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- MOVER II -

A COMPUTER PROGRAM FOR MODEL VERIFICATION OF DYNAMIC SYSTEMS

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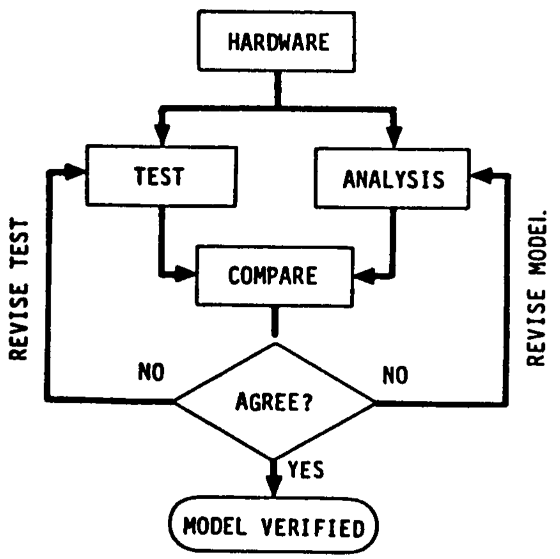
DYNAMIC MODEL VERIFICATION

Dynamic model verification is the process whereby an analytical model of a dynamic system is compared with experimental data, adjusted if necessary to bring it into agreement with the data, and then qualified for future use in predicting system response in a different dynamic environment. There are various ways to conduct model verification. The approach adopted in MOVER II employs Bayesian statistical parameter estimation. Unlike "curve fitting" whose objective is to minimize the difference between some analytical function and a given quantity of test data (or "curve"), Bayesian estimation attempts also to minimize the difference between the parameter values of that function (the model) and their initial estimates, in a least squares sense. The objectives of dynamic model verification, therefore, are to produce a model which (1) is in agreement with test data, (2) will assist in the interpretation of test data, (3) can be used to help verify a design, (4) will reliably predict performance, and (5) in the case of space structures, facilitate dynamic control.



OBJECTIVES

- MATCH ANALYSIS AND TEST
- INTERPRET DATA
- VERIFY DESIGN
- PREDICT PERFORMANCE
  - IMPEDANCE
  - DISPLACEMENT
  - LOADS
  - FATIGUE
  - ETC.
- FACILITATE CONTROL

HISTORY OF DEVELOPMENT

One of the earliest attempts in automating the Bayesian parameter estimation procedures was begun in 1972. Under Contract to NASA, a computer code called MOUSE was developed and demonstrated on the Saturn V launch vehicle. Although the methodology used in developing MOUSE was quite general, it was only applicable to one-dimensional shear beam models. In 1976, two efforts funded by NASA were begun in parallel to further develop the MOUSE concept. The first effort was directed towards general dynamic systems, i.e., models which might be constructed from lumped parameter, finite elements, modal coordinates, or some combination of the three, and which might also contain heavy damping. The computer code MOVER was developed to automate the verification of such systems, and won a NASA New Technology award in 1982. The second effort was geared towards efficient model verification of large, lightly damped systems typified by aerospace structures, with specific application to the Space Shuttle Orbiter finite element model; the computer code CATELAST was developed to automate this procedure. Over the past several years, an advanced version of MOVER has evolved. Called MOVER II, it incorporates modal synthesis and substructuring techniques for modeling large multi-component systems and provides a variety of graphic outputs to facilitate interpretation of results. MOVER II has been used to verify models of turbo-pumps rail vehicles, launch vehicles and high-speed rotating machinery.

- 1973 - MOUSE (MODEL OPTIMIZATION USING STATISTICAL ESTIMATION)
- 1977 - MOVER (MODEL VERIFICATION)
- 1978 - CATELAST (CORRELATION OF ANALYSIS AND TEST FOR LARGE STRUCTURES)
- 1984 - MOVER II

MOTIVATION

Compared with the state-of-the-art of model generation and analysis, which has matured considerably over the past decade or so, the state-of-the-art in experimental model verification is still very much in its infancy. Structural testing, particularly dynamic testing and data processing, has also progressed significantly in recent years, but the proven ability to assimilate experimental data systematically into a specified model configuration to obtain an improved set of model parameters values, has not experienced the same steady growth. The original objectives for the MOUSE code were (1) to revise the mass and stiffness parameters of a finite element model using a Bayesian statistical estimator, (2) impose no limits on the amount of test data required, and (3) provide a quantitative measure of the significance of the revised parameter values based on the quantity, quality and suitability of the data. Practical experience with MOUSE, however, indicated the need to satisfy several additional objectives: (4) incorporate a modeling capability applicable to general structural models, regardless of configuration or size; (5) estimate damping, as well as mass and stiffness parameters, even for structures with closely spaced modes; (6) eliminate the requirement for "pure" modal data; (7) require that the program resolve experimental data (to obtain natural frequencies, orthogonal mode shapes and modal damping) from sinusoidal response which may contain contributions of several closely spaced modes; and (8) require that the program be compatible with conventional analytical and experimental data.

1) RETAIN STATE-SPACE/FREQUENCY DOMAIN FORMULATION FOR LINEAR TIME-INVARIANT SYSTEMS

2) REPLACE NETWORK MODELING CAPABILITY IN MOVER WITH ADDITIONAL CAPABILITY FOR MODELING STRUCTURAL/MECHANICAL SYSTEMS

3) INCORPORATE SUBSTRUCTURING

4) ADD PARAMETER SENSITIVITY ANALYSIS IN THE FORM OF RESPONSE DERIVATIVES TO FACILITATE PARAMETER SELECTION

5) ADD INTERPRETIVE/DIAGNOSTIC OUTPUT AND GRAPHICS

- CONVERGENCE HISTORY OF OBJECTIVE FUNCTION AND PARAMETER ESTIMATES
- COMPARISON OF PRIOR MODEL AND REVISED MODEL TO DATA USED IN ESTIMATION
- SIGNIFICANCE INDICATOR FOR PARAMETER ESTIMATES
- CORRELATION MATRIX OF REVISED PARAMETER ESTIMATES

- MOVER II -

MODELING AND PARAMETER ESTIMATION CAPABILITIES

MOVER II has been structured to allow the verification of general dynamic systems. Lumped parameter models can be input by providing the equation(s) of motion for simple elements and/or components; this facilitates the analysis of discrete springs, dampers and simple components. Complex structural/mechanical models can be verified by inputting either a finite element representation (i.e., mass, damping, stiffness matrices) or by a modal representation (i.e., generalized mass, damping, stiffness). Finally, complex dynamic systems can be synthesized from combinations of lumped, finite element and modal models through the application of displacement constraints between individual components and subassemblies.

MOVER II has the capability of updating initial parameter estimates associated with lumped, modal and finite element models. In addition, submatrix scaling parameters can be estimated rather than individual finite element parameters. The submatrix scaling parameters are capable of increasing or decreasing the overall mass and stiffness of selected components and/or subassemblies. This step makes the analysis of large problems more tractable by reducing the number of variable parameters, while at the same time avoiding numerical difficulties associated with estimation of the individual parameters of small structural elements.

MODELING -

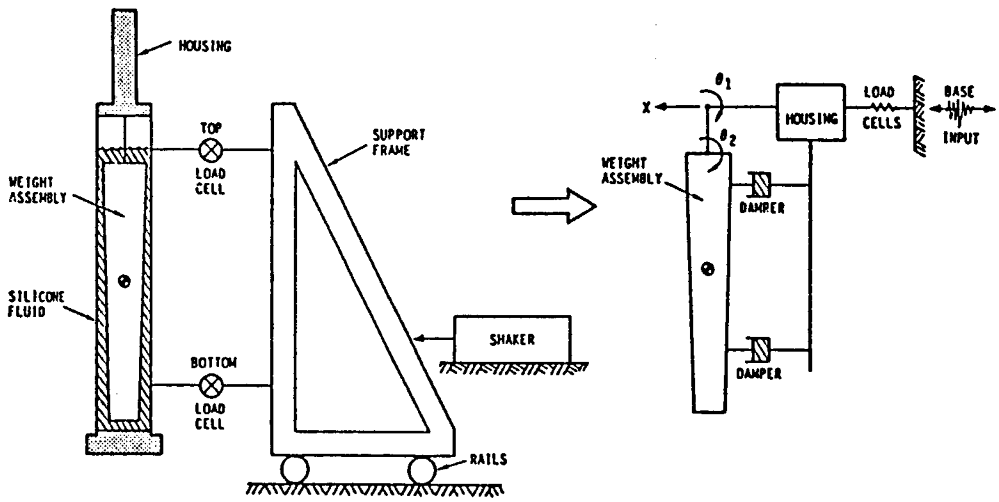
- LUMPED PARAMETER MODELS
- FINITE ELEMENT MODELS
- SUBSTRUCTURING

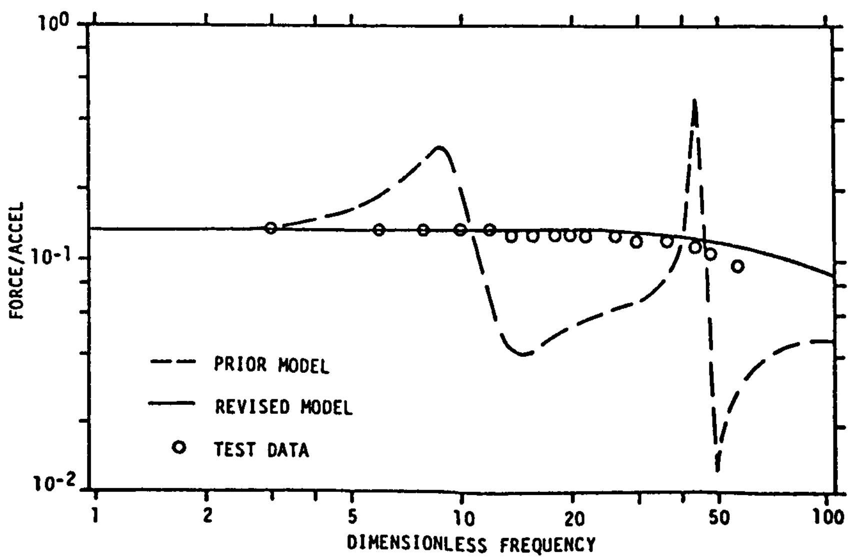
PARAMETER ESTIMATION -

- DISCRETE PARAMETERS
  - Linearized Finite Element Parameters
  - Lumped Stiffness, Mass and Damping
- DISTRIBUTED PARAMETERS
  - Linearized Linked Finite Element Parameters
  - Submatrix Scaling Coefficients
  - Modal Matrix Parameters

LUMPED PARAMETER MODELS

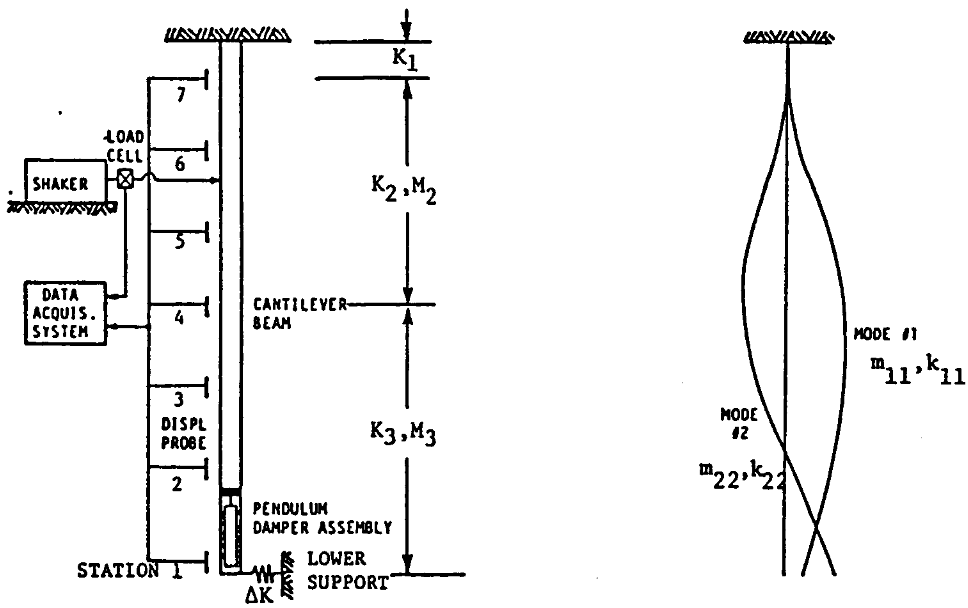
The figure below shows an example of a damper component that was successfully verified using MOVER II. The damper component was modeled as an axi-symmetric, lumped parameter system with two rotational degrees of freedom in- and out-of-plane of the paper. The mass of the weight assembly was accurately measured, and its value was fixed during the verification process. The rotational damping, C_R, and the translational damping, C_L, were then estimated using load cell data acquired from random input shake tests. The results of the verification process showed that the prior model was grossly in error and that MOVER II adjusted the damping parameters to bring the revised model into good agreement with experimental response measurements.

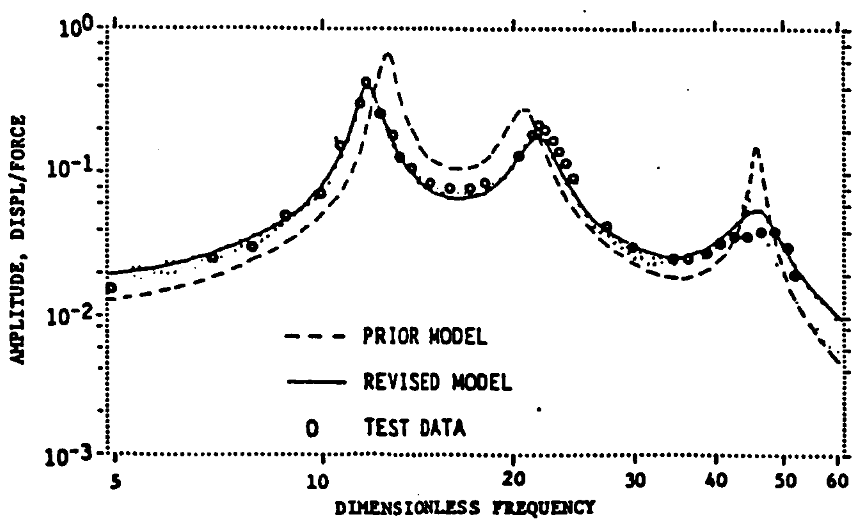




FINITE ELEMENT/MODAL MODELS

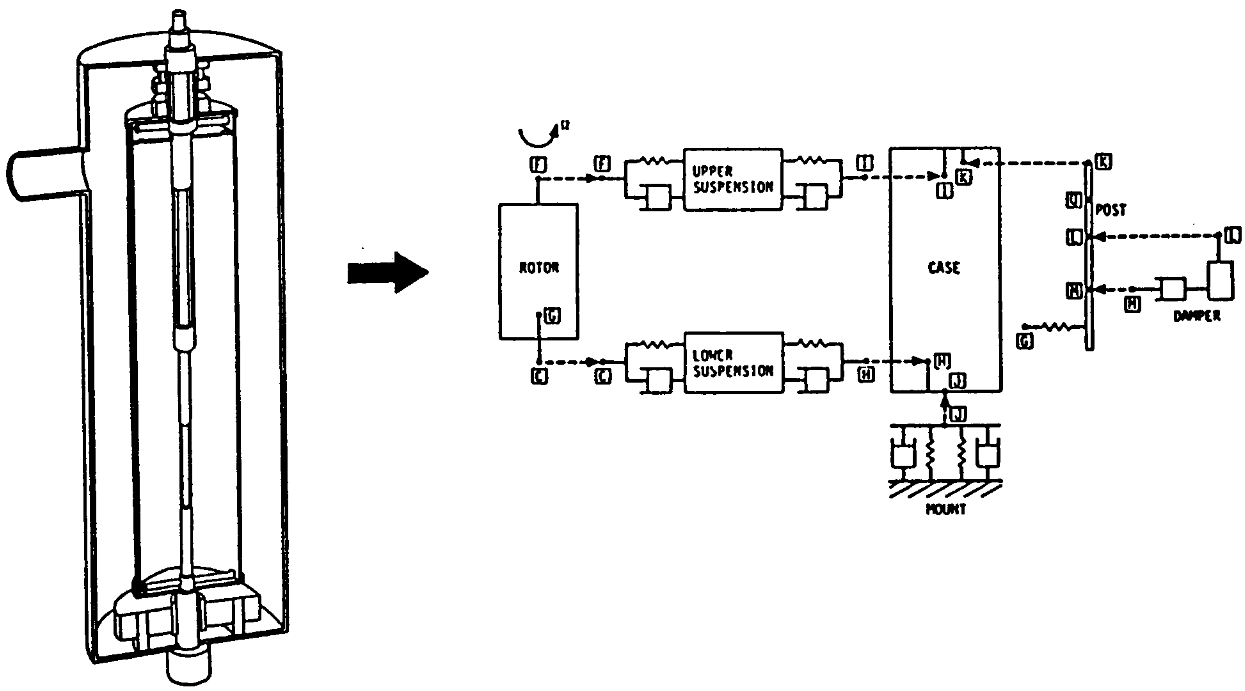
The figure below shows a cantilevered column, fixed at one end, constrained by a spring at the opposite end, with a pendulum damper assembly (previously verified). Transfer function data acquired during single-point random and sine testing were used to verify both a finite element and modal representation of the column assembly. Submatrix scaling parameters were used to update prior estimates of stiffness and mass properties of three distinct sections of the assembly, as well as the generalized mass and stiffness of the first two column bending modes. The results of this verification effort were successful at both the finite element and modal level as demonstrated by the improved correlation between revised model frequency response and experimental test response.





SUBSTRUCTURED MODELS

MOVER II's real strength lies in its ability to synthesize complex dynamic systems from component and subassembly models. As demonstrated in the figure below, a complex model of rotating machinery can be synthesized by combining lumped, modal and finite element models. In terms of model verification, MOVER II can first be used to verify component and subassembly models, thereby reducing verification efforts at the system level. Note that the damper component and column assembly were previously verified, allowing their parameters to be fixed during verification of the system. To construct the system dynamic model, the spinning rotor is attached to a modal representative of the case by lumped parameter models of the upper and lower suspensions. The column assembly is attached to the top of the casing, and a modal model of the case is attached to ground by a lumped model representing the support mount. This synthesis is accomplished through application of displacement constraints. Once constructed, system parameters (including lumped, modal, and/or finite element parameters) may be updated using the submatrix scaling option.



- MOVER II -

DATA REQUIREMENTS

MOVER II requires the mass, damping and stiffness matrices for component and subassembly models. These can be derived from finite element models, lumped models, or from reduced modal models. The user can then synthesize the complete dynamic system by defining physical coordinates and supplying appropriate displacement constraints between components and subassemblies. To perform Bayesian parameter estimation, submatrix scaling parameters to be updated must be defined and initial estimates of their values assigned, along with confidence in those estimates. In addition, the force distribution used during testing must also be reflected in the model.

MOVER II updates parameter estimates based on experimentally obtained Frequency Response Functions (FRF). The user must therefore supply amplitude and phase data at discrete test frequencies for comparison with model estimates. In addition, the user must input the confidence associated with the FRF; these can be estimated from coherence data obtained from time series analysis of the vibration data.

MODEL -

- SUBSTRUCTURE MASS, DAMPING, STIFFNESS MATRICES
- FORCE DISTRIBUTION
- SUBSTRUCTURE CONNECTIVITY
- INITIAL PARAMETER VALUES AND CONFIDENCE ESTIMATES

TEST -

- COMPLEX FREQUENCY RESPONSE FUNCTIONS (AMPL/PHASE)
- CONFIDENCE LEVEL ON FRF (COHERENCE)

- MOVER II -

COMPUTATIONAL TOOLS

MOVER II incorporates several features which facilitate the analysis and model verification of complex structural/mechanical dynamic systems. To accommodate dynamic systems that may contain heavy damping or asymmetric damping matrices, the equations of motion are handled internally in first-order form. A complex eigensolver is then used to extract the complex modes; the problem size can then be reduced by using MOVER II's modal truncation option. During the parameter estimation phase of the analysis, sensitivity calculations (response changes due to parameter perturbations) are performed closed-form using eignevalue/eigenvector derivatives calculated internally. These sensitivity calculations feed into a Bayesian estimator which compares analytical FRF response/parameter confidence with experimental FRF response/confidence to update critical modeling parameter estimates. The Bayesian estimator allows quantitative confidence levels to be assigned to revised parameter estimates and experimental data to be processed sequentially.

- FIRST-ORDER EQUATION FORMULATION
  (ASYMMETRIC M, C, K)
- COMPLEX EIGENSOLVER
- CLOSED-FORM SENSITIVITY CALCULATIONS
- MODAL TRUNCATION
- BAYESIAN ESTIMATOR
- SEQUENTIAL DATA PROCESSING

- MOVER II -

PRINTED OUTPUT

MOVER II allows the user to obtain various types of printed output. To aid during initial problem setup, intermediate calculations are available to the user for assessing (1) Model generation, (2) Modal extraction, (3) Sensitivity calculation, (4) Response calculations, and (5) Bayesian estimation. During normal execution, MOVER II outputs during each estimation cycle updated (1) Eigenvalues/Eigenvectors, (2) Complex frequency response, (3) RMS response variation (model vs. data), (4) Original, prior and revised parameter estimates. When MOVER II has converged on a solution, a revised parameter convariance matrix is printed which allows the user to assess the confidence in the updated parameter values.

INITIAL OUTPUT

- ECHO PRINT OF INPUT DATA

OUTPUT FOR EACH ITERATION

- EIGENVALUES/EIGENVECTORS
- COMPLEX FREQUENCY RESPONSE
- RMS RESPONSE VARIATION (CALC'D VS. MEAS'D)
- ORIGINAL, PRIOR, REVISED PARAMETER ESTIMATES

FINAL OUTPUT

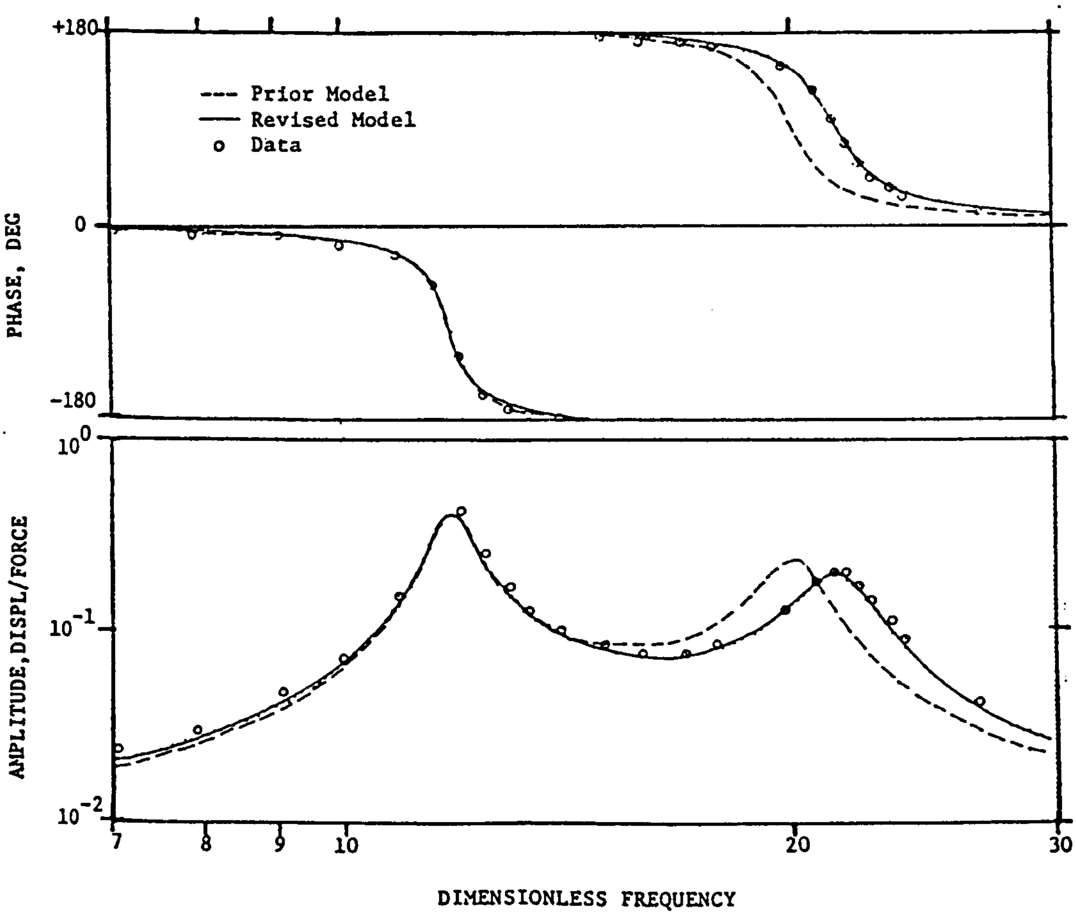
- REVISED PARAMETER COVARIANCE MATRIX

GRAPHICAL OUTPUT

MOVER II includes a graphics package to facilitate the model verification process. The package allows the user to obtain the following x-y plots:

- Amplitude and phase of complex frequency response as functions of frequency; plots of both prior model and revised model frequency response as well as measured frequency response, are overlaid on the same graph.

FREQUENCY RESPONSE COMPARISONS

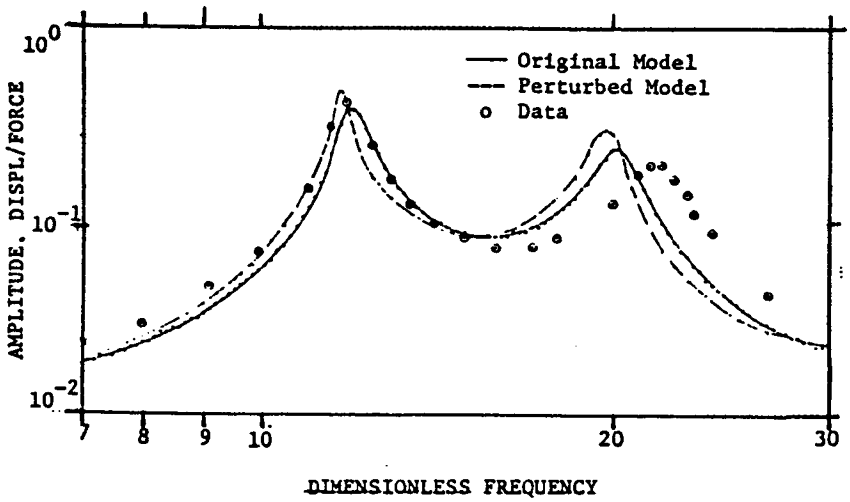


GRAPHICAL OUTPUT (CONTINUED)

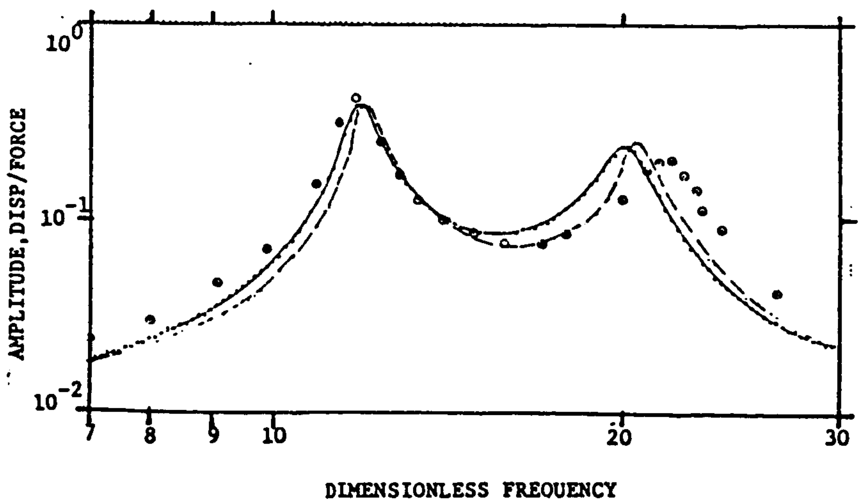
MOVER II also plots -

- Sensitivity of response to selected parameters; plots of perturbed frequency response amplitudes as a function of frequency for individually varied parameters, showing comparisons with nominal frequency response amplitude and measured data.

SENSITIVITY PLOTS
(Ampl w.r.t. Parameters $\dot{M}_3$ and ΔK)



(a) Parameter M_3



(b) Parameter ΔK

GRAPHICAL OUTPUT (CONTINUED)

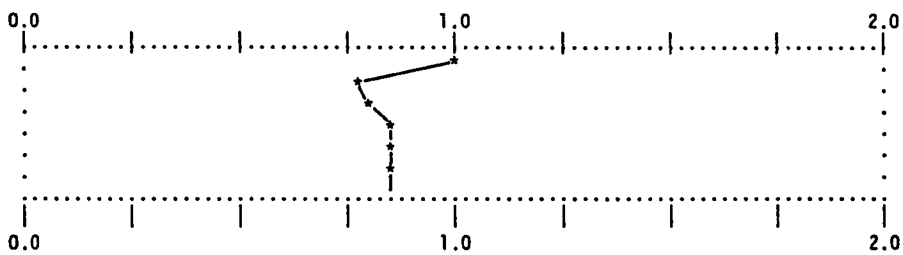
Additional x-y plots provided by MOVER II include:

- History of parameter adjustments as a function of iterative Bayesian estimation cycle showing convergence characteristics of each estimated parameter.
- Statistical significance of individual parameter estimates as a function of their variation from intial parameter estimates.

These graphics greatly facilitate the model verification procedure and are particularly useful during the initial and intermediate phases of ground testing, model verification and structural modification.

*** MODE NO. 2 GENERALIZED MASS (GAMMA2) ***

CYCLE #	PARM VALUE
1	1.00000E+00
2	7.68081E-01
3	7.98866E-01
4	8.57914E-01
5	8.46938E-01
6	8.52537E-01



PARAMETER ESTIMATE STATISTICAL SIGNIFICANCE

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            -4==================-2===================0===================2===================4
PARAMETER 1  IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIX-O-XIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
PARAMETER 2  IIIIIIIIIIIIIIIX--O--XIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
PARAMETER 3  IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIX-O-XIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
PARAMETER 4  IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIX---O---XIIIIIIIIIIIIIIIIIIIIIIIIIIIIII
PARAMETER 5  IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIX-------------O-------------XIIIIIIIIIIIIIIIIIIIIII
            -4==================-2===================0===================2===================4
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CONCLUSIONS

MOVER II has been used extensively and successfully over a period of several years to verify the structural/mechanical models of civil, mechanical and aerospace systems. Experience has shown the importance of using both component and system level test data in a structured verification effort. The techniques utilized in MOVER II should find further application in the space program. The control of large structures in space will require accurate structural models for maneuvering, pointing, and shape maintenance. These models will be verified to the maximum extent possible prior to launch, but will most likely require final adjustment to reflect as-built conditions in a zero-g environment. It is apparent that some form of model verification techniques will play an important role in the successful deployment of these large systems.

1) MOVER II IS AN OUTGROWTH OF A SERIES OF MODEL VERIFICATION COMPUTER PROGRAMS ORIGINALLY FUNDED BY NASA/MSFC BEGINNING IN 1971

2) MOVER II HAS BEEN USED EXTENSIVELY TO VERIFY HIGH-SPEED ROTATING MACHINERY USING A SUBSTRUCTURING APPROACH FOR MODEL VERIFICATION AS WELL AS MODELLING ITSELF

3) A SIMILAR SUBSTRUCTURE MODELING AND MODEL VERIFICATION APPROACH IS ENVISIONED FOR LARGE SPACE STRUCTURES