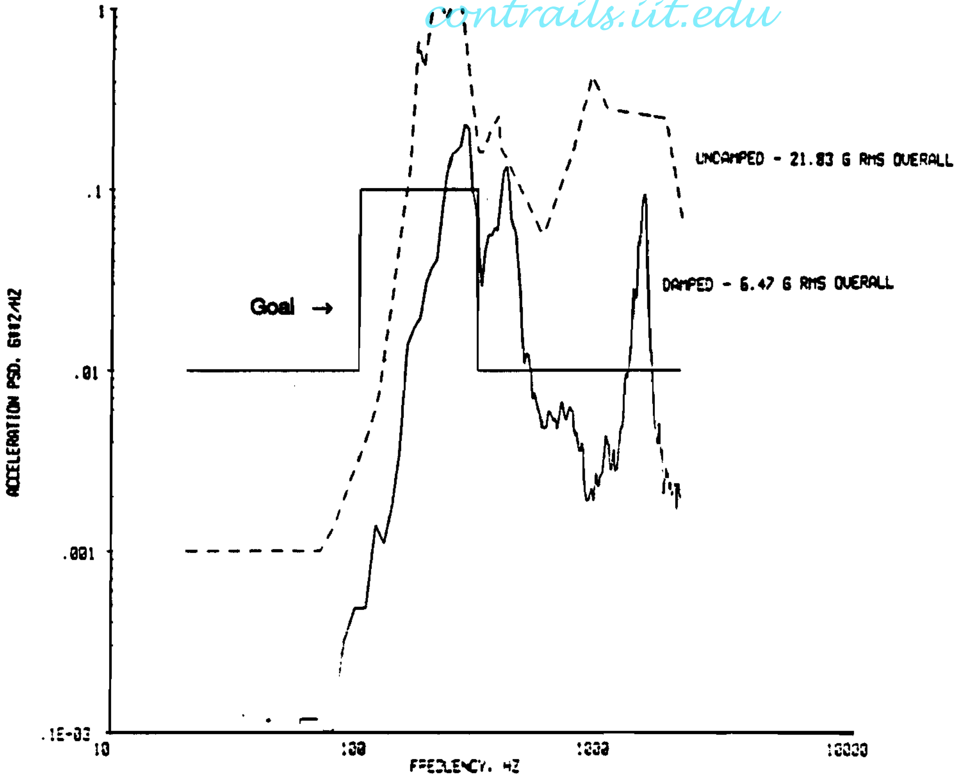


Figure 7. Envelopes of DTV Encrypter Axial Response

Step 1: Identify SEA Subsystems
- Substructure
- Identify similar modes

Step 2: Identify Junctions
- Point, line, and area junctions

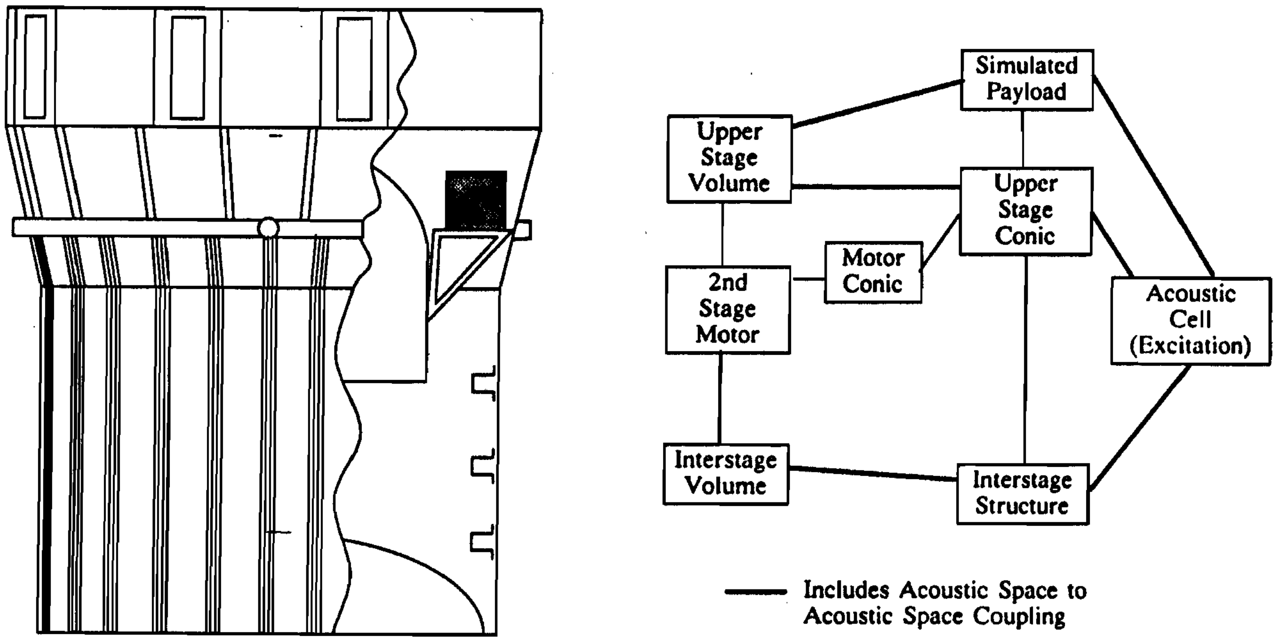
Step 3: Compute Power Inputs
- Impedance formulation

Step 4: Compute SEA Parameters
- Modal densities
- Coupling factors
- Damping factors

Step 5: Power Balance Equations
- Form matrix equation
- Solve for modal energies

Step 6: Response Statistics
- Relate to modal energies
- Mean response
- Standard deviation

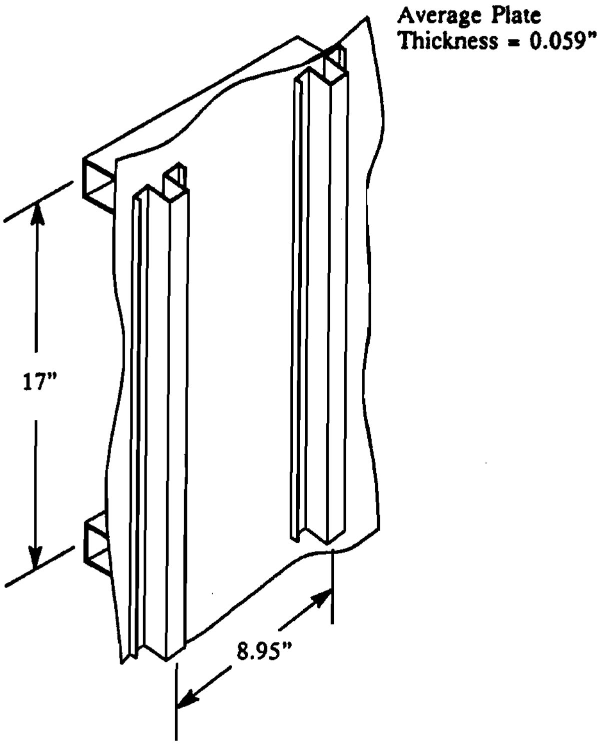
Figure 8. General Procedure for SEA



DTV

Power Flow Diagram

Figure 9. SEA Model for DTV Vibroacoustic Response Analysis



- Use VAPEPS EQPL Processor to Calculate Equivalent Homogeneous Plate Properties
- Two Possible Approaches:

1. Include Rings in Equivalent Plate Calculation

Thickness = 2.18 in
Modulus = 7.51E+05 psi
Density = 1.90E-05 lbf s^2/ in

2. Consider Rings as Boundary Conditions

Thickness = 0.299 in
Modulus = 3.41E+06 psi
Density = 8.44E-05 lbf s^2/ in

Figure 10. Interstage Panels Equivalent Plate Calculations for VAPEPS SEA Model

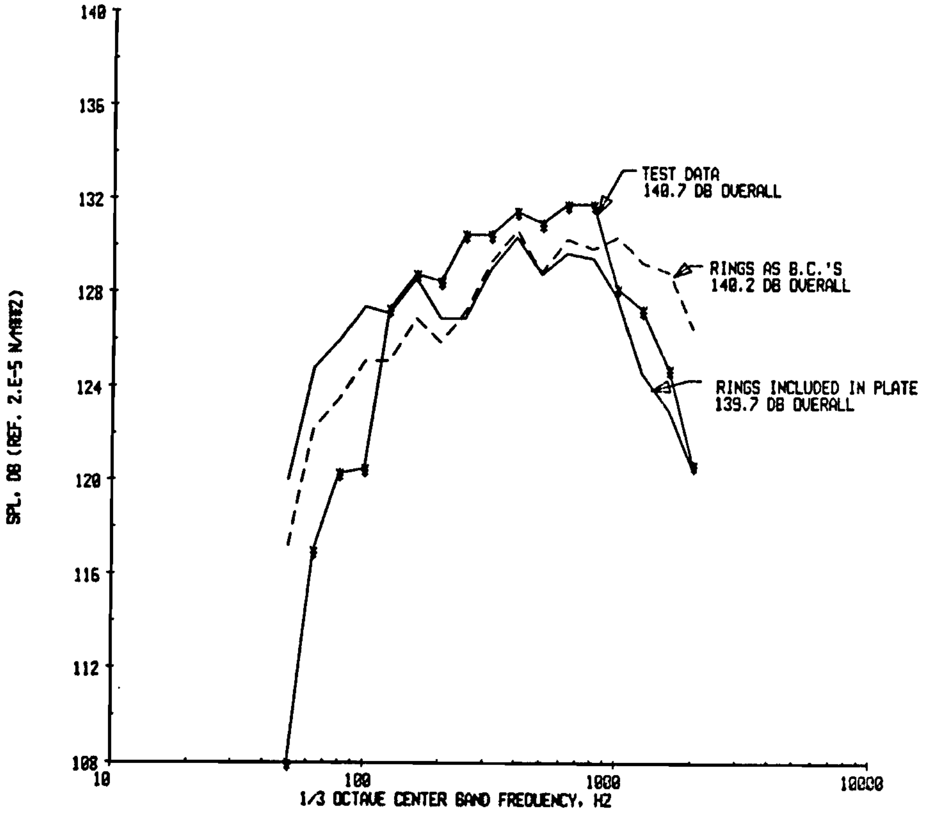


Figure 11. *DTV Interstage Internal Acoustic Response*

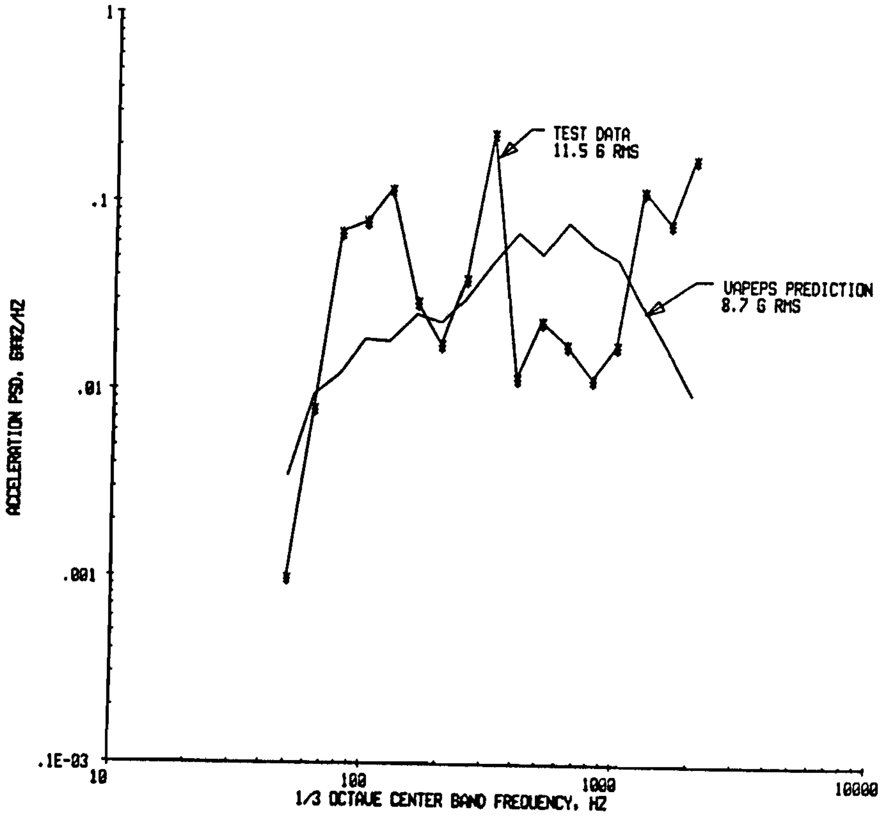


Figure 12. *DTV Interstage Battery Vibroacoustic Response*