Combined Testing and Analysis on a PC using MSC/pal and STAR

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ABSTRACT

This paper presents our recent experiences in the use of MSC/pal to model the dynamics of a structure, and in the use of the SMS STAR system to perform a modal test of the same structure. Both of these complementary engineering tools run on an IBM-PC AT type of computer, and both yield a set of modal parameters which define the linear dynamic properties of a structure.

The paper points out the advantages of finite element modeling, modal testing, and Structural Dynamics Modification (SDM), and eigenvalue modification technique which can be used with either analytical or experimental modal data.

It then describes how combined testing and analysis was used on a substructuring problem. In the case presented here, two different flat plate structures were tested separately using STAR, and then "attached together" using the SDM capabilities of the STAR system. Then, these two substructures were also modeled using MSC/pal, first as "unattached" structures, and then attached together. Finally, the combined substructures were tested, and the modal properties resulting from SDM, the finite element model, and the test were compared.

Some comments regarding the amounts of time required to perform the modal test, perform SDM calculations, and build the finite element model are also included.

INTRODUCTION

The IBM-PC computer technology has progressed to the point where it is now feasible to implement computationally intensive software programs on an IBM-PC AT, which were heretofore relegated to more powerful mini and mainframe computers. Both the MSC/pal finite element modeling package and the SMS STAR structural analysis package are such computationally intensive programs. When MSC/pal is used for structural dynamics applications, its eigensolution capabilities can require a substantial amount of CPU power and a large memory. The STAR system, on the other hand, performs complex curve fitting operations of measured data and displays the resulting mode shapes in a live animated display. These functions also require substantial computer resources.

Both of these software packages are fundamental tools that any engineer or dynamicist should have available for solving noise, vibration, or failure problems in mechanical structures. Having these capabilities on a desktop computer, where they are readily accessible and usable, represents a tremendous advantage in comparison to using remote mini or mainframe computing facilities.

Although the largest finite element modeling and modal testing jobs may still require a larger computer system, a growing number and variety of structural testing and analysis problems can be adequately solved with a desktop system. The continued growth in computational power and memory capabilities, combined with the lowering of the cost of desktop computers are making them increasingly more attractive for engineering applications.

Advantages of Finite Element Modeling

MSC/pal allows the user to build a finite element model of a structure on a desktop computer. It interfaces to the most popular drafting software package on the PC; AutoCAD, which allows the user to begin the modeling process by laying out the geometry of the structure with the latest computer-aided drafting techniques.

Finite element modeling (FEM) is used in the design cycle of new mechanical parts or systems because it offers a number of advantages. Using FEM, a mathematical model (static or dynamic) of the structure can be built before the first prototype structure is even built.

Finite element models are typically used for the following analyses:

- *Static loads analysis* to observe high stress and strain areas.
- *Modal analysis* to find the natural frequencies and deformations (mode shapes) of the structure.
- *What If investigations* where the effects of "design changes" (changes in the material properties and geometry) on the static or dynamic properties of the structure are investigated.

- *Dynamic loads analysis* where time histories of the structural response to "real world" dynamic loads is simulated.

However, since a finite element model is an approximation to the real structure, the accuracy of the model depends to a degree on the skill of the user in choosing the discretization (node point selection) and element types for the model. Therefore, it is usually unwise to rely solely on the use of a finite element model for the above analyses without some prior verification of it through the testing of the real structure.

Advantages of Modal Testing

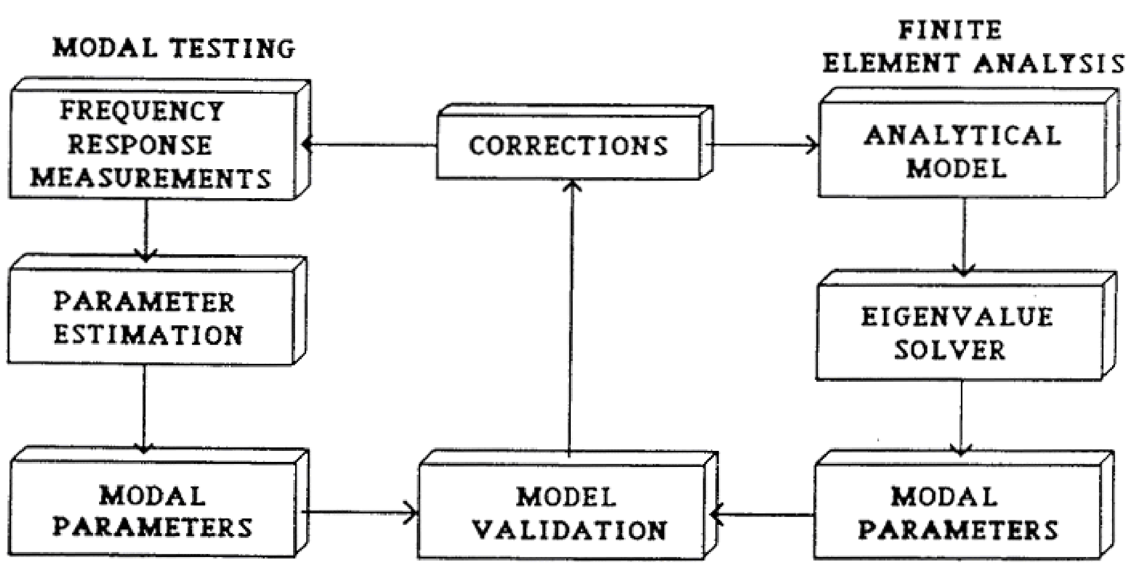
The modes of vibration, (or eigenvalues and eigenvectors), can be used to completely characterize the dynamic properties of a structure. Furthermore, the modes are very sensitive indicators of changes in the structure's static or dynamic properties. Hence, modal testing, which is used to identify the modal parameters (natural frequencies, damping, and mode shapes) of a real structure can also be used to verify the accuracy of a finite element model of the structure. This verification process is shown in the figure below.

The SMS STAR system uses the transfer function (or frequency response function) method to identify the modal properties of structures. It interfaces to most of the popular multi-channel FFT analyzers on the market today. FRF measurements are made with the analyzer and transferred to STAR either via disk storage or via the IEEE-488 Instrument Interface. These measurements are then processed in STAR to estimate the modal parameters, and the mode shapes can be displayed in animation to verify the test results.

Modal testing, then, offers the following advantages:

- *Verification of analytical models* by comparison of modal parameters.
- *Troubleshooting* noise and vibration problems on structures or machinery which is already in service.
- *Evaluation of design changes* on prototypes before production changes.
- *Development of dynamic models* for parts of structures which are difficult to model.

Combined Testing and Analysis



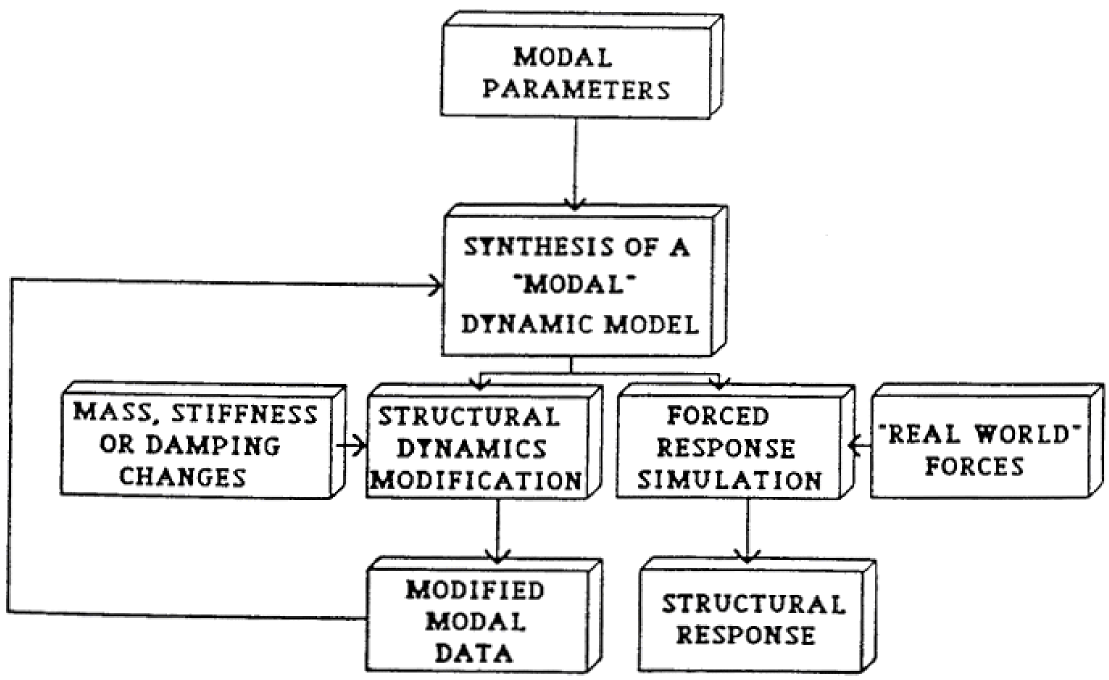
Combined Testing and Analysis

It is clear from the lists of advantages above that a combined use of modal testing and finite element modeling and analysis gives the engineer or structural dynamicist the best possible chance of understanding and solving difficult noise and vibration problems. Furthermore, once a finite element model or a set of experimental modes of a structure has been verified, additional analyses can be performed with the data to better understand structural problems. Two advanced analyses which utilize a modal model of the structure are Structural Dynamics Modification (SDM) and Forced Response Simulation (FRS), as shown in the figure below.

SDM can be used to perform simple "What If" investigations on a structure. It can be used to quickly determine how the modal properties change when scalar springs, dampers, and point masses are added to (or subtracted from) a structure. SDM solves an eigenvalue problem **in modal space,** as opposed to an FEM eigenvalue problem which is solved in **physical space,** and hence SDM can generate eigensolutions for the modified structure much more rapidly than an FEM eigensolver.

FRS can be performed either with a time-domain or a frequency-domain form of the equations of motion, once the modes of a structure are known. The figure below shows how forced structural responses can be synthesized using either the time domain or frequency-domain model expressed in terms of modal parameters. Either of these two models will yield the responses at any DOF of the structure as functions of measured or synthesized forcing functions at any combination of input DOFs.

Structural Dynamics Modification and Forced Response Simulation



A Substructuring Problem

To illustrate some of the advantages of combined testing and analysis, a substructuring problem was solved with the combined use of MSC/pal and STAR. First, MSC/pal was used to model the dynamics of two flat plate substructures, and to generate their **rigid body** and **fundamental flexible** modes of vibration. Then, the two structures were tested using STAR to measure their flexible modes. (Rigid body modes are typically not obtained experimentally). The results of the analytical model and the modal test were then compared.

Next, the two substructures were "attached together" using the SDM capabilities of STAR. The analytical **rigid body** modes, plus the **measured flexible** modes of the uncoupled substructures were used as input data to SDM. (The analytical flexible body modes could also have been used). Then the coupled substructures were modeled by building a new FEM with MSC/pal, and the SDM results were compared with the new FEM modes for the combined substructures.

Finally, the substructures were bolted together and tested again to obtain a new set of experimental modes for the combined structure. The experimental modal parameters were then compared with both the SDM and the FEM results for the combined substructures.

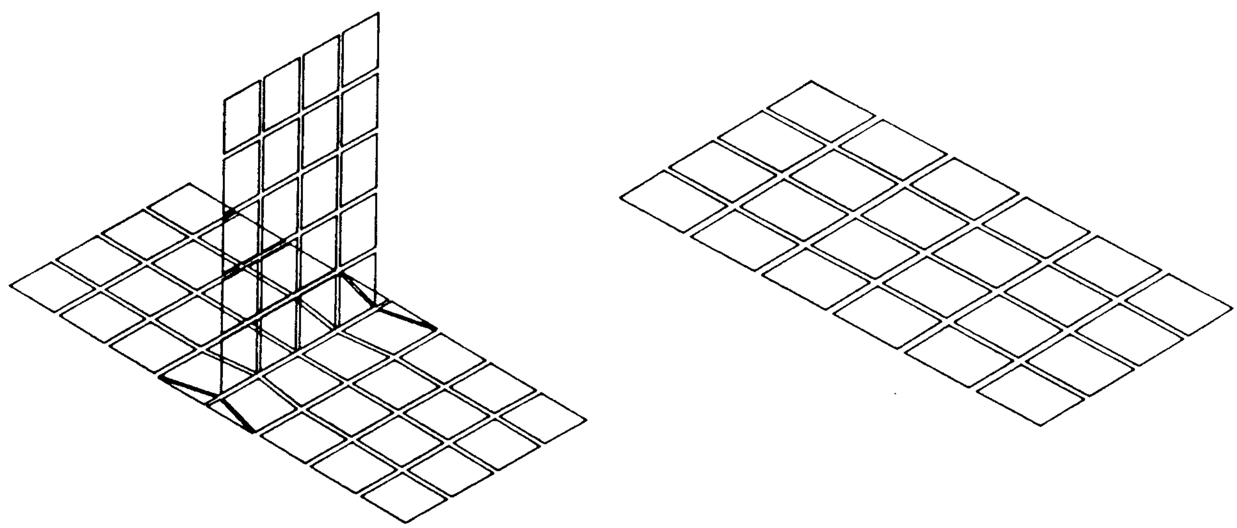
Finite Element Models

MSC/pal was used to build finite element models of the two substructures. The models are shown below. Substructure #1, the T plate, was modeled with 72 nodal points and 6 DOFs (3 translations and 3 rotations) at each node, for a total of 432 DOFs in the model. Substructure #2, the flat plate, was modeled with 35 nodal points and 6 DOFs at each node, for a total of 210 DOFs.

Quadrilateral plate elements were used in both substructure models. The plates were made out of aluminum, so a Young's modulus of 9.5 million psi, a Poisson's Ratio of .33, and a mass density of 9.78×10^{-2} lbm/cubic inch were used.

After the models were built, the rigid body modes, and the first 4 flexible modes of both substructures were found with the eigensolver in MSC/pal. The frequencies of the flexible modes are listed in Table 1.

Finite Element Models



Modal Test of the Substructures

Each of the two substructures was then tested using impact testing, a 2-channel FFT analyzer, and the STAR software. The impacting force and acceleration were measured with an Impact Hammer Testing Kit. The FRF measurements were made with the FFT Analyzer and transferred to the IBM-PC computer via an IEEE-488 Interface, under control of the STAR software.

Each substructure was testing while resting on a piece of foam rubber, to approximate free-free boundary conditions. The structures were impacted at the same geometric locations as the nodal points in the finite element models. Since all of the modes of interest (the lower frequencies) had predominant motions normal to the plane of each flat plate, measurements were only taken in those directions which were normal to the plate surfaces.

A total of 72 FRF measurements were made on substructure #l, and a total of 35 measurements were made on substructure #2.

One advantage of modal testing over analytical modeling is that the frequencies *and damping* of the modes can be readily identified by curve fitting any one of the FRF measurements. Although damping is always present and measurable in test data, it is typically ignored in finite element modeling because it is difficult to select accurate damping properties for the structure. This is not a serious drawback when comparing analytical and experimental results, however, since the damping forces in most structures are usually insignificantly small compared to the inertial (mass) and restoring (stiffness) forces. The experimental and analytical modal frequencies are compared in Table 1 below. The mode shapes of the flexible modes are also shown.

Table 1.
Comparison of MSC/pal and STAR Modal Parameters

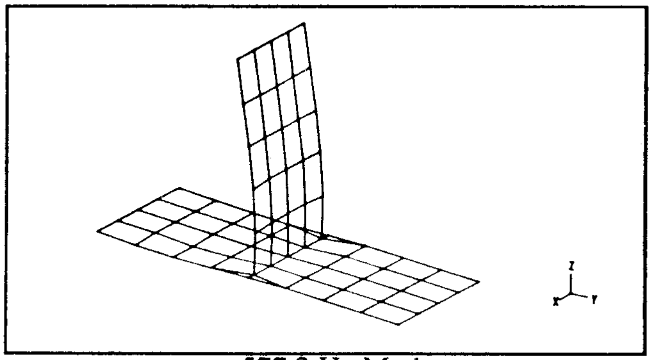
Substructure #1

Mode No.	Analytical Modes Frequency (Hz)	Experimental Modes Frequency (Hz)	Experimental Modes Damping (%)
1	577.2	554.4	.57
2	978.1	1056.5	.38
3	1495.2	1464.3	.16
4	1721.8	1754.9	.24

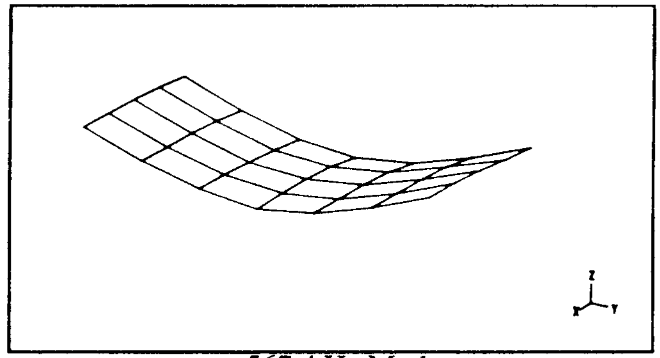
Substructure #2

Mode No.	Analytical Modes Frequency (Hz)	Experimental Modes Frequency (Hz)	Experimental Modes Damping (%)
1	567.4	607.4	1.12
2	745.4	795.7	.83
3	1484.2	1693.6	.27
4	1567.1	1749.1	.50

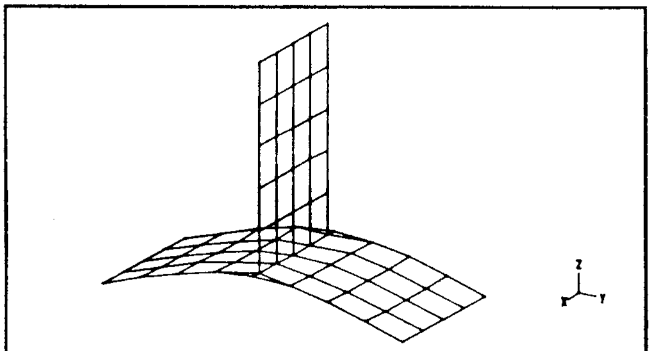
Mode Shapes of the Fundamental Flexible Modes



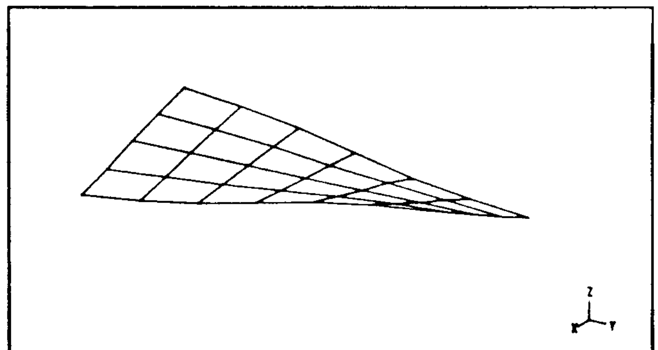
577.2 Hz Mode



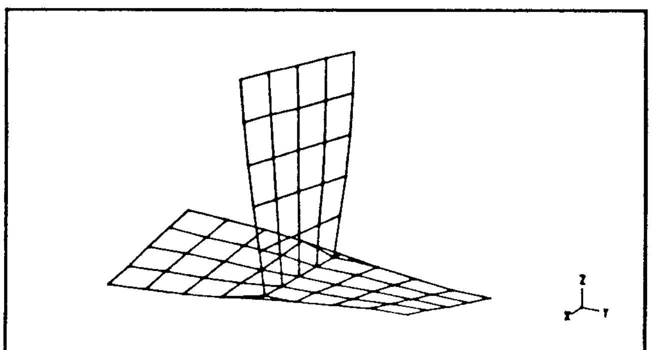
567.4 Hz Mode



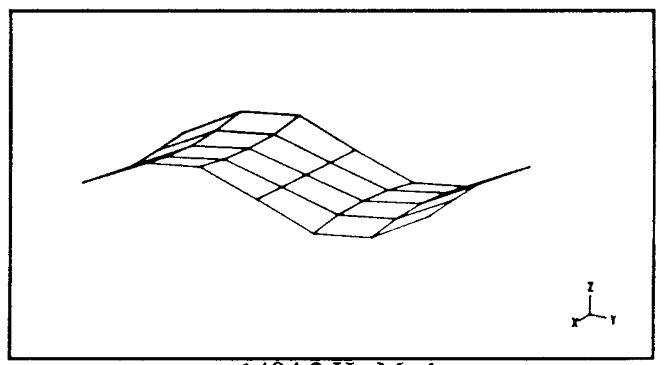
978.1 Hz Mode



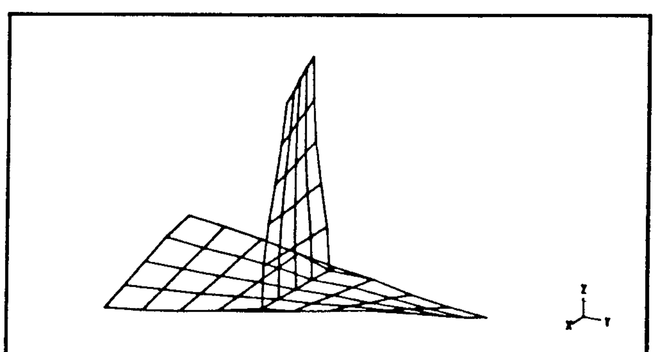
745.4 Hz Mode



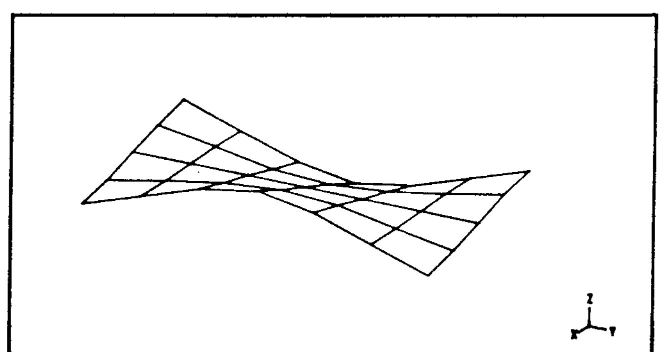
1495.2 Hz Mode



1484.2 Hz Mode



1721.8 Hz Mode



1567.1 Hz Mode

Modes of the Combined Substructures

Using the modal parameters (frequencies, damping, and mode shapes) of the two unattached substructures, the SDM commands in STAR were used to couple the two substructures together and generate the mode shapes of a new structure, as shown below. The coupling was modeled by placing *infinite* translational stiffnesses (rigid links) and *infinite* rotational stiffnesses (rigid torsional springs) between the common node points on the two substructures, as shown in the diagram below.

Next, the new finite element model of the entire structure, (combined substructures), was built, and the eigensolution of this new model was found using MSC/pal.

Finally, the two substructures were bolted together, and a model test of the complete structure was performed using STAR. The Driving Point measurement (where the excitation and response are the same point), is shown in the figure below.

The modal frequencies from the two analytical methods and the modal test are compared in Table 2, and the mode shapes are also shown on the following page.

Stiffness Modifications made to Attach Substructures Together

(Common Nodes were Tied Together with Rigid Links and Infinite Rotational Stiffnesses)

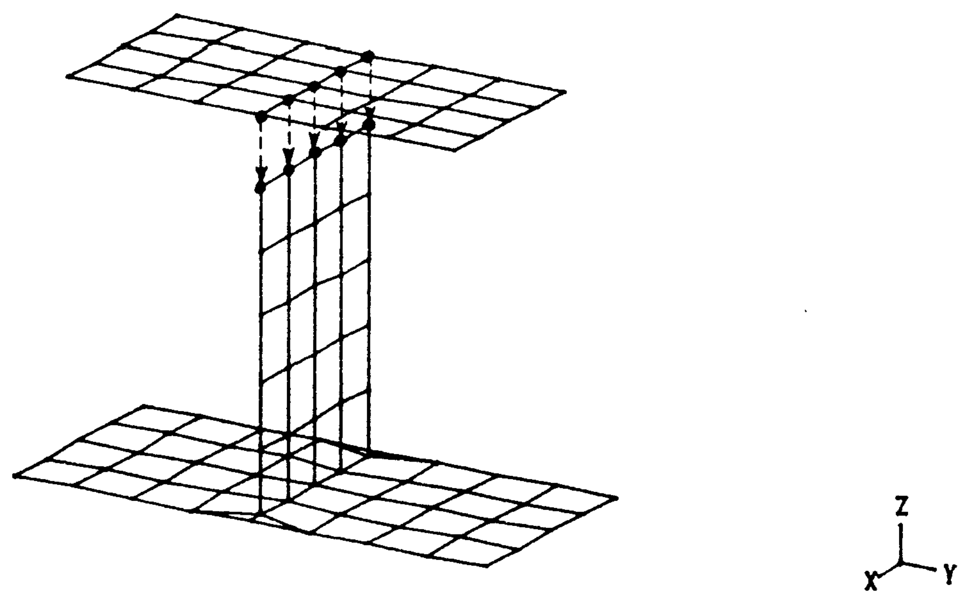
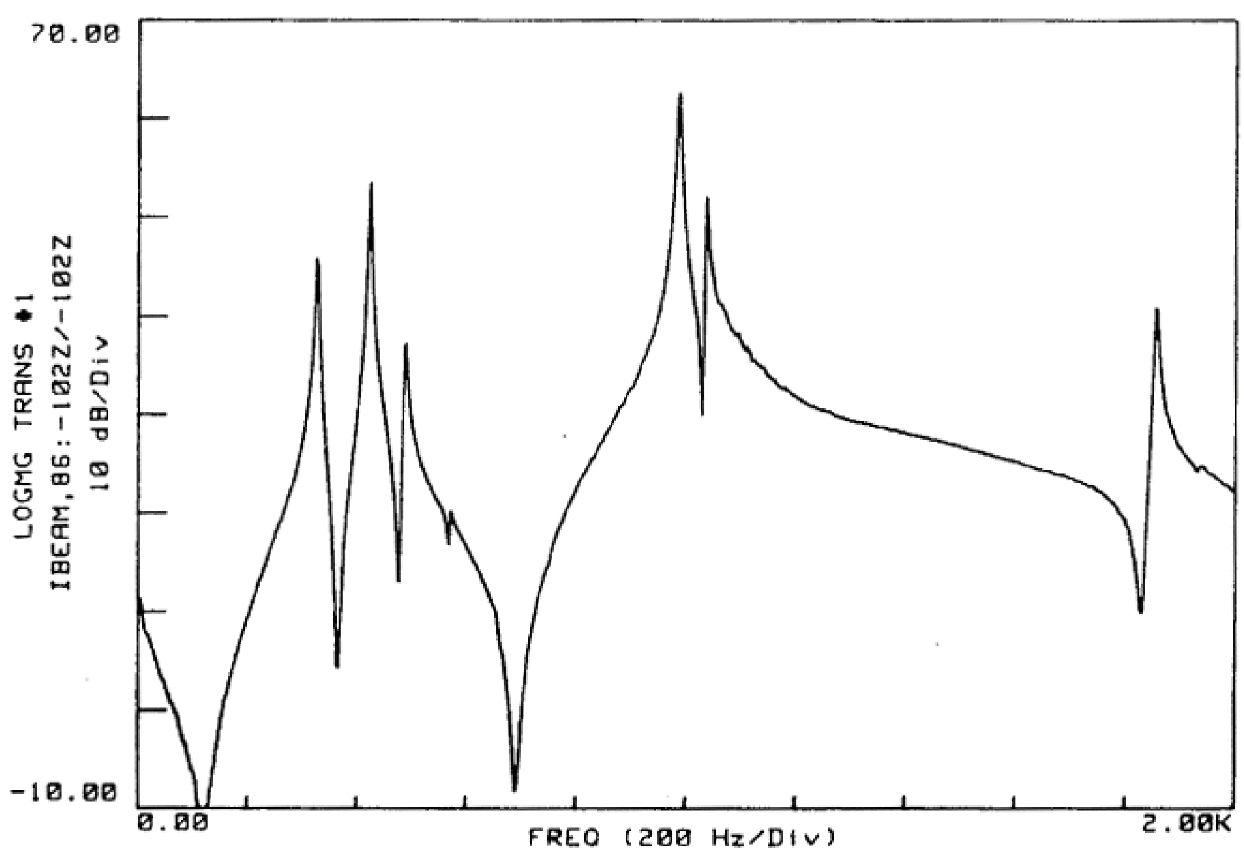


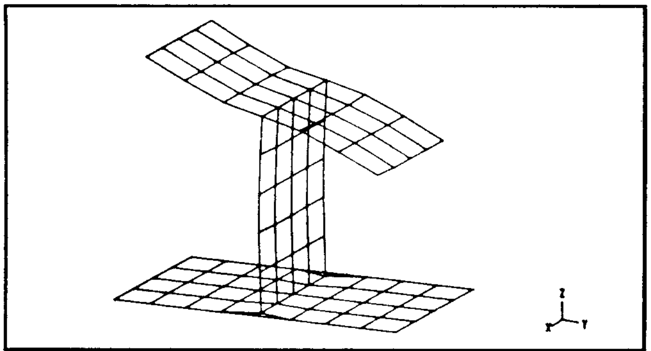
Table 2. Comparison of SDM, MSC/pal, and Experimental Modal Frequencies for Combined Substructures

Mode No.	SDM Modes Frequency (Hz)	MSC/pal Modes Frequency (Hz)	Experimental Modes Frequency (Hz)
1	339.1	332.2	331.2
2	395.9	394.9	424.7
3	527.4	492.9	490.2
4	642.8	625.3	573.6
5	----.-	931.1	986.9
6	964.9	933.0	1037.0
7	975.1	962.4	1040.8

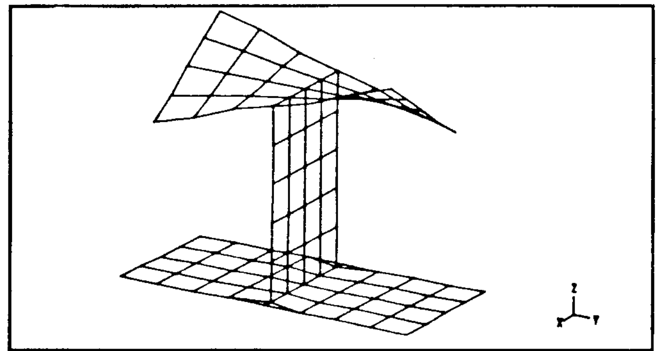
Driving Point Frequency Response Measurement



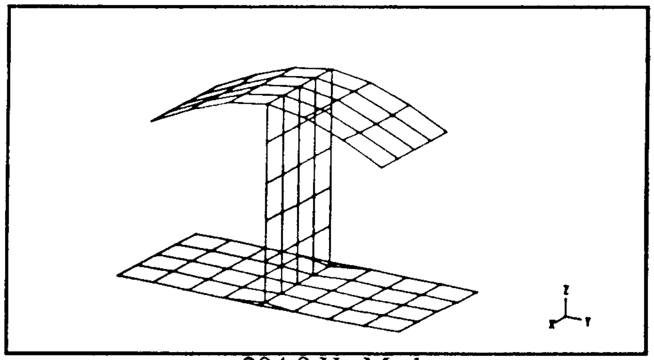
Mode Shapes of the Combines Substructures



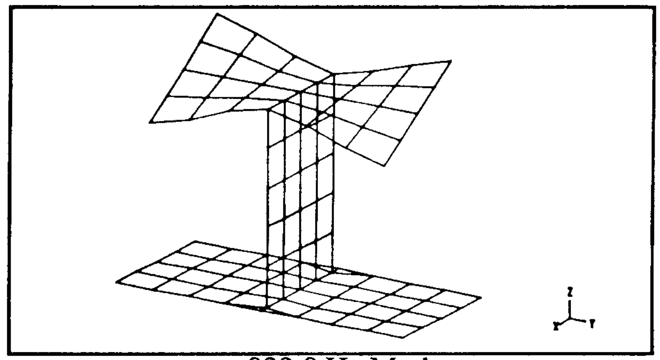
332.3 Hz Mode



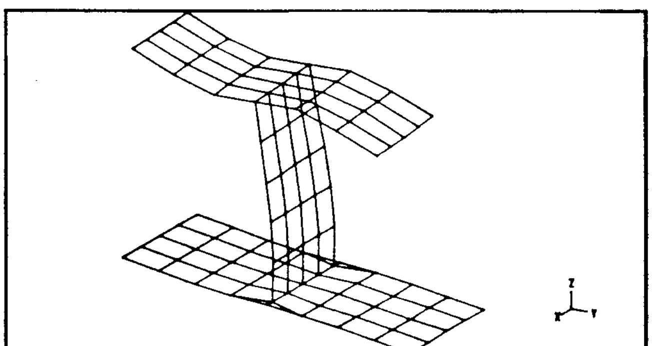
931.1 Hz Mode



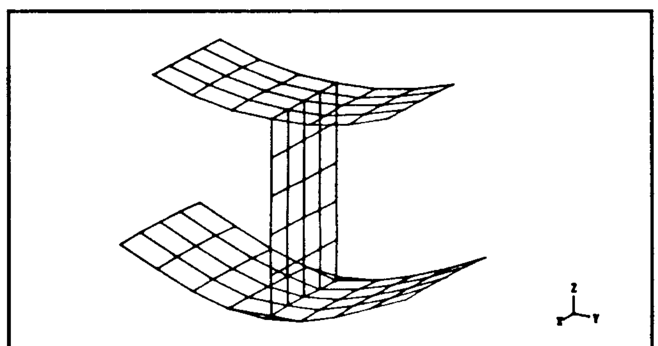
394.8 Hz Mode



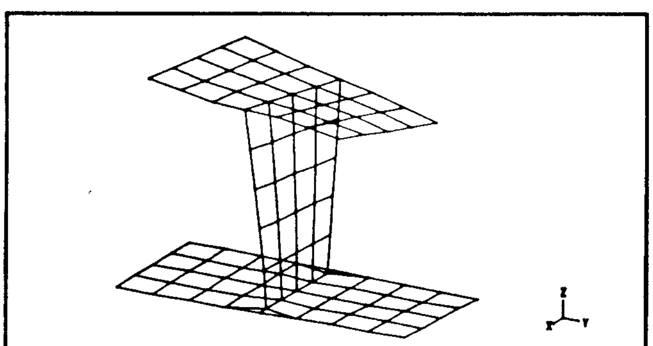
933.0 Hz Mode



492.9 Hz Mode



962.4 Hz Mode



624.3 Hz Mode

CONCLUSIONS

We have presented some results here which show how two new powerful structural analysis tools for the IBM PC, namely MSC/pal and SMS STAR, can be used to model and measure the dynamic properties of mechanical structures. First, we used these tools to build finite element models for, and test, two simple structures; an aluminum T plate and an aluminum flat plate. Then we "attached" these two substructures together using the Structural Dynamic Modification (SDM) capabilities in STAR. This was done by modeling the coupling together of the two structures with translational and rotational stiffeners. Then, to compare answers, a new finite element model of the combined substructures was built, and the combined substructures were also tested.

The results shown in Table 1. indicate, first of all, that it is possible to model and test simple flat plate structures, and obtain comparable results from these two very complementary procedures. With some minor refinements to the model and the test procedure, results within 10% of one another are achievable. The results presented here are within 12% for all modes.

The results shown in Table 2. indicate that the modal properties of the fundamental modes of a structure can be used directly to perform substructuring analyses. The results of the eigenvalue modification process used in SDM were very comparable to those of the finite element model and the modal test of the combined substructures.

Each of these tools provides unique capabilities for understanding and solving structural vibration problems. The primary advantage of finite element modeling is that it provides an analytical model from which structural modifications and forced response simulations can be performed. The primary advantage of modal testing is that it validates the finite element model.

The primary advantage of SDM is that it allows the investigation of structural modifications much more rapidly than reformulating and solving the finite element equations**.** In the substructuring case presented here, the following times were needed to determine the modes of the combined structures:

Method	Approx. Solution Time
MSC/pal	15 minutes
Modal Test	3 hours
SDM	30 seconds

These results demonstrate that both MSC/pal and STAR running on an IBM PC are very useable tools for measuring and analyzing the dynamics of structures.