Development of a Nonlinear Frequency Response Program for Simulating Vehicle Ride Comfort

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ABSTRACT

Dynamic models have been used in the automotive industry as predictive tools in simulating the vibrational characteristics of vehicles. However, existing models are limited in their ability to deal with nonlinear characteristics such as the frequency and amplitude dependency of connectors. A practical frequency response program has been developed that can treat the nonlinear vibrational characteristics of various connectors. This program interfaces with an MSC/NASTRAN FEA model, which is used to assemble the baseline system matrices for the nonlinear solution. The program includes such nonlinear capabilities as frequency/amplitude-dependent elastomeric connectors, velocity-dependent viscous damping elements and Coulomb friction damping. This paper outlines the program and gives an example of its application to an analysis of vehicle ride comfort, the results of which correlated closely with experimental data.

1. INTRODUCTION

One difficulty experienced in conducting dynamic frequency response analyses of structures is the problem of how to treat the nonlinear characteristics of the structure to be analyzed. Nonlinear characteristics are generally present to one degree or another between the inputs and outputs of nearly all structures. To be sure, there are numerous examples of successful analyses premised on linearity, in cases involving either weak nonlinear characteristics or a narrow range of analytical conditions. However, nonlinear analysis must be applied to structures for which the presence of friction cannot be ignored, such as in the case of automotive suspension characteristics. Moreover, when the structure in question involves a large-scale model, such as a finite element model of the entire vehicle body, it is impractical to use a general-purpose nonlinear code that treats characteristics in the time domain. In short, the following problems occur in conducting a vehicle-level analysis that attempts to take into account the nonlinear characteristics of the engine mounts, shock absorbers or other components.

- A practical general-purpose code does not exist for conducting frequency response analyses of a system model that includes nonlinear characteristics such as amplitude or frequency dependency.
- The creation of a system model that includes nonlinear characteristics or the inclusion of such characteristics in an analytical model is cumbersome.
- Performing the calculations for a large-scale model, such as an finite element model of the entire vehicle body, requires an inordinate amount of CPU time.

With an eye toward overcoming these problems, the authors have developed a simple and practical nonlinear frequency response program, which combines an MSC/NASTRAN linear model with a FORTRAN-based convergence calculation program. This frequency response program has been incorporated into a simulation model for analyzing vehicle ride comfort. An overview of the program is presented along with an example of its application.

2. NONLINEAR VEHICLE CHARACTERISTICS

One method of evaluating vehicle ride comfort is to conduct shaker excitation tests. This is mainly done by applying a displacement or force at the tire patch and evaluating the resulting vibration response of the floor panel or some other component. The results of previous studies have shown that frequency response characteristics vary depending on the amplitude of the applied displacement force (Fig. 1).

The dependency of vibration transfer functions on the amplitude of the applied displacement force is determined by the nonlinearity of the components and connectors that make up the vehicle. Typical nonlinear characteristics include the amplitude and frequency dependency of the connectors that join components, such as shock absorbers or hydrostatic engine mounts (Fig. 2).

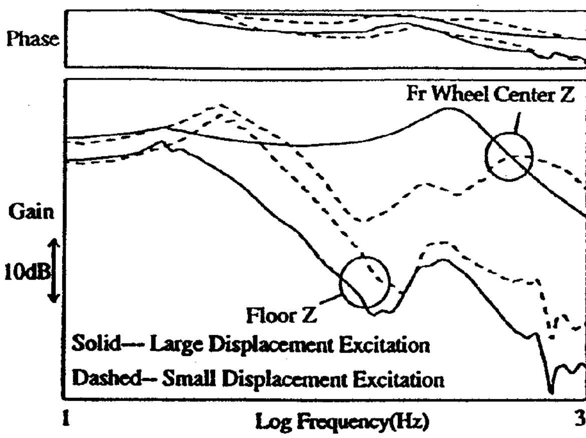

Fig. 1 Transfer Function Amplitude Dependency

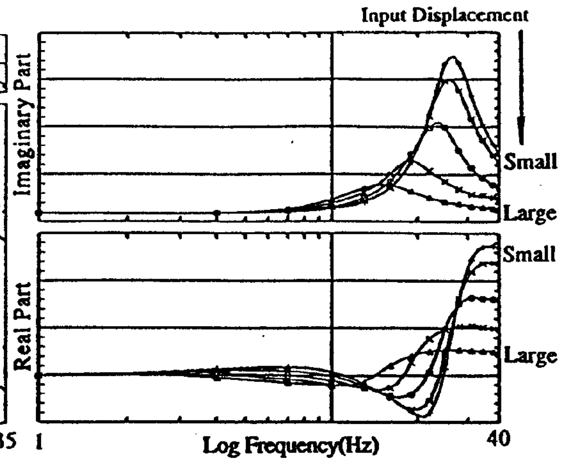

Fig. 2 Frequency & Amplitude Dependency of Hydrostatic Engine Mount

3. OUTLINE OF NONLINEAR CONVERGENCE CALCULATION PROGRAM

3.1 Analytical Capabilities

Capability for analyzing nonlinear connectors

The MSC/NASTRAN program defines linear stiffness- hysteresis damping elements, CELAS1 and CELAS2, and linear viscous damping elements, CDAMP1 and CDAMP2. The program developed by the authors makes it possible to give these elements the quality of nonlinearity as indicated below.

- A stiffness-hysteresis damping element (CELAS) that has both amplitude and frequency dependency
- A viscous damping element (CDAMP) that displays both amplitude and frequency dependency
- A viscous damping element (CDAMP) that has velocity dependency
- A viscous damping element (CDAMP) that displays both frequency and amplitude dependency, based on an equivalent viscous damping approximation of friction

Method of inputting nonlinear characteristics

The frequency response characteristics of dynamic stiffness and viscous damping are input into a universal file for each excitation amplitude. The input data on nonlinear characteristics are subjected to cubic spline interpolation at every frequency using the FORTRAN program. The results are referenced at every convergence calculation step based on the relative displacement of the nonlinear connectors.

Analytical methods

Convergence calculations are performed at every frequency over the entire range of specified frequencies beginning from the low frequency side. The program allows a choice of the either an modal or direct frequency response analysis.

3.2 Analysis Procedure

(1) The first step is to create a suitable MSC/NASTRAN model or select an existing model (Figs 3 and 4, from reference [1]).

(2) A modal frequency response analysis (a modal eigenvalue analysis is also possible) or a direct frequency response analysis is then performed and the required data blocks are written out using DMAP ALTER.

· SOL111 (or SOL103) --- GPLS, BGPDTS, GEOM2S, LAMA, CM, BM, USET

· SOL108 --- GPLS, BGPDTS, GEOM2S, CKDD, CBDD, CMDD, USET

(3) A universal file is created containing the nonlinear characteristics of connectors. This file contains frequency response data for every excitation amplitude. The data are obtained by conducting excitation tests to measure the nonlinear characteristics of insulators and other components.

(4) A universal file containing excitation force data is created. This file contains data on the applied excitation force and forced displacement, velocity and acceleration.

(5) A user input file is created. This involves designating element ID numbers for the nonlinear connectors and specifying the analysis conditions.

(6) FORTRAN convergence calculations are performed.

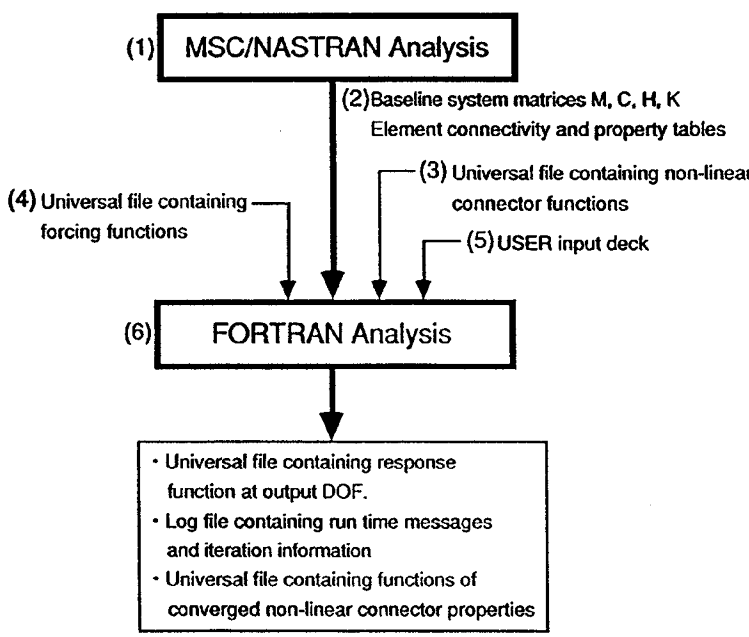

Fig. 3 Analysis Procedure

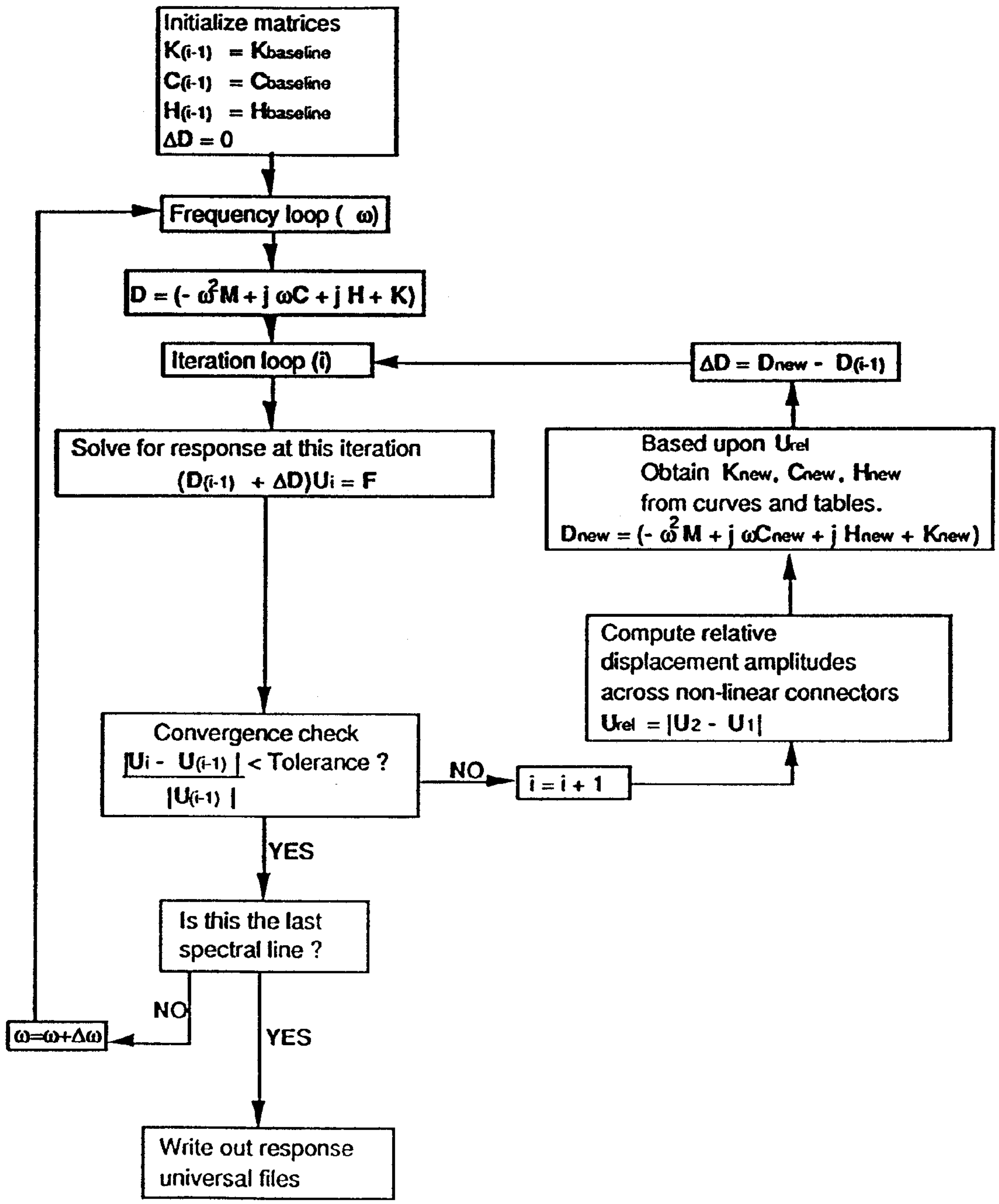

Fig. 4 Nonlinear Solution Scheme

4. APPLICATION EXAMPLE

4.1 Analytical Model

The relatively small-scale finite element models used in the vehicle vibration analysis are indicated in Fig. 5. A vertical displacement input was applied at the front tire patch, and an analysis was made of the vibration transfer functions. After creating the required data blocks with the MSC/NASTRAN program, the nonlinear frequency response was analyzed using the FORTRAN-based convergence calculation program. The vibration transfer functions obtained when large- and small-amplitude excitation was applied were then compared with the corresponding experimental data.

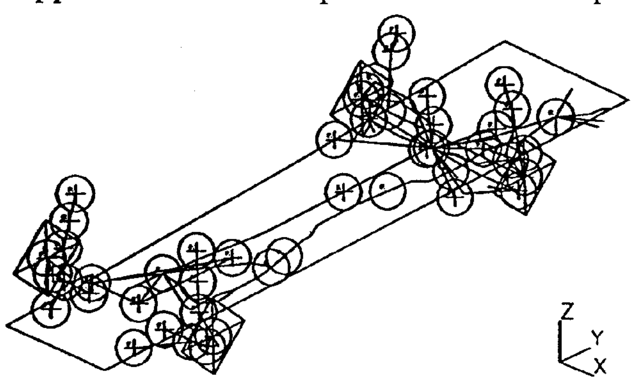

Fig. 5 MSC/NASTRAN Baseline FE Model

4.2 Analysis Results

As shown in Figs. 6 and 7, the analysis results correlated well with the experimental data. The dependency of the transfer functions on the amplitude of the applied excitation was reproduced as a result of taking into account the amplitude and frequency dependency of suspension friction and that of the characteristics of the hydrostatic engine mounts and shock absorbers. The results obtained with this same NASTRAN baseline model thus confirmed the validity of the proposed method in treating the amplitude and frequency dependency of major connectors.

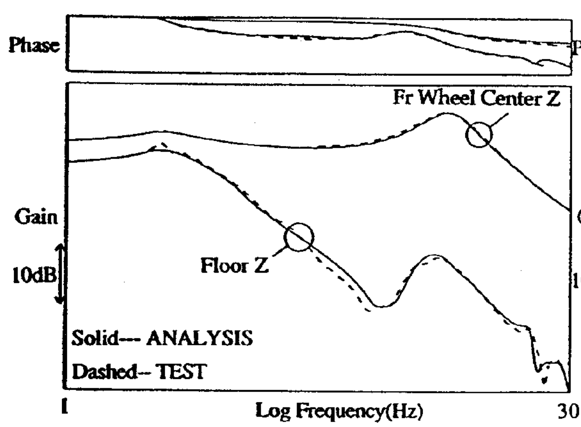

Fig. 6 Large Displacement Excitation at Front Tire Patch

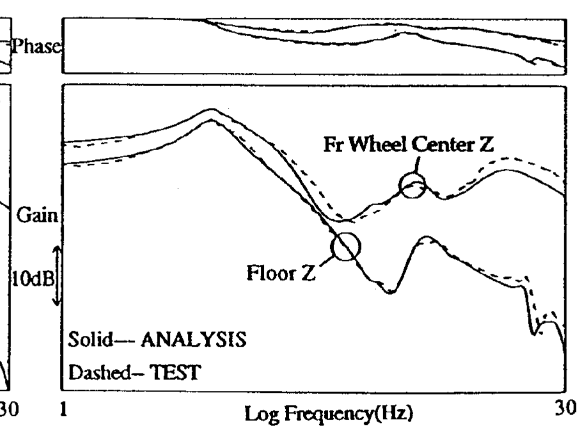

Fig. 7 Small Displacement Excitation at Front Tire Patch

4.3 Validity of Nonlinear Analysis

The validity of the nonlinear analysis procedure presented in the previous section was then confirmed quantitatively. Analyses were conducted in which suspension friction and the front hydrostatic engine mounts, which have a large effect on vibration transfer functions, were modeled as linear characteristics. The results obtained were then compared with the nonlinear analysis results and experimental data. The results of both analyses clearly showed that the application of nonlinear analysis improved analytical accuracy, thereby verifying the validity of the proposed method.

4.3.1 Front suspension friction

Equivalent viscous damping values[2] were calculated from the relative displacement of the front struts at a given frequency. Those values were compared with the vibration transfer functions obtained when large vertical excitation was applied to the front tire patch. As seen in Fig. 8, the nonlinear analysis results correlate more closely with the experimental data than the linear analysis results.

4.3.2 Front hydrostatic engine mount

The dynamic stiffness values measured for the front engine mounts when subjected to excitation of a given amplitude were compared with the vibration transfer functions that were obtained when large vertical excitation was applied to the front tire patch. As seen in Fig. 9, the nonlinear analysis results show closer correlation with the experimental data than the linear analysis results.

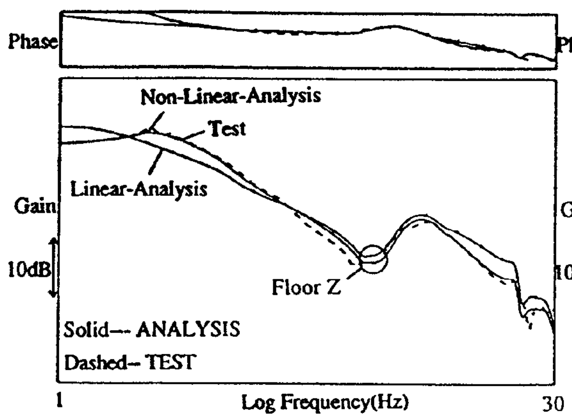

Fig. 8 Linear vs. Nonlinear Analysis of Suspension Friction

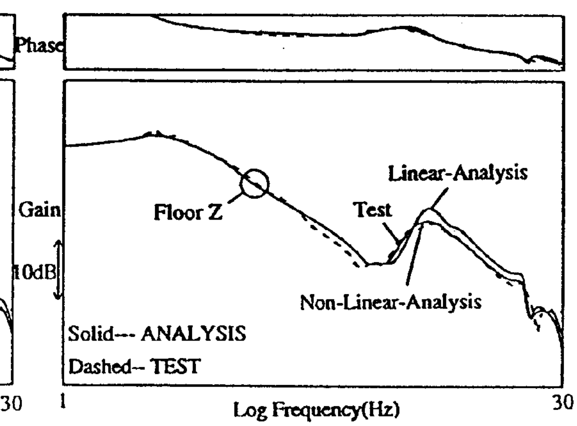

Fig. 9 Linear vs. Nonlinear Analysis of Front Engine Mount

5. APPLICABILITY TO LARGE-SCALE FE MODELS

The applicability of the proposed method to large-scale models, such as a finite element model of the entire vehicle (Fig. 10), was examined. The amount of CPU time that would be required to perform the nonlinear convergence calculations was a critical issue with respect to analysis efficiency and cost. It was decided to use the super element capability of MSC/NASTRAN to achieve a substantial improvement in analysis efficiency. Accordingly, body parts that have many degrees of freedom are analyzed as super elements. The exterior degrees of freedom are reduced, while leaving the nonlinear connectors as residual structures. This has the effect of reducing the degrees of freedom that must be dealt with by the FORTRAN program. As a result, the convergence calculations can be executed within a realistic amount of CPU time.

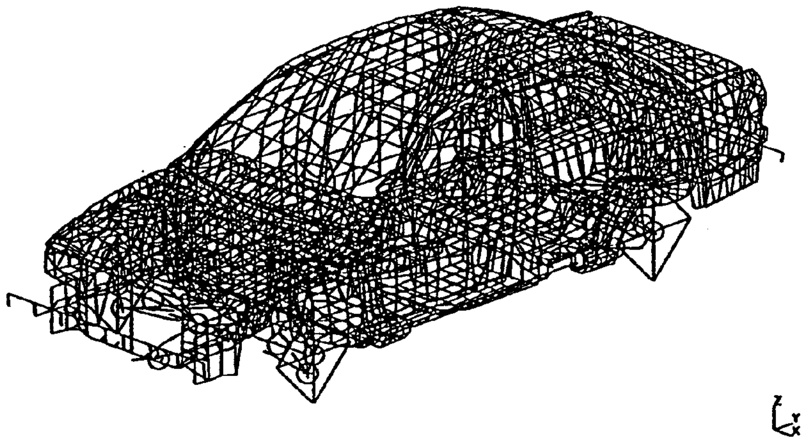

Fig. 10 Full Vehicle Model with Trimmed Body

6. CONCLUSION

A FORTRAN-based convergence calculation program has been developed as a practical method for conducting frequency response analyses of system models that include nonlinear connectors. The term nonlinear connectors here refers to stiffness-hysteresis damping elements and viscous damping elements, all of which display both excitation amplitude dependency and frequency dependency.

One feature of this method is that the matrices created with a MSC/NASTRAN model can be used as the input data of the FORTRAN convergence calculation program. This is accomplished through data blocks, i.e., binary data obtained by OUTPUT2. As a result, it is possible to give amplitude and frequency dependency to any arbitrarily chosen stiffness-hysteresis damping elements and viscous damping elements in existing MSC/NASTRAN models.

This method uses the MSC/NASTRAN super element capability to analyze large-scale models such as a finite element model of an entire vehicle. This allows the nonlinear connectors to be left as residual structures, thereby enabling the convergence calculations to be executed within a realistic amount of CPU time.

Friction can also be transposed to an equivalent viscous damper that displays amplitude and frequency dependency.

When the method was applied to an analysis of vehicle ride comfort, it reproduced with good accuracy the excitation amplitude dependency that is observed in the transfer functions of vehicle vibration. It was also shown that this method is a valid approach to modeling the nonlinearity of connectors, which has a large influence on vibration transfer functions.

REFERENCES

(1) *Program RIDE Users Manual,* SDRC Engineering Services Division, Inc., Milford, OH, March 1993.

(2) Watari, Atsushi, *Machine Vibration,* Maruzen Kabushiki Kaisha, Tokyo, 1966.