

Educational Computer Program for Simulating Behavior of Structures under Dynamic Loads

Mohammed-Noor N. Al-Maghrabi and Ahmed A. Abdou El- Abbasy

Abstract— Saudi Arabia has constructed many universities in the last decade. Civil, mechanical, and mining engineering departments have courses deal with dynamics and vibrations. Dynamics and vibrations are yet extremely complex subjects and demand costly laboratory resources. Since the faculties of engineering in these universities are new, there are no laboratories for dynamics and vibrations yet. It was obvious that, without laboratory work, the students were not able to understand the nature of dynamic behavior. Therefore, students' results were frustrating in the first semester when these courses were taught. The authors suggested another facility to be replaced instead of the laboratory. The idea was to simulate the performance of elements under dynamic loads, virtually, using computer software. Hence, this software was developed to demonstrate the response of structures subjected to dynamic loads and earthquakes. This software helped students to understand the nature of dynamic loads and their effects on bodies. The final results of students and their grades were improved comparing with their results without this suggested software. Dynamics topics covered by the software and its components are illustrated in the paper. This software has proved its capability to improve teaching of dynamics and earthquake engineering. The software is also a helpful tool for making any parametric studies consuming long times of repetitive calculations.

Index Terms—Dynamics of structures, education, simulation, software

I. INTRODUCTION AND LITERATURE REVIEW

THE destruction caused by the 1906 San Francisco earthquake marked the beginning of a long and rich history of research and innovation in engineering, seismology and geology at Stanford University. Following that catastrophic event, William Rogers developed the first instrument to experimentally investigate soil effects during earthquakes. Through the 1930s research continued, laying the foundation for many current analytical and design approaches, particularly through the work of Bailey Willis following the 1925 Santa Barbara Earthquake, the same earthquake that inspired a young John Blume to enter the field of Earthquake

Engineering. In 1934 Professor Lydik Jacobsen and his student, John Blume, developed the first field instrument for strong shaking of structures and investigated the performance of several buildings. They created one of the earliest multi-dimensional building models and studied its performance on a shaking table. During the 1940s an impact table for simulating earthquake ground motions was used to study the mechanical performance of large shear walls, masonry structures, frames and other structural elements. These experiments were important for understanding building vibrations and the implications of dynamic performance on static design.

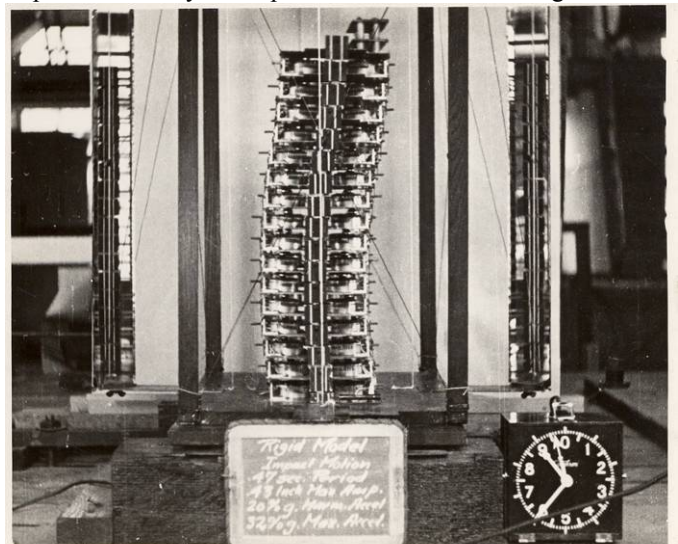


Photo 1. The First Field Instrument for Strong Shaking of Structures, Blume Center [1]

In order to encourage the advancement of earthquake engineering research and education at Stanford, John A. Blume proposed the formation of the Earthquake Engineering Center that bears his name. Since its founding in 1974, the Blume Center has functioned as the umbrella for all earthquake engineering activities at Stanford University. The Blume Center has published more than one hundred technical reports and has organized major conferences, such as the second US National Conference on Earthquake Engineering and the Fourth International Conference on Seismic Zonation. Researchers at the Blume Center have done pioneering work in many aspects of earthquake engineering, including seismic hazard and risk analysis, earthquake occurrence and ground motion modeling, component and system reliability, experimental research on small-scale models of structures and components, evaluation of damage potential of ground

Manuscript received February 1, 2014.

Mohammed-Noor N. Al-Maghrabi is with the Mining Engineering Department, King Abdulaziz University, P.O. 80204 Jeddah 21589, Saudi Arabia, (almaghrabi@yahoo.com), .

Ahmed A. Abdou El-Abbasy, was with the Higher Technological Institute, Egypt. He is now with the Department of Civil Engineering, Jazan University, Jazan, KSA USA (corresponding author to provide phone: +966546557677; e-mail: aaelabbasy@yahoo.com).

motions, and development of seismic design methodologies [1].

A detailed literature review of modeling structures subjected to dynamics loads is presented in [2].

The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) is the product of more than a decade of planning by the earthquake engineering community. The NEES network infrastructure encompasses management headquarters; 14 earthquake engineering and tsunami research facility sites located at universities across the U.S. -- available for testing on-site, in the field, or through telepresence; and cyber infra-structure operations that connect the work of the experimental facilities, researchers, educators and students. The NEES assets jointly provide the means for collaboration and discovery to improve the seismic design and performance of civil and mechanical infrastructure systems. As of September 2010, the National Science Foundation (NSF) Division of Civil, Mechanical and Manufacturing Innovation (CMMI) has supported 160 NEES research awards through annual research program solicitations. The NEES project is named in memory of the late George E. Brown, Jr., former chairman of the House Science committee and a champion of engineering and science in Congress for more than 30 years. Congressman Brown left behind a deep and expansive legacy that has shaped science and science policy in America. In 1977, he authored the legislation creating the interagency National Earthquake Hazards Reduction Program (NEHRP), which in turn, led to the creation of NEES. NEES is authorized by the U.S. Congress under NEHRP and funded by NSF.

Headquarters provides day-to-day leadership and management for NEES network operations and serves as the focal point for all NEES activities including education, outreach and training and management of the equipment site operations (research facilities). The NEES hub research cyber infrastructure, which is powered by HUB zero software developed at Purdue University specifically to help the scientific community share resources and collaborate, unites the experimental facilities. The NEES website provides data curation, a curated central data repository; telepresence; simulation, computational, data visualization and collaborative tools; hybrid simulation and multi-site hybrid simulation capabilities; user support services; middleware; and a cyber-security framework [3].



Photo 2 The NEES hub, Network for Earthquake Engineering Simulation [3]

Headquarters provides day-to-day leadership and management for NEES network operations and serves as the focal point for all NEES activities including education, outreach and training and management of the equipment site operations (research facilities). The NEES hub research cyber

infrastructure, which is powered by HUB zero software developed at Purdue University specifically to help the scientific community share resources and collaborate, unites the experimental facilities. The NEES website provides data curation, a curated central data repository; telepresence; simulation, computational, data visualization and collaborative tools; hybrid simulation and multi-site hybrid simulation capabilities; user support services; middleware; and a cyber-security framework [3].

Nowadays, there is a lot of educational software for structural dynamics. Frame3DD is free open-source software for static and dynamic structural analysis of 2D and 3D frames and trusses with elastic and geometric stiffness. It computes the static deflections, reactions, internal element forces, natural frequencies, mode shapes and modal participation factors of two- and three- dimensional elastic structures using direct stiffness and mass assembly [4].

Noise and Vibration Solutions For Excel is a collection of open source Microsoft Excel spreadsheets for Vibro-Acoustics analysis. These applications provide useful tools for engineers to understand and solve their noise and vibration problems. They can also serve as teaching aids for explaining physical principles in Acoustics and Vibration [5].

Dynamic System Solver – DYSSOLVE (pronounced as “dissolve”) is an open-source software to solve structural dynamics problems. It is written in platform-independent, widely used Matlab programming language. A compiled version is available which does not require Matlab license. DYSSOLVE is designed to fill the need for a lightweight, classroom instruction and learning tool. Various problems which can be solved include Single and multi-degree of freedom spring-mass-damper systems, Dynamic Analysis of Frame Structures, Ritz-beam, Spring-connected pendulum, String vibration, Visualization of beam and plate modes. The software architecture is such that more modules can be easily integrated or developed [6].

Structural Dynamics and Vibration Laboratory, McGill University is concerned with theoretical knowledge as well as the development of new tools and methods capable of bringing solutions to practical problems in the industrial sphere. Related research and education are focused on Vibration, Acoustics, Structural Dynamics, Nonlinear Dynamics, and Wave Propagation [7].

II. LEARNING OBJECTIVES OF THE SOFTWARE

The most learning objectives of the software are electronically, please do the following:

- 1- To help students, in the absence of a structural dynamics laboratory, to understand the nature of dynamic loads, their characteristics, and their effects on structures compared with those of static loads.
- 2- To help the demonstrator to teach the course of structural dynamics and earthquake engineering, easily and with exerting less efforts.
- 3- To clarify the differences between:
 - a) Free vibrations and forced vibrations.
 - b) Undamped and damped vibrations.

- c) Under-damped, critical-damped, and over-damped vibrations.
 - d) Harmonic, impulsive, and general loading.
 - e) Single degree of freedom (SDOF) and multi degree of freedom (MDOF).
 - f) Response spectrum and time history.
- 4- To make parametric studies of dynamic properties of structures.
- 5- To help students to check their solving of exercises and assignments comparing their manual calculations with the software results.

III. SOFTWARE OUTCOMES (ABET STANDARD OUTCOMES)

- A. An ability to apply knowledge of mathematics, science, and engineering fundamentals.
- C. An ability to design a system, component or process to meet desired needs.
- E. An ability to identify, formulate and solve engineering problems.
- I. A recognition of the need for, and an ability to engage in life-long learning.
- J. A knowledge of contemporary issues.
- K. An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

IV. INTEGRATION OF THE SOFTWARE INTO THE COURSES

The developed software is used in teaching the courses which deal with dynamics and vibrations in several stages while demonstrating the course. First, at the beginning of a lecture dealing with a new subject, the software is used to illustrate the nature of this phenomenon, e.g., what is the meaning of free vibration, forced vibration, response spectrum, time history of earthquakes, etc. Second, this software is used to show and explain the differences between some dynamic properties such as under-damped, critical-damped, and over-damped vibrations. The software could also be used to perform a parametric study for a certain dynamic property without making long complicated calculations. Finally, the software is a good tool for the students to check their answers of the exercises and assignments.

V. SOFTWARE DESCRIPTION

This software was written to demonstrate the response of structures subjected to either free or forced vibrations or an earthquake ground motion. Single Degree of Freedom (SDOF) systems and Multi Degree of Freedom (MDOF) systems are included. It was designed and written using Microsoft Visual Basic 6 software because of:

Its interface makes the program friendly used.

- 1- Its powerful drawing capabilities give the results enough clarity.
- 2- Its ability to call other common software such as Microsoft Office, AutoCAD, and much other commercial software (MATLAB was used here).

It is important to mention that all results are demonstrated graphically on the screen and with an output file. Graphical modules include drawing displacement, velocity, and acceleration responses in addition to animation of the system for a specific time.

Undamped, underdamped, critically damped, and overdamped systems are covered by the software. Harmonic loading, impulsive Loading, general arbitrary loading, and forces due to ground acceleration of earthquakes are involved through the software. Drawing true and pseudo response spectrum for a certain earthquake and damping ratio is also included. The software is used for educational purposes such as explaining the differences between: undamped and damped vibrations, different types of damped systems (underdamped, critically damped, or overdamped), free and forced vibrations, SDOF system and MDOF system, true and pseudo response spectrums, adding stiffnesses in parallel and in series, properties of stiff system and soft system. The software could also be used for parametric studies, saving time and effort to perform long and complicated calculations, such as: effect of damping ratio ξ on the difference between true and pseudo response spectrums, effect of damping ratio ξ on the logarithmic decrement δ , effect of the frequency ratio $r = \bar{\omega} / \omega$ on the response of a SDOF system under harmonic loading, especially for $r = 1$ (resonance) and $r \neq 1$. Force frequency and structure frequency are denoted here by $\square$ and ω , respectively.

To verify the software accuracy, many solved examples and problems, especially, those given by Chopra [8], Paz [9], and Sobaih [10] were resolved using the proposed software and the results were identical. Thus the software is accurate enough to be used for educational purposes.

The main advantage of this software is enabling researchers in the field of dynamics of structures to make parametric studies using it saving time and effort to perform long and complicated calculations. One of these parametric studies could be a comparison between true and pseudo response spectrum of velocity or acceleration with different damping ratios.

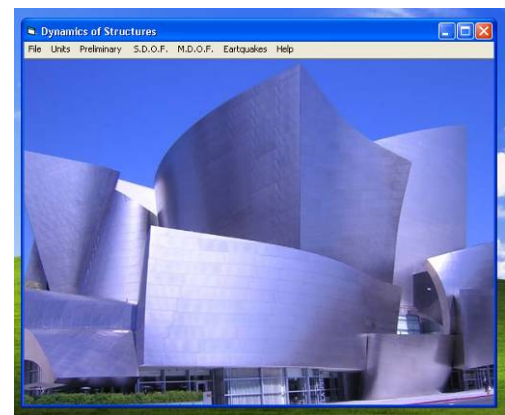


Fig. 1 Main Interface and Main Menu of the Software

The main interface of the software including the main menu appears as shown in Fig. 1. The figure shows that the main menu consisting of seven pull down menus. All components of this main menu are shown in Fig. 2.

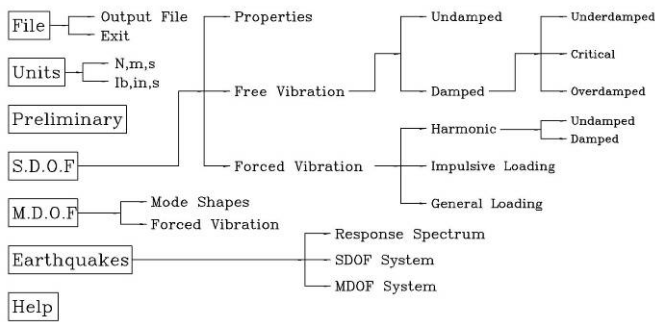


Fig. 2 All Components in the Main Menu of the Software

VI. SOFTWARE COMPONENTS

The software consists of 28 forms and two modules. Appendix (A) demonstrates most important features of the software.

VII. ASSESSMENT THE SOFTWARE IMPORTANCE

Two methods were conducted to evaluate the importance of the proposed software as a tool in teaching the courses dealing with Structural Dynamics and Earthquake. They are:

- 1- Comparing the students' results at the end of the spring and fall 2011 semesters, where this software was not developed yet, with their results of the next semesters till the end of the fall 2013 semesters, where this software was used while teaching the course. Figure 3 shows this difference in results.

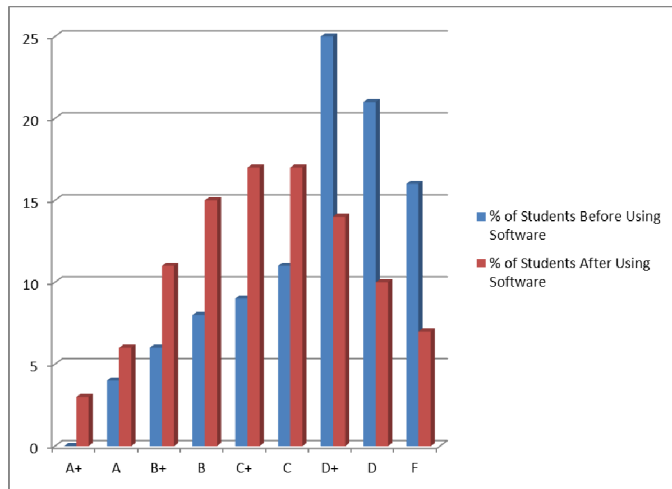


Fig. 3 A Comparison Between Students' Results After and Before Developing the Software

It is obvious, as shown in Fig. 3, that using the proposed software improves the students' results which become more compatible with the normal distribution (bell shape). This means the software is effective in teaching the dynamics of structures.

2- Survey Methodology: In order to gauge student perception of the effectiveness of the software during teaching the courses dealing with Structural Dynamics and Earthquake Engineering, students were surveyed at the end of the semesters. The survey was administered as part of the end-of-semester peer evaluation and all students in the courses were

required to complete the survey. Students responded to each question using a 5-point Likert scale with 5 = strongly agree and 1 = strongly disagree [11]. The survey results are shown in Table 1.

Overall, students appear to have positive perceptions concerning the software. However, it is interesting to note that students said in their comments that the software was so attractive that they use it as a game in their free times.

TABLE I
STUDENT PERCEPTIONS OF THE SOFTWARE EFFECTIVENESS

Survey Question	Likert Average	Range of Responses
The software was very effective to clarify the course	4.64	3-5
Understanding the subjects increases just after start using the software	4.73	3-5
Software is so easy to use and friendly interactive while input data	4.52	3-5
Results drawn by software explains the nature of structural dynamics	4.81	3-5
I advise my colleagues in other universities to use this software as a guide in studying dynamics of structures and earthquake engineering	4.33	2-5
The software helped me while preparing the course assignments and reports and save time and effort of long mathematical calculations	4.80	4-5
Design of program interfaces for input data and output results is suitable for educational purposes.	4.49	3-5

VIII. CONCLUSION

In general, it appears that the courses dealing with structural dynamics and earthquake engineering has effectively improved by using the proposed software. Based on students' perceptions and their results, it appears that the software helped them in understanding the nature of structural dynamics including single and multi-degrees of freedom responses under different types of dynamic loads, earthquakes, or even free vibrations. Based on comments received, it appears that students perceive the benefits of the software. The software is also used to perform parametric studies and check of solutions of exercises and assignments. Students' results improved after using this software in teaching the course than the earlier semesters when this software was not used yet. Further research may be done by more surveying to improve the facilities of the software and to apply it on different types of structures as trusses, grids, and space structures.

APPENDIX (A)

This appendix demonstrates the most important features of the software.

Preliminary Calculations

Moments of Inertia
☒ Rectangular ☐ Circular
 Calculate
 Inertia =

Calculation of Element Stiffness
 Diagrams showing different boundary conditions: Fixed-Fixed, Fixed-Pinned or Pinned-Fixed, Pinned-Pinned.
 E = I = L =
 Determine K K =

System Stiffness
 Start
 Element Stiffness =
 N.B.: First element must be added in parallel
☒ in parallel ☐ in Series
 Add
 Effective Stiffness =

System Mass
 Start
☒ Concentrated weight ☐ Concentrated weight
 Add
 Total mass =

Return to the Main Menu

Fig. A.1 The Form of Preliminary Calculations

Properties of SDOF System

Input Data
☐ Calculated Before ☒ Input Now
 Stiffness (k) =
 Mass (m) =

Output Results
 Natural Period (T) = Seconds
 Natural Frequency (f) = Hertz
 Circular Frequency (ω) = rad./sec.
 Critical Damping (C_{cr}) =

Calculate Properties Send to an Output File Return to Main Menu

Fig. A.2 The Form Properties of SDOF Systems

Undamped Free Vibrations of SDOF System

Initial Conditions
 Initial displacement (y_0) =
 Initial velocity (v_0) =

Response at a certain time
 Time =
 Displacement =
 Velocity =
 Acceleration =
 Inertia Force =

Basic Response Elements
 Amplitude ρ =
 Phase angle α =
 Phase angle θ =

Get Response Parameters Write in the output file Calculate Draw Response Return to Main Menu

Fig. A.3 The Form Undamped Free Vibrations of SDOF Systems

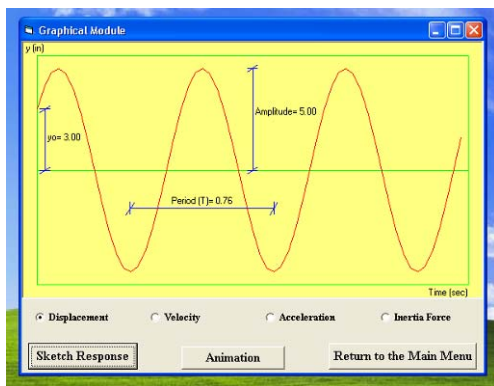


Fig. A.4 Graphical Module for the Undamped Free Vibrations of SDOF Systems

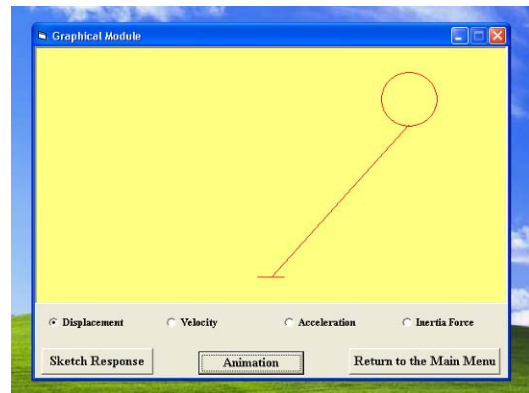


Fig. A.5 The Animation Part of the Graphical Module

Underdamped Free Vibrations of SDOF System

1-Input Data
 Initial displacement (y_0) =
 Initial velocity (v_0) =
 Damping ratio (ζ) =
 Check "Underdamping"
 Damping coefficient (C) =

3-Response at a certain time
 Time =
 Displacement =
 Velocity =
 Acceleration =
 Inertia Force =

2-Basic Response Elements
 Amplitude ρ =
 Phase angle θ =
 Damped circular frequency ω_D =
 Damped Period T_D =
 Logarithmic decrement δ =

4-Amplitude Reduction
 % (X_{i+n} / X_i) =
 No. of Cycles =

Go Write Clear Draw Response Return to Main Menu

Fig. A.6 The Form of the Underdamped Free Vibration of SDOF Systems

Critically Damped Free Vibrations of SDOF System

Initial Conditions
 Initial displacement (y_0) =
 Initial velocity (v_0) =

Response at a certain time
 Time =
 Displacement =
 Velocity =
 Acceleration =
 Inertia Force =

Write in the output file Draw Response Return to Main Menu

Fig. A.7 The Form of the Critically Damped Free Vibration of SDOF Systems

Overdamped Free Vibrations of SDOF System

Input Data
 Initial displacement (y_0) =
 Initial velocity (v_0) =
 Damping coefficient (C) =
 Check "Overdamping"
 Damping ratio (ζ) =

Response at a certain time
 Time =
 Displacement =
 Velocity =
 Acceleration =
 Inertia Force =

Write in the output file Draw Response Return to Main Menu

Fig. A.8 The Form of the Overdamped Free Vibration of SDOF Systems

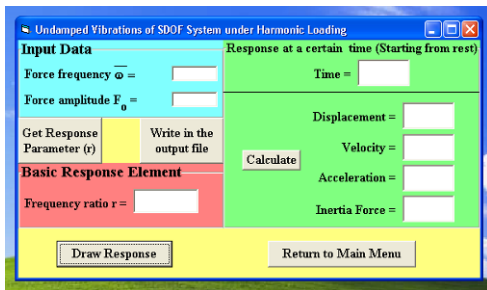


Fig. A.9 The Form of the Undamped Vibration of SDOF Systems Under Harmonic Loading

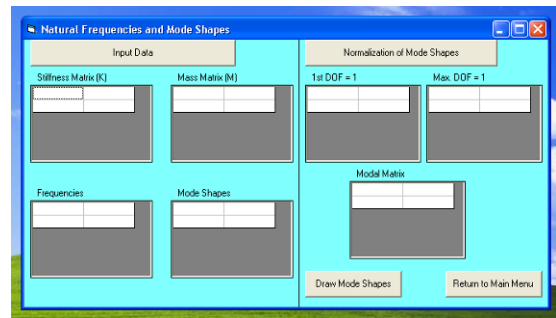


Fig. A.13 The Form of the Natural Frequencies and Mode Shapes

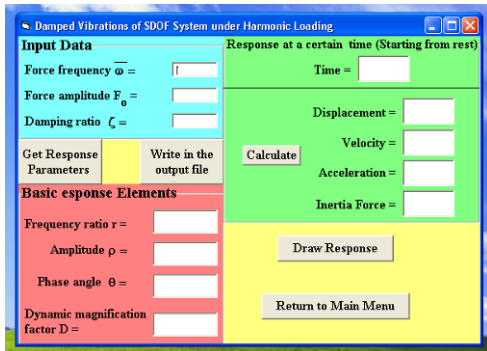


Fig. A.10 The Form of the Damped Vibration of SDOF Systems Under Harmonic Loading

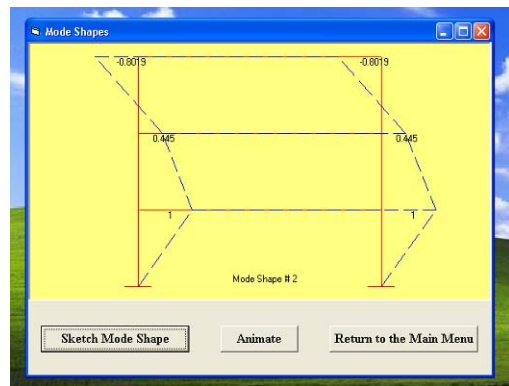


Fig. A.14 The Form of the Mode Shapes Graphical Module

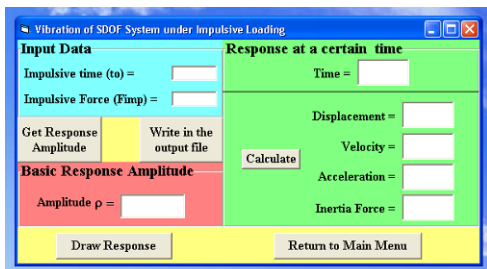


Fig. A.11 The Form of the Vibration of SDOF Systems Under Impulsive Loading

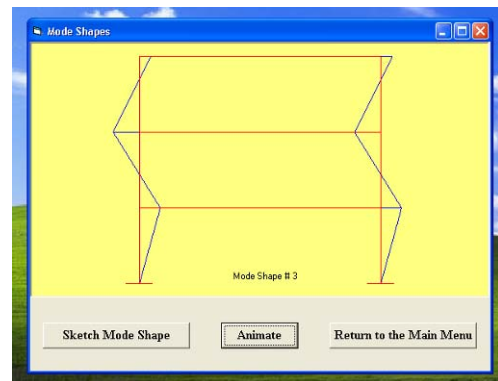


Fig. A.15 Animation of the MDOF System

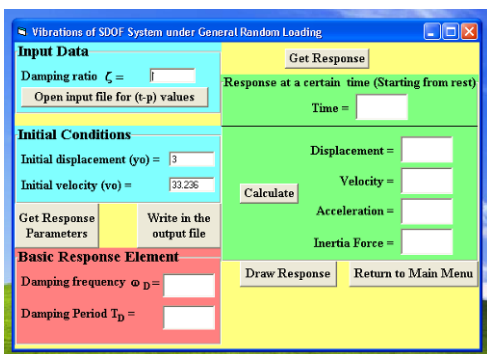


Fig. A.12 The Form of the Vibration of SDOF Systems Under General Random Loading

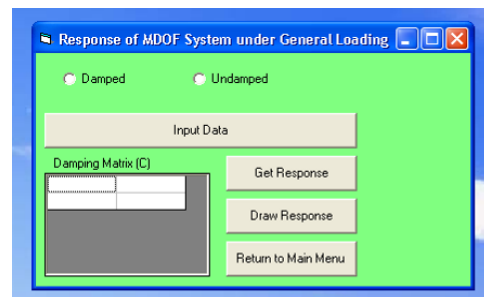


Fig. A.16 Response of MDOF System under General Loading

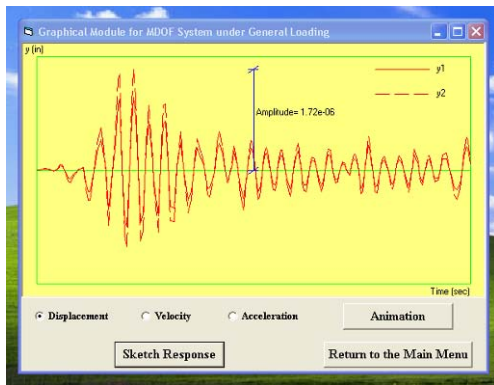


Fig. A.17 Sketch Response of MDOF System under General Loading

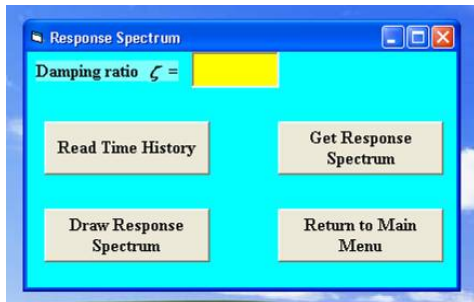


Fig. A.18 The Form of Response Spectrum

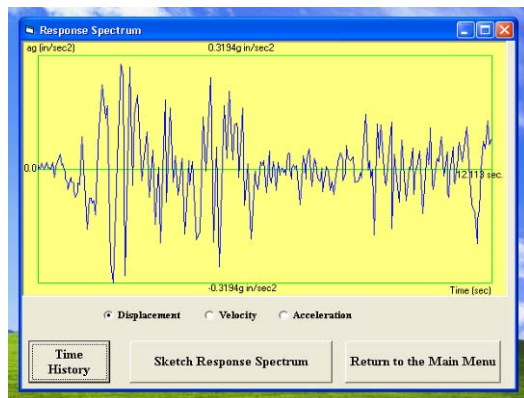


Fig. A.19 Time History of El-Centro Earthquake

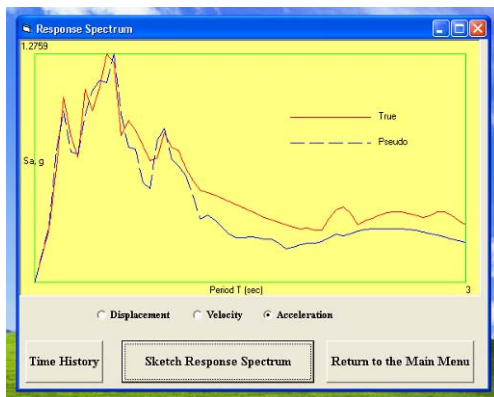


Fig. A.20 True and Pseudo Acceleration Response Spectrum

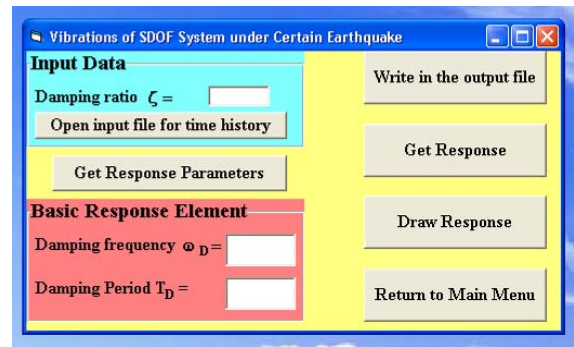


Fig. A.21 The Response of SDOF System Subjected to an Earthquake

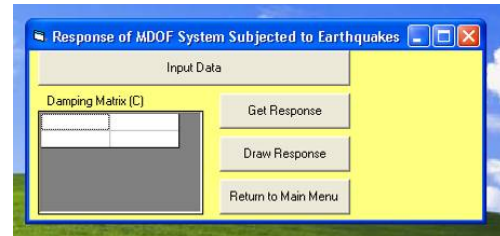


Fig. A.22 The Response of MDOF System Subjected to an Earthquake

REFERENCES

- [1] <https://blume.stanford.edu/>
- [2] P. D. Moncarz, "Theory and Application of Experimental Model Analysis in Earthquake Engineering," Report No. 50, The John A. Blume Earthquake Engineering Center, Department of Civil and Environmental Engineering, Stanford University, Stanford, USA, June 1981, 272 pp.
- [3] <http://nees.org/home>
- [4] <http://frame3dd.sourceforge.net/>
- [5] <http://www.noisestructure.com/index.php>
- [6] <https://sites.google.com/site/dyssolve/>
- [7] <http://structdynviblab.mcgill.ca/index.html>
- [8] A. K. Chopra, "Dynamics of Structures: Theory and Applications to Earthquake Engineering," second edition, Pearson Education, Singapore, 2001, 844 pp.
- [9] M. Paz, "Structural Dynamics: Theory and Computation," second edition, Van Nostrand Reinhold Company, New York, 1985, 561 pp.
- [10] M. E. Sobaih, "Earthquake Engineering: Volume 1 Seismic Analysis," Cairo, 2003, 170 pp.
- [11] Likert Rensis, "A Technique for the Measurement of Attitudes, Archives of Psychology," 140 (1-55), 1932.