USING MSC/NASTRAN FOR THE CORRELATION OF EXPERIMENTAL MODAL MODELS FOR AUTOMOTIVE POWERTRAIN STRUCTURES

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ABSTRACT

This paper describes the methods and analyses used in the correlation of experimentally determined modal models to analytical solutions. The paper illustrates the significant benefits of Component Mode Synthesis and Design Sensitivity Analysis options available in MSC/NASTRAN in the correlation process. Neutral File Interface programs and remote orthogonality calculation methods that simplify the communication between the FEA solution and the laboratory results are also discussed. Three (3) specific experimental procedures formulated the basis for the paper. The first, a simple free-free beam case is presented. The second and third are examples of more complex automotive transmission assemblies with special boundary condition issues and internal component influences. Specific recommendations for improving correlation potential both in laboratory test methods and in the finite element modeling task have been provided.

INTRODUCTION

The requirement to provide correlation between Finite Element Analysis (FEA) results and the results from experimental measurements in dynamic analysis work has been long standing. Both analytical and experimental environments have provided tools for the examination of differences that may occur in the dynamic model solutions. Many different approaches to this issue have been presented in the technical literature [1]. Recent work in the field has resulted in several commercially available software programs to link the FEA results to the experimentally determined results. The most effective of these provide an environment for graphical comparisons of the animated mode shapes as well as mathematical evaluations of the correlation of analytical mode vectors to the experimental mode vectors. This paper provides examples of the improvements available for the correlation of analytical and experimental mode shapes for dynamic structures in commercially available software packages and within the capabilities of MSC/NASTRAN.

PROBLEM DEFINITION

The problem definition for correlation is difficult to define for the general case. Analytical and experimental perspectives on this issue vary considerably. Both the FEA solver and the experimental software programs for dynamic analysis contain such features as sensitivity analysis, structural modification prediction, and Modal Assurance Criterion (MAC) solution capabilities. Each correlation exercise requires the skillful exploitation of these resources to arrive at reasonably well correlated mathematical models for the dynamic problem under study. Several key issues associated with the implementation of the correlation process are proper test definition of the dynamic condition under study, access to adequate boundary condition information to properly configure the analytical restrains and boundary definitions, and the ability to communicate the results of the analytical or experimentally determined solutions between the often different operating environment for the two (2) modeling methods. In order the study the effectiveness and limitations of commercially available correlation programs, several experiments were carried out for which substantial prior knowledge of the dynamic behavior of the test object was available and both analytical and experimental mathematical models were defined. Three (3) different test cases were examined that contained special circumstances created to address the problematic aspects of the correlation process. The first case was a simple free-free steel beam which provided a simple test case for the communication of the FEA dynamic solution and geometry database to the test measurement computer database. In this case, the grid density (or nodes, as they are referred to in the experimental geometry model) was very close to the experimental measurement point density. Detailed statistics for each test case have been provided later. The second case was a fixed-free powertrain component for which the boundary conditions were well defined and the major modes of interest were known to be well separated and uncoupled. In this case the grid density was markedly different between the analytical model and the experimental model but the FEA model was relatively small and did not allow the use of superelement methods or dynamic solutions using Component Mode Synthesis (CMS). The final test case involved another type of powertrain component in the fixed-free condition for which the test fixture modes and component modes were known to be coupled and the FEA solution contained both full space and CMS results and used several superelements in the model generation. It was anticipated that these test cases would identify the correlation program limitations and alternative methods for completing the correlation process would be offered. The alternative methods that were evaluated in this work were limited to those available within MSC/NASTRAN.

ANALYSIS

The correlation method under study in this paper was developed to relate the modifications of a mathematical model to its physical parameters. This has been achieved through the use of correction factors or multipliers for the mass and stiffness matrices for the structure. These multiplication factors were formulated based on comparing the test results to the FEA results. The execution of this method requires that the mass and stiffness matrices data sets be consistent in content, format, and matrix size [2]. This limitation requires the expansion of the test dataset matrices. It is important to note also that the modal results derived from the experimental data contain complex valued mode shapes to real normal modes, whereas the FEA results are real valued. A further complication of the process is recognized since the integration of the experimental data set into the FEA result can contain many discrepancies with respect to completeness of the experimental mode shape. These discrepancies arise from the typical limitations of the test environment, namely, the measurement data do not generally contain rotational degrees of freedom and the measurement density often does not approach the grid density of the FE representation.

The success of the correlation activity depends on the ability to operate on the FEA and experimental data sets to assure conformity. In this way, variations in the results from the two (2) data sets can be studied. The use of sensitivity analysis, design optimization (SOL 200) [3] and engineering judgement on the resultant conformed data sets have been popular methods for the correlation analyst. Automating this process can offer many advantages to the analyst by minimizing the efforts required to condition the various output configurations from the experimental environment and reduce to demand for highly structured input. The need for a "neutral file interface" to assure conformance of geometric parameters, material properties, and mathematical matrix results has been widely discussed [4]. LMS International developed an automated FEA to test data correlation program and neutral file interface/translator which was used in this paper. The input for the MSC_NF translator [5] consisted of the OUTPUT2 binary file from MSC/NASTRAN. A listing of the data blocks used in the translation process has been provided in Table 1. The implementation of the translation file is achieved through special instructions in the MSC/NASTRAN Executive Control Deck. ALTER numbers for Normal Modes (SOL 103) are used for the OUTPUT2 file generation. The ALTER numbers assure the proper translation of geometry, material properties, element matrices, and eigenvectors.

TABLE 1 - MSC/NASTRAN DATA BLOCK NAMES USED FOR MSC_NF TRANSLATION

nr	NAME	DEFINITION
1	GEOM2	element definition
2	CSTM	coordinate system transform matrix
3	GPL	grid point list
4	GPDT	grid point data table
5	GEOM4	constraints table
6	MPT	material property table
7	EPT	element property table
8	KDICT	dictionary of element stiffness matrix
9	KELM	element stiffness matrix
10	MDICT	dictionary of element mass matrix
11	MELM	element mass matrix
12	OPHIG	eigenvalues and eigenvectors

The result of the MSC_NF translation file is an ASCII file that contains all of the necessary dynamic characteristics of the component or system under study with formatted structure suitable for introduction into the experimental measurement modal analysis computer. Once the results reside in the local measurement computer environment, several relatively straightforward automated procedures and interactive graphical sessions are available to complete the correlation process. The process includes data integration, geometry correlation, MAC calculations, COMAC calculations, orthogonality checks, scaling and normalization activities, and animated displays.

Whether the correlation process is conducted in the FEA computer environment or the experimental computer environment, the optimization and sensitivity methods are the same. Both environments utilize Bayesian parameter estimation schemes which minimizes the computation error, in the least squares sense between the FEA and test datasets. The efficiency of the implementation of the methods is related to the familiarity of the analyst to the computer operating environment. The examples shown in this paper were executed in the experimental measurement computer for the first two (2) cases. The third case was executed using the analytical computer environment due to the limitations of the experimentally based software and the high resolution of the system dynamic behavior afforded by the high analytical grid density animation.

DISCUSSIONS

The discussions have been structured around the three (3) correlation experiments mentioned above. Each experiment required unique correlation requirements and capabilities. A definitive statement of the correlation objective and problem summary preface each discussion section.

Experiment #1 - Free-Free Beam (cylinder)

The objective of this experiment was to demonstrate the function of the CAD*I Neutral Interface File, known as MSC_NF, on a test configuration for which the natural frequencies were simply determined and had a high confidence of experimental measurement. The mathematical solution for the first three (3) normal modes was determined from the Euler Equation [6]. A finite element model was generated to determine the first three (3) fundamental modes for the beam. The model consisted of 51 grid points and 50 CBEAM elements. An experimental modal test was also conducted in a free-free test configuration for which 12 discrete measurement points were used to create the geometry to describe the beam. The problem under study was the performance of the MSC_NF translator and the successful manipulation of the FEA data set in the experimental modal computer environment. Further, since the test data was only collected for one direction of excitation, the translator was evaluated for its ability to address the mismatch in the degrees of freedom, and phase error from symmetry of the part. Table 2 lists the natural frequencies determined from the simple calculation, the FEA solution, and experimentally measured data.

TABLE 2 - FREE-FREE BEAM NATURAL FREQUENCIES
FIRST THREE (3) FUNDAMENTAL MODES

Mode Number	Frequency Determination Method		
	Manual	FEA Solution	Modal Measurement
1	66.518	66.844	66.90
2	183.223	183.858	182.03
3	359.319	359.407	356.86

The results for this simple test case showed very good agreement, as had been anticipated. Figure 1 is an illustration of the interactive graphic mode available in the correlation software to assure geometric correlation. Using the automated sequences in the software, this step is a prerequisite to any correlation calculation. This step allowed for the identification of common test and analysis node locations and resultant property matrix sizes.In this test case, the coordinate system identified in the laboratory and in the FEA model were not consistent. The software allowed for the manual input of Euler angle modifications to the FEA global geometry to align the coordinate systems. Since the geometry was relatively uncomplicated, grid/node matching remained automated and depended solely on the default settings of the software. Following geometric correlation, the integration of the test data set matrices and the analytical data set matrices is performed. This integration takes the form of a review of the resultant Mode Scale Factors (MSF) for both the experimental and analytical results. The test data set is expanded from the 12 degree of freedom model to the 306 degree of freedom FEA data set. After the integration and expansion, MAC [7] and COMAC [8] calculations are provided on the data sets. The MAC and COMAC results are provided in both a tabular format as shown in Table 3, and in graphical format, as shown in Figure 2. Modulus Difference Matrix (MDM) results were also provided with the COMAC. The MAC provides a numerical assessment of mode shape correlation between any (2) modes on the basis of model modal complexity, in terms of weighted modal displacements and phase angle limits. MAC values close to 1.00 indicate good correlation of grid/node displacements and phasing for a given mode shape. The COMAC quantifies the MAC value for each degree of freedom for a defined mode pair. This parameter and the MDM are generally displayed together in an attempt to identify local discrepancies between defined mode pairs. COMAC values close to 1.00 and MDM values close to 0.00 indicate good local correlation. Since the correlation of the test data to the FEA solution was very good (less than 1.0% error), optimization and sensitivity studies were not required. For simple problems of this type, the automated correlation process is suitable for use. The interactive graphical interface that allows the simultaneous review of animated mode shapes for both the analytical and experimental models is very useful.

FIGURE 1 - INTERACTIVE GRAPHICAL DISPLAY

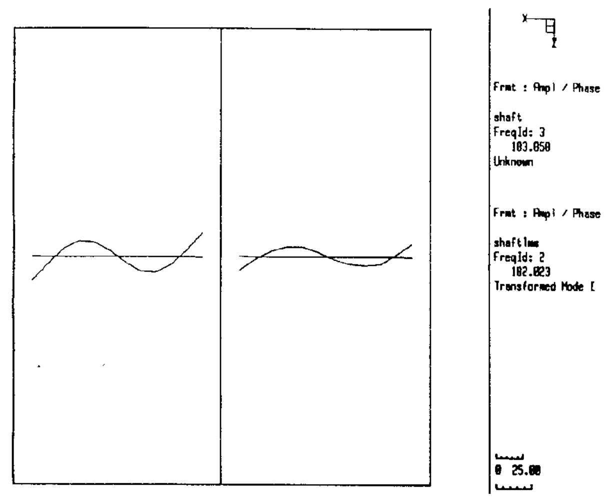

FIGURE 2 - MAC & COMAC GRAPHICAL OUTPUT FORMAT

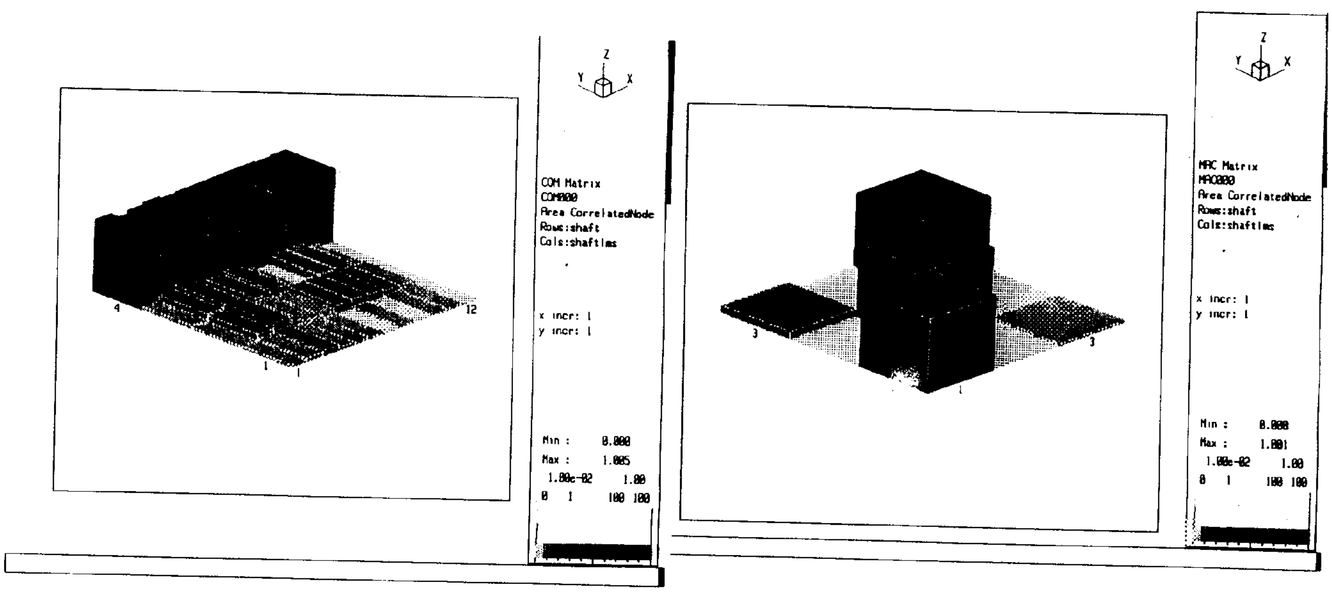

TABLE 3 - MAC & COMAC TABULAR OUTPUT

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Modulus Difference and Comac Matrix : COM000   Correlation Analysis :

	Comp Id	Node Id	Dof	66.844 / 66.9	183.86 / 182.02	359.41 / 356.86	Comac Value
1	1	1	z	0.04097	0.03311	0.05679	0.99989
2	1	6	z	0.06216	0.12145	0.13902	0.91627
3	1	10	z	0.08672	0.20301	0.19893	0.96600
4	1	15	z	0.04677	0.01194	0.00099	0.99683
5	1	19	z	0.03132	0.07293	0.11688	0.96440
6	1	24	z	0.02073	0.06107	0.15061	0.98412
7	1	28	z	0.00031	0.12653	0.05943	0.98566
8	1	33	z	0.02273	0.13128	0.00538	0.98670
9	1	37	z	0.00992	0.11118	0.13202	0.99730
10	1	42	z	0.01524	0.09005	0.13533	0.99513
11	1	46	z	0.03551	0.07746	0.06181	0.98026
12	1	51	z	0.00000	0.00000	0.00000	1.00000

CADA-X   Rev 2.5
msclink1

Modal Correlation : (MAC > 0.750)   Set_1: shaft Set_2: shaftlms

	Set_1 mode	Set_1 Hz	Set_2 mode	Set_2 Hz	diff Hz	diff %	MAC
1	1	66.844	1	66.900	0.056	0.1	0.996
2	3	183.858	2	182.023	-1.835	-1.0	0.972
3	5	359.407	3	356.860	-2.547	-0.7	0.968

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msclink1

MAC Matrix for Area: CorrelatedNodes   Name : MAC000   Rows: shaft Cols: shaftlms

		Hz	1 / 66.9	2 / 182.02	3 / 356.86
1	1	66.844	0.99555	0.00554	0.03427
2	3	183.86	0.00012	0.97178	0.00445
3	5	359.41	0.10213	0.00049	0.96772

Experiment #2 - Fixed-Free Powertrain Assembly

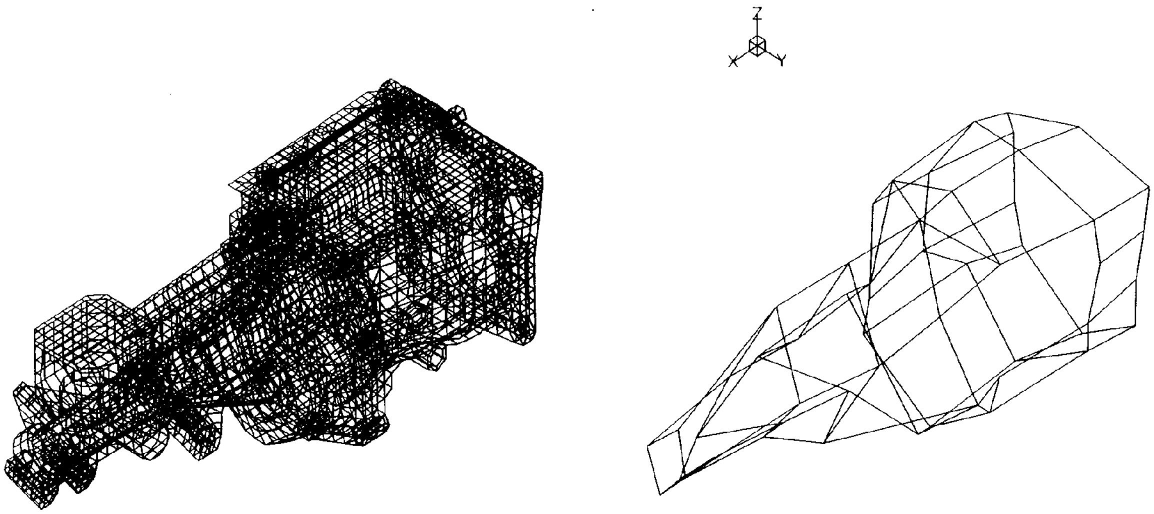
The objective of this experiment was to evaluate the expansion process used to match the experimentally derived modal model to the FEA developed model. In this experiment, the finite element model consisted of 5055 grid points and 6615 elements. The FEA model statistics are provided in Table 3. The experimental modal model was constructed from 80 triaxial measurement points. Figure 3 shows both the analytical model and experimental model geometries. In this test case, the model under study was fixed on one end and excited in the vertical direction with a small electrodynamic shaker. The modes of interest in the study were fundamental vertical and lateral bending modes. Since the shape of the test item was complex and non-symmetric, manual calculations of these modes were not practical. In addition, the correlation software code required internal modification to increase the programmed defaults for work vector size to accommodate the approximate 30,000 DOFs in the analytical model. Hardware modifications to the HP730 host machine were also required to reconfigure available memory and swap space. Once the software code and hardware were modified, the identical correlation process utilized in the first experiment was carried out for this test case. The geometric correlation was first followed by data integration and MAC and COMAC calculations. The results of the first iteration from the automated process are provided Table 4. The problems under study in this evaluation were resolution of the expansion process when significant differences are present in the experimentally determined measurement nodes and the grid point density in the FEA model.

Secondly, the experimental modal model was constructed using three (3) separate components (similar to SUPERELEMENTS) in the geometry module. This required that the modal solutions were "global" solutions based on the combined responses of the three (3) separate component entities. Another problem under evaluation was the ability of the MSC_NF translator to process analytical models in the 30,000 DOF size category. Since manual intervention and calculation were required to execute the correlation process, both manual and automatic correlation processes were reviewed. Because of the significant differences in the grid density of the FEA to the node density of the test model, the automated geometric correlation function did not perform well. The basis for the automatic procedure was defined by the mean distance between FEA grid points from which a sphere is constructed to search for the nearest test node location. Since the grid density was very high (see Figure 3), the sphere developed to match test node points was very small and geometric correlation was not achieved. Manual intervention for the sphere radius was required to achieve correlation. Unfortunately, increasing the sphere tolerance reduced the assurance that the proper grid to node match was achieved. This resulted in lower than expected correlation values as expressed in the MAC.

TABLE 3 - EXPERIMENT #2 FEA MODEL STATISTICS

Element Type	Element Count	Totals
CBEAM	32	6615 elements
CQUAD4	4748	5055 grid
CHEXA	573	
CPENTA	117	
CTRIA3	1145	

FIGURE 3 - EXPERIMENT #2 EXPERIMENTAL
AND ANALYTICAL GEOMETRIES



ANALYTICAL EXPERIMENTAL

TABLE 4 - EXPERIMENT #2 CORRELATION & MAC RESULTS

MODE	Test Data (Hz)	Trial #1	FEA Results Corr. %	MAC	MAC for Corr. Nodes
1	217.5	170.5	21.6	0.82	0.91
2	247.5	180.7	26.9	0.88	0.84
3	279.4	229.9	17.7	0.66	0.71
4	311.2	236.4	24.0	0.29	0.58
5	383.8	432.0	12.6	0.71	0.89

<u>Experiment #3 - Fixed-Free Powertrain Assembly (w/Superelements)</u>

The objective of this experiment was to evaluate the performance of the correlation software for a modal test which contains ill-defined boundary conditions, non-linear influences in the range of excitation for the experiment, and closely coupled modes. Like experiment #2, the modal test measurement density was very low compared to the FEA grid size. The original FEA model contained 3176 grid points and 5774 elements. The FEA model was expanded as a result of several MSC/NASTRAN sensitivity iterations to include an additional 304 grid points and 657 elements. The final FEA model statistics are provided in Table 5. The analytical model also utilized six (6) superelements which divided the model in logical sections based on the test configuration and existing structural boundaries. The modal test model contained 57 triaxial measurement points. The modal test geometry was also divided into similar superelement boundaries (called components). Figure 4 shows the analytical and experimental geometries. The problem summary for this experiment is extensive. It contains many of the common difficulties for correlation analysts who are required to achieve high levels of correlation in the mathematical models so that model updating and structural modifications can be evaluated. One significant problem resulted from the fact that the correlation software available for the first two (2) experiments did not support the use of superelements. Although the model was relatively small, the use of superelement methods (Tip Runs) was critical for the practical evaluation of the sensitive areas of the model, particularly with respect to model updating for test fixture induced issues and revised boundary conditions. The concept of Component Mode Synthesis (CMS) was to provide an accurate reduction of each of the superelement responses for normal modes, constraint modes, and rigid body modes [9]. Further enhancements to the basic mode set included inertia relief modes and substructure normal modes for various boundary conditions. These resulted in a powerful technique for studying local dynamic phenomenon within individual superelements and interfaces. The efficiencies associated with running the FEA solutions with Component Mode Synthesis and Superelement Methods is shown in Table 6. From the table it can be observed that a single Tip Run represents only a small percent of the total time required to run the full solution sequence but retains all of the necessary dynamic analysis results including the sensitivity analysis modifications for the superelement modification of interest. In addition to the sensitivity studies, another key function which provided significant insight to the differences in the dynamic behavior of the analytical and experimental models was the use of the XYPLOT command to provide single location Frequency Response Functions (FRF) for analytical grid points. This form of output for individual grid points was very helpful for comparison to the experimentally derived model which uses FRFs in its assembly of the global dynamic response animations. This plotting feature required that the input excitation location and type be modeled in the FEA and the structure perturbed to obtain the FRF outputs. An example of the FEA grid point FRF and the experimentally measured FRF are shown in Figure 5. Table 7 illustrates the correlation achieved after only three (3) sensitivity runs. Further efforts to improve the correlation to better that 10% percent were not required for this model.

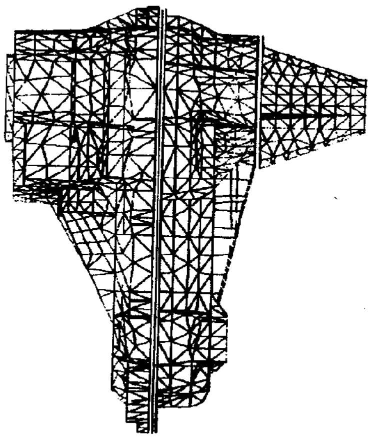
TABLE 5 - EXPERIMENT #3 FEA MODEL STATISTICS

Element Type	Element Count	Totals
CBEAM CQUAD4 CTRIA3	60 5487 884	6431 elements 3480 grid

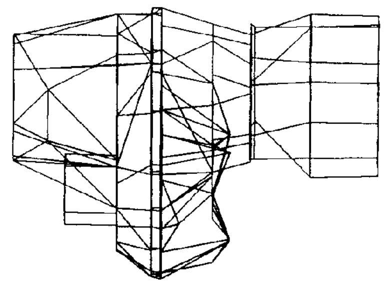
TABLE 6 - COMPARISON OF SUPERELEMENT TO FULL SOLUTION RUN TIMES

Model Description	I/O sec	CPU sec
Full Model Run (SOL 103)	**494**	**981**
Single Level Superelement Run (SOL 103)		
Semap Run	19	16
Duration of 6 Tip Runs		
Tip se50	123	473
Tip se350	125	369
Tip se750	24	48
Tip se850	16	22
Tip se950	45	36
Tip se975	104	150
Duration of Residuals	60	41
Duration of Totals	**516**	**1139**

FIGURE 4 - EXPERIMENT #3 ANALYTICAL
AND EXPERIMENTAL GEOMETRIES



ANALYTICAL

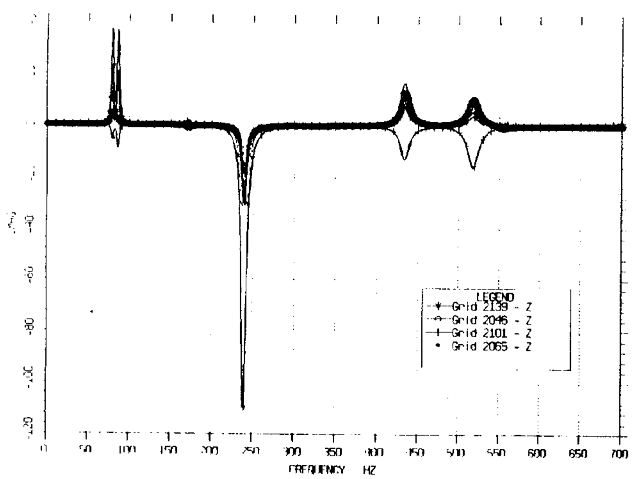


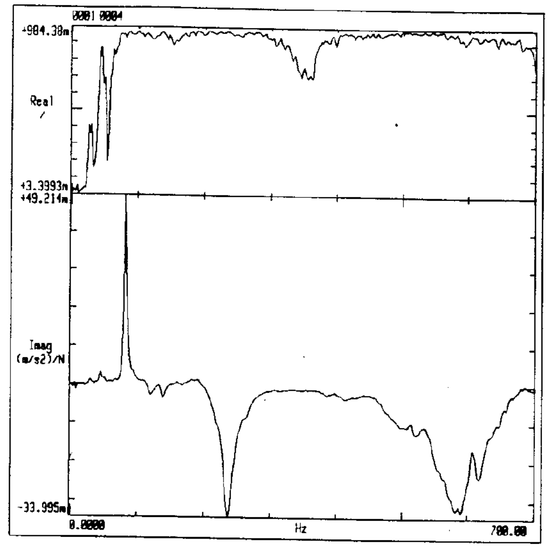
EXPERIMENTAL

TABLE 7 - EXPERIMENT #3 CORRELATION RESULTS

MODE	Test Data (Hz)	FEA Results Trial #1	Corr. %	Trial #3	Corr. %
1	81.9	106	29.4	78.9	3.6
2	119.6/138.2	126	n/a	87.4/174.	n/a
3	233.7	238	1.8	249	6.6
4	385.9	299	22.5	416	7.8
5	412.4	486	17.8	452	9.6
6	513.4	535	1.3	520	1.3

FIGURE 5 - FRF SAMPLE OUTPUT FROM MSC/NASTRAN
AND MODAL TEST COMPUTER





MSC/NASTRAN MODAL COMPUTER

CONCLUSIONS

The utility of the graphical interface for model correlation is a significant benefit to the correlation analyst. The neutral file translation program discussed in this work simplifies the interface between the FEA environment and the experimental measurement environment. Unfortunately, the significant resources within MSC/NASTRAN cannot be fully realized using the commercially available software due to its inability to function with models containing superelements. Also the performance of the software is somewhat limited when the model size approaches the 30,000 DOF size. Component Mode Synthesis and sensitivity analyses within MSC/NASTRAN offer significant insight into the correlation difficulties for specific problems. These tools coupled with the superelement method for modeling provide an important and economical environment for researching the correlation issues in a program. Further work should be done to facilitate the communication between FEA solution data sets and experimental solution data sets. Another important communication tool would be the ability to compare analytical and experimental geometries for spacial correlation as well as FRF results. Working with SEREP [9] methods for the reduction of large scale FEA models are a necessary element for successful correlation programs. An analytical model sizes and levels of complexity grow, reduction and automation in the format requirements for design optimization software would be beneficial for correlation studies for which the variabilities between the analytical and experimental data sets could be derived from the experimental data set sensitivity analysis output. These types of improvements would allow the correlation process to migrate into the large scale system level models currently being developed in the automotive industry.

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