Paper No. 1205. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

COMPUTATIONAL SYSTEM FOR ESSAY SIMULATION IN MODAL EXPERIMENTAL DYNAMICS

C. GENATIOS and M. LAFUENTE

Instituto de Materiales y Modelos Estructurales, Universidad Central de Venezuela
P.O. Box 50361 Caracas 1050A Venezuela, Fax: (58-2) 6624441 / 6627206 email: genatio@conicit.ve

ABSTRACT

This article describes the main features of a computational program that simulates the various experimental procedures employed in structural dynamics. These procedures are normally applied in order to determine the dynamic (modal) properties of structures. It also contemplates the analysis of response signals. The importance of this simulator consists on the obtention of the structural response in order to evaluate the influence of the various practical parameters previously chosen by the user of these experimental techniques. These parameters condition modal interference and a correct choice allows the best possible signal for the identification of the system's properties. Testing techniques are: free vibration (time and frequency domains analysis), forced harmonic vibration (under the action of counter rotating masses devices or shaking tables), irregular (random) vibration and ambient vibration. The practical parameters conditioning the response are such as: load application device's location, transducers location, type of transducer, structural typology, base (relative) movement interference, and various signal processing choices. The essays are simulated according to the user's choice, and different response analysis procedures are followed in order to evaluate the dynamic properties. An example is included.

KEYWORDS:

Computer system, experimental dynamics, essay simulation, dynamic properties, structural response, response simulation, response signals, properties identification, structural identification.

INTRODUCTION

Dynamic properties assessment by testing is a current practice in earthquake engineering. Its goal is in general the verification of the structural models and the evaluation of the properties of structures subjected to severe loads. These essays entail an effort in terms of hours of work, equipment handling and signal processing. This fact justifies a preliminary task before carrying out the test in order to foresee the results and to choose the most convenient testing strategy. As a example, an adequate simulation allows the evaluation of the consequences of various choices that have to be taken by the user such as the location of the load applying device in order to minimize the modal interference in the determination of the first and second vibration modes and damping coefficients of a building with translational-torsional coupling. This computational system has been developed as a part of a research program in experimental dynamics which includes structural tests, evaluation of experimental procedures, structural identification from response signals and structural models readjustment.

TESTING PROCEDURES

The essays possibilities are: free vibration (including response interpretation in the time and frequency domains), forced harmonic vibration (produced by shaking tables or counter rotating masses excitation generators), irregular (random) vibration (earthquakes, wind, etc.) and ambient vibration. These techniques were included in the computer program. Various methods have been programmed in order to evaluate the structural properties: identification and selection of the peaks that represent maximal modal responses, identification of modal damping coefficients, and modal shapes reconstruction. Frequency analysis includes windowing and averaging techniques (Bernardini et al. 1990, Genatios, 1991, Kapsarov, 1990).

Structure of the computational system

The computational system simulates the dynamic essays normally applied to structures in order to determine its dynamic properties: natural periods (or frequencies), damping coefficients and modal shapes. Excitation and response signals are generated by the system for each testing procedure. A signal analysis module has been included in order to evaluate the properties of the structure.

Figure 1 presents the global structure of the system, composed by four independent modules sharing the data base that is generated and stored in hard core memory. The program has been developed for IBM compatible computers and can be easily adapted to other systems.

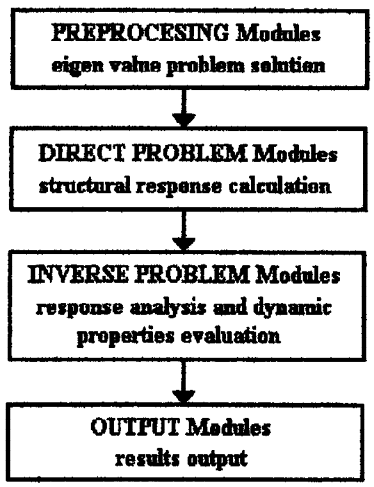


Fig.1 SIMDYN1:System's configuration

Preprocessing module:

Figure 2 shows the first module: the preprocessing module. Its task is the solution of the eigenvalue problem corresponding to the structure to be analyzed. The input data is the geometry of the structure, the properties of the material, the masses and the boundary conditions. The program assembles the global matrices and solves the eigenvalue problem following the space iteration algorithm (Bathe, 1982). The results are the natural frequencies and the modal shapes. These results are immediately stored in hard core memory.

Direct problem module:

The second module is the direct problem module (fig. 3), which calculates the response of the structure subjected to the loads actions previously generated according to the testing technique chosen by the user. As it was mentioned before, testing procedures are: free vibration, forced harmonic vibration (by shaking table or by counter rotating masses load generators), irregular (random) vibration acting on the base of the structure and ambient vibration.

The type of analysis is defined by the user following preprogrammed options. These selections are registered and stored in a data base called *menu*. This data base is immediately stored in hard core. For the structural response generating procedure, this menu is recovered so it controls the analysis. The menu will again be recovered by other modules for the interpretation of the signals in the inverse problem module and in the output module. The task definitions is done by the user following preprogrammed paths that are defined interactively after each decision is taken. This is a complex decision taking structure that has been preprogrammed in order to orientate the simulation procedure definition by the user.

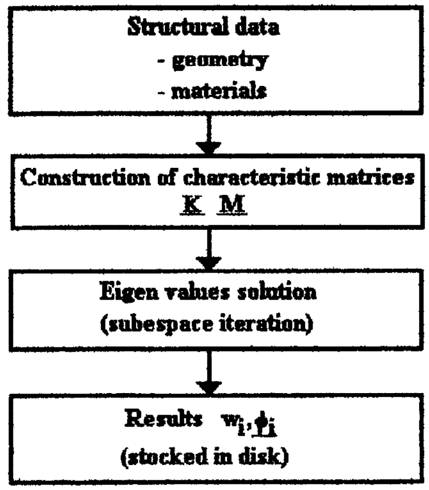


Fig.2 PREPROCESSING Module: Solution of eigenvalues problem

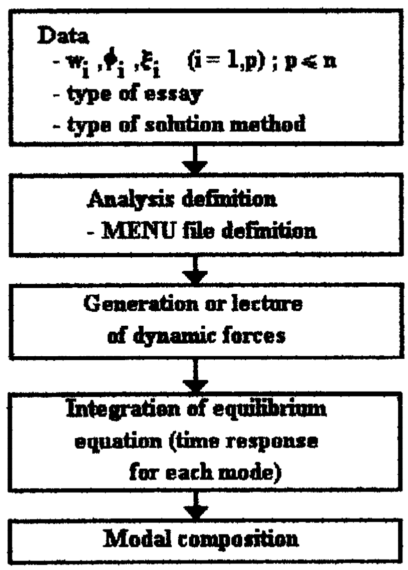


Fig.3 DIRECT PROBLEM Module: Response calculation

The data concerning the structural system is recovered from hard core storage after the preprocessing module solution. Load actions can be recovered from hard core stored files previously defined by the user, containing records such as accelerograms. Loads can also be chosen by the user from various options proposed by the program, depending on the testing procedure. These possibilities are: harmonic loads, random loads, user defined functions by straight lines segments during time and displacement and/or velocity initial conditions.

Six integration schemes have been programmed for the time integration of the equilibrium equation: Differences, Houbolt, Wilson Ø, Newmark, Hilbert-Hughes and Hibbit. (Bathe, 1982, Hilbert et al. 1977). Equilibrium verification is included for each time step. The user can chose the variables controlling each integration procedure, but optimal values are also available in order to guarantee the precision and stability of the integration methods. The response is generated for each mode, allowing separate modal analysis and superposition analysis. The time history response is stored for its subsequent interpretation.

Inverse problem module:

Figure 4. shows the inverse problem module. This unit analyses the response signal in order to determine the dynamic properties of the structure. The data is recovered from hard core; it is composed by the menu, and the partial modal and the total (superposed) response (corresponding to the original degrees of freedom of the structure). The menu controls the response treatment procedures, according to the user choices previously recorded during the direct problem module definition.

The first part of this module performs the discrete Fourier transform of the response signal (in particular the FFT). Various windowing techniques are included (Brighman, 1974): triangular, Hanning, Hamming, Blackmann, rectangular, (user defined limits). User defined windows can be employed, as long as the user specifies them by straight line segments. Windows can be applied several times, according to the users' choice.

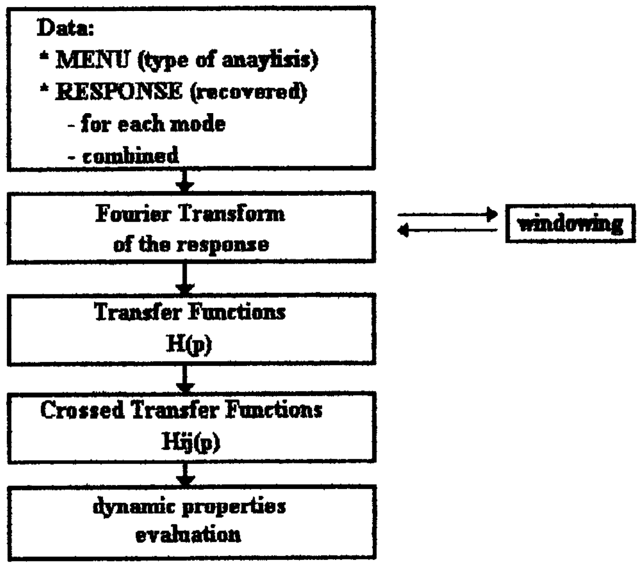


Fig 4. INVERSE PROBLEM Module
Response analysis and evaluation of dynamic properties

The next step is the calculation of the transfer functions H(p), and the correlated (or crossed) transfer functions, according to the reference degrees of freedom chosen by the user.

Whenever the averaging techniques are employed, the analysis must take into consideration various responses and their corresponding Fourier transforms and transfer functions. This procedure sends the program back to the direct problem module in order to generate new loads and to obtain new responses. This step must be repeated for each response to be taken into consideration in the average.

Afterwards, this module evaluates the dynamic properties of the structure in the frequency domain. Response registers are evaluated in order to identify the values of interest, allowing the identification of the resonance frequency values and the determination of the damping coefficients. Various formulas can be employed: bandwidth, modified bandwidth and opposite components bandwidth (Genatios, et. al. 1992).

The results of the various operations are then stored in hard core memory in order to be recovered for output curve plotting by the next module.

Output Module

Figure 5 shows the output module. The data is recovered from hard core memory and the interpretation of this results is guided by the menu file. This interpretation allows the identification of the various response records and the execution of the program according to the users' choices. Curves are plotted with the help of a graphics support library.

NUMERICAL EXAMPLE

The following example illustrates the results of the simulation procedure. Figure 6 shows a four story framed building with masses lumped on the slabs and four lateral degrees of freedom. This building has a main shear behavior.

Modal damping coefficients are fixed to 5%. The solution of the eigenvalue problem leads to the following values of vibration periods:

$T_1 = 0.4$ s. $T_2 = 0.163$ s $T_3 = 0.103$ s $T_4 = 0.0756$ s

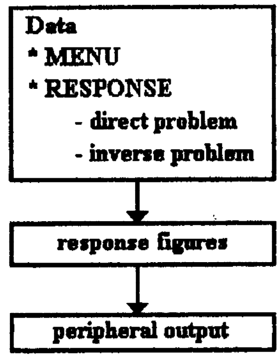


Figure 5. OUTPUT Module: Results presentation

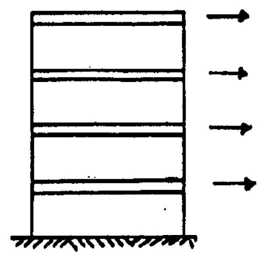


Fig. 6: 4 story framed building

The modal shapes are:

μ_1^t = [0.18257 ; 0.36515 ; 0.54772 ; 0.73030]

μ_2^t = [-0.40452 ; -0.58431 ; -0.31463 ; 0.62925]

μ_3^t = [0.58835 ; 0.26149 ; -0.71909 ; 0.26149]

μ_4^t = [-0.67593 ; 0.67593 ; -0.28968 ; 0.04828]

Free Vibration Test

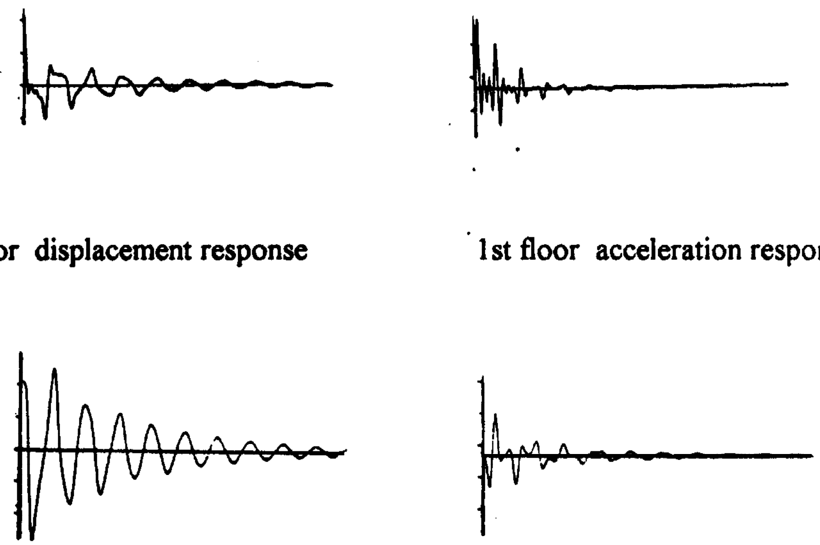
The free vibration essay is carried out with a 5 ton. load applied to the first floor, generating a deformation that constitutes the initial displacement condition.
$\underline{U_0}^t$ = [0.00072 ; 0.00726 ; 0.04369 ; 0.30429] (cm)

Time response (displacements and accelerations) allow the determination of the first vibration period and the damping coefficient of the first vibration mode (by the logarithmic decay formula). Figure 7 shows the time response for the first and forth floors. Higher modes evaluation requires the application of the Fourier transform to the frequency domain. Figure 8 shows the registers corresponding to the application of the FFT to the registers of fig. 7 (displacement and acceleration registers of the first and forth floors). The analysis of this curves allows the evaluation of the modal properties for all modes, in particular, the acceleration register of the first floor, enhances the response of the higher modes. This fact shows one of the advantages of the simulation procedure: for the example that is analyzed, acceleration transducers are preferable to displacement transducers for the evaluation of the higher modes by free vibration tests, modal interference on acceleration registers is lower for higher modes' evaluation than on displacement registers, leading to better identification results. On the other hand, for first mode's identification procedure, displacement transducers are preferable to accelerometers because they reduce higher modes' interference.

Harmonic vibration test

A harmonic vibration test was then simulated for the same building. Figure 9 shows the dynamic amplification curves for the building subjected to a shaking table harmonic vibration test, with a constant displacement amplitude acting on the base of the structure. It shows the response of the first and forth floor. Dynamic properties can be directly evaluated from the relative displacement response for the fundamental mode, instead, for the acceleration curves, it becomes almost impossible due to strong modal interference. First floor's curves enhance higher modes' response more than higher floors. Forth floor's curves enhance fundamental mode evaluation.

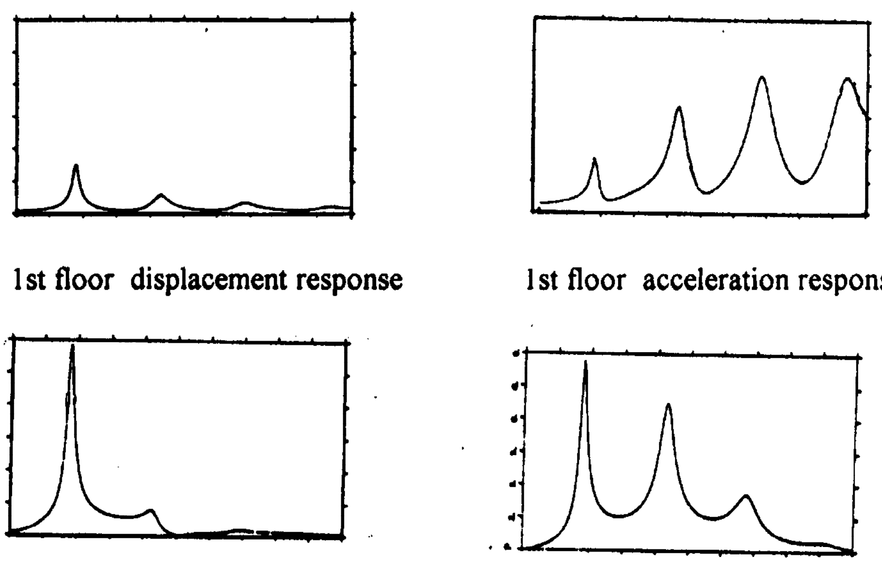
Figure 10 shows the dynamic amplification curves for a counter rotating masses vibration generator located on the first floor. This response curves are shown for the displacement amplitudes curves of the 1st and 4th floors. It can be observed that displacement curves produce better results than accelerations curves. A larger explanation can be found in Genatios 1991, 1994.



1st floor displacement response   1st floor acceleration response

4th floor displacement response   4th floor acceleration response

Fig. 7: free vibration test, time response
load applied to 1st floor



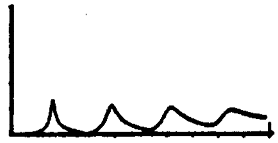
1st floor displacement response   1st floor acceleration response

4th floor displacement response   4th floor acceleration response

fig. 8: free vibration, frequency analysis

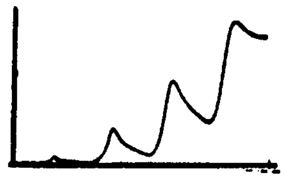
Irregular vibrations acting in the base of the structure:

In order to illustrate this procedure, the structure is subjected to the action of a given accelerogram: Bear Valley, N61E, date 4/9/1972, with a peak acceleration of 420.7 gal (fig. 11). The transfer functions correspond to the acceleration responses of the 1st and 4th floors (also fig. 11). They also illustrate that 4th floor's response enhances fundamental mode's evaluation and 1st floor's registers diminish this characteristic.

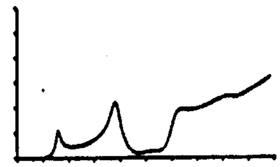


1st floor displacement response

1st floor acceleration response

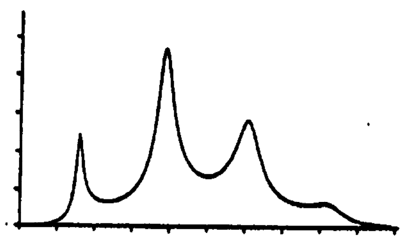


4th floor displacement response

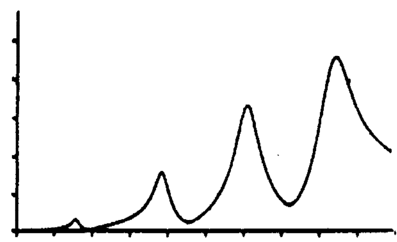


4th floor acceleration response

fig. 9 : dynamic amplification curves
shaking table harmonic forced vibration test

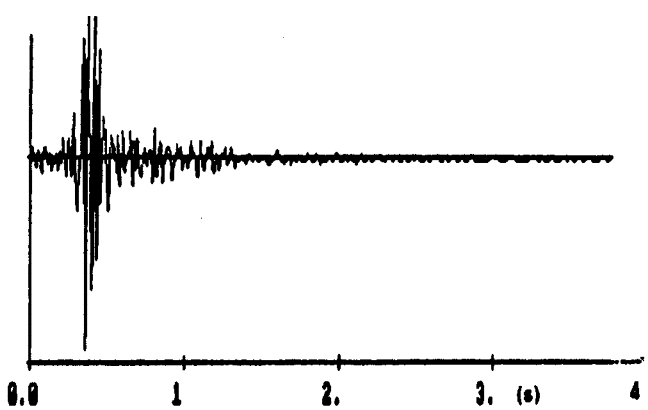


1st floor, amplitude of displacements



4th floor amplitude of displacements

fig. 10 : dynamic amplification curves
counter rotating masses vibration generator
load applied in 1st floor



(a) Ground Acceleration, Bear Valley N61E
Max. Acceleration 470.9 gals

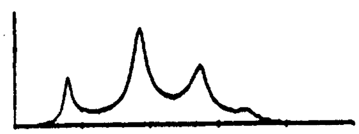
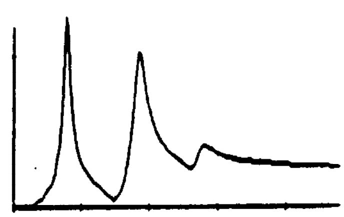


fig 6 (b) 1st floor response

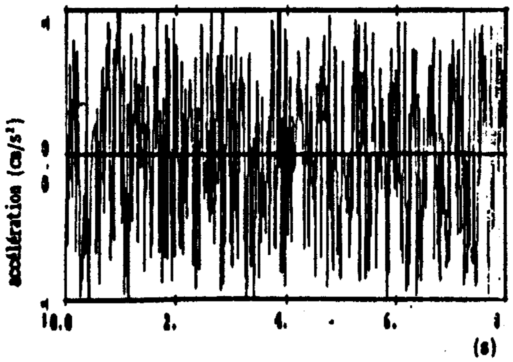


(c) 4th floor response

fig. 11 : irregular vibration test (eathquake)

Ambient Vibration:

Ambient vibration tests normally require the use of averaging techniques in order to compensate the lack of frequency uniformity of the excitation. In this case, ambient vibration has been simulated by a random generator and 40 averages have been employed. Figure 12 shows the average transfer functions; they allow properties evaluation.



(a) pseudoaleatory excitation simulating ambient excitation

(b) 1st floor displacement spectrum

(c) 1st floor acceleration spectrum

fig. 12 : ambient vibration test

CONCLUSIONS

The presented computer program allows the simulation of dynamic testing procedures normally employed in structural dynamic identification. This facility enables to foresee the response to be obtained by the tests, according to the available finite element models. These models, after the tests, will normally by corrected. The advantage of this simulation is the prediction of the consequences of the decisions taken by the user, because these decisions condition the results of the tests and the possibilities of obtaining a successful experimental procedure. These practical parameters conditioning the response are: load application device's location, transducers location, type of transducer, structural typology, base (relative) movement interference, and various signal processing choices. The simulation procedure will permit an optimal experimental procedure. It must be mentioned that the computer program also allows the response signal analysis procedure, so it can also be employed for the analysis of experimental results together with the numerically simulated ones.

The continuation of this effort includes the implementation of integrating algorithms for the nonlinear analysis of structures. Also identification algorithms and model readjustment iterative algorithms are foreseen (Hoff,1989, Mertens, 1989, Rouanet, 1987).

REFERENCES

Bathe,K-J. "*Finite Element Procedures in Engineering Analysis*", Prentice Hall, pp.732, New Jersey 1982.

Bernardini,A., Gori,R., Modena,C. "Structural Identification of a Monument for its Seismic Behavior Forecasting". *Proceedings 9th European Conference on Earthquake Engineering* Moscow sept.1990.

Brighman,O. "*The Fast Fourier Transform*", Prentice Hall, pp.252 1974.

Genatios,C. "*Contribution à l'evaluation des procédés expérimentaux pour la détermination des propriétés dynamiques des structures.*" Th. Dr. INSA Toulouse France, 1991.

Genatios,C., Lafuente,M., Lorrain,M. "On the use of Free Vibration Frequency Techniques for Dynamic Properties Evaluation". *Proceedings 10th WCEE*, Madrid, July 1992.

Genatios,C., Lafuente,M., López,O. *"Assessment of the experimental techniques in the dynamic identification of structures"* 10 European Conference on EarthquakeEngineering, Austria, 1994.

Hilbert,H., Hughes,T., Taylor,R. "Improved Numerical Dissipation for Time Integration Algorithms in Structural Dynamics". *Earthquake Engineering and Structural Dynamics*, Vol.5, pp.283-292, 1977.

Hoff,C. "The use of reduced finite element models in system identification" *Earthquake Engineering and Structural Dynamics*, Vol. 18, pp.875-887, 1989

Kapsarov,H. "Dynamic properties of a 305 m. high reinforced concrete chimney based on ambient, forced and free vibration experiments".*Proceedings 9th European Conference on Earthquake Engineering*, Moscow, sept.1990.

Mertens,M "The complex stiffness method to detect and identify non-linear behavior of SDOF systems" *Journal of Mechanical Systems and Signal Processing*. (3), pp. 37-54, 1989.

Rouanet,C. "*Contribution à l'identification structurale: adequation d'un modèle mathématique à des resultats d'essais*". Thèse Dr. pp.206 Ecole Nationale Supérieure de l'Aéronautique et de l'Espace, Toulouse, France, 1987.