EDUSOFT PACKAGE FOR STRUCTURAL ENGINEERING
Web-based Educational Material using JAVA for Structural Dynamics

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Keywords: Structural Dynamics, Web-based Applications, Single Degree-of-freedom Systems, Multiple Degree-of-freedom Systems, Modal Analysis, Time History Analysis, Earthquake Spectra, Multi-story Buildings.

Abstract: In this work, we present the construction of an integrated, web-based software package offering structural dynamics analysis capabilities for use by both undergraduate and graduate students in civil engineering programs who specialize in earthquake engineering. The software package is built on a Java platform and comprises five modulus, focusing on the analysis of single and multiple degree-of freedom systems, modal analysis of 2D and 3D frames, and earthquake spectra construction.

1 INTRODUCTION

Greece is the most earthquake-prone country in the EU, so infrastructure built must conform in terms of structural design to the European code EC8 (CEN, 2004). To this end, Civil Engineering departments in Greece have been offering courses in structural dynamics and earthquake engineering (Chopra, 2007) since the 1980's. Two difficulties are encountered here: (i) students must have a good structural analysis background from past semesters and (ii) any meaningful examples that must be worked out carry a large volume of computation, often necessitating the use of finite element packages that turns out to be cumbersome because the structure has to be modelled a priori.

In this work, we develop versatile, easy to use educational tools for solving problems in structural dynamics. The web turns out to be the preferred way of access by setting up a dedicated electronic address as http://edusoft.civil.auth.gr, "edusoft" being an umbrella address containing a number of application programs. Access to "edusoft" is free, unlimited and applications are open-source under the GPL license, which obviates the need to register users and at the same time precludes unauthorized external use. Under code numbers TE1800 and TE 2400 for the Dynamics of Structures I and II courses, we have the five modules ("jesdof", "espec", "jframe", "jsisma" and "jTframe") described herein. Once accessed, the environment is interactive and good quality graphs as well as real time animation of the response are produced. We note that a Java runtime environment (JRE) has to be activated in the receiving computer for the programs to function (Gosling et al., 2005), and the language of application is Greek.

It should be mentioned here that development of educational packages on various types of electronic platforms is an ongoing activity. As examples, we mention diverse work ranging from that of (Katsanos et al., 2011) on seismic design of reinforced concrete buildings based on the Matlab platform for professional engineers and that of (Sobhaninejad et al., 2011) on integrated earthquake simulation comprising hazard quantification, disaster quantification and post-earthquake recovery for use by government agencies and planners.

Finally, two object-oriented, open source software frameworks that create both parallel and serial finite element computer applications for structural response to dynamic loads such as earthquakes are OpenSees (http://nees.org) and Nemesis (http://www.nemesis-project.org) projects. These platforms are written in C++ and utilize Fortran numerical libraries as well as interpreted/scripting languages (i.e., Tcl, Pyhton, etc.). However, the scale of computation and modeling details are vastly higher compared to our work, and requires from the user competence in dynamic structural analysis.

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EDUSOFT PACKAGE FOR STRUCTURAL ENGINEERING - Web-based Educational Material using JAVA for Structural Dynamics.
DOI: 10.5220/0003901402990303
In *Proceedings of the 4th International Conference on Computer Supported Education* (CSEDU-2012), pages 299-303
ISBN: 978-989-8565-07-5

2 SDOF MODULE "JESDOF"

The most fundamental concept in structural dynamics is the single degree-of-freedom (SDOF) oscillator, whose understanding is crucial for students. This was the rationale behind the development of software module "jesdof". More specifically, four subcategories of data must be defined: (a) elastic properties (stiffness), mass and energy-loss (damping); (b) initial conditions for the displacement and velocity; (c) definition of the external source of excitation (dynamic loading), either as an ASCII file containing discrete values at equally spaced time intervals, or by a mathematical expression; and (d) parameters associated with the time integration algorithm used to numerically solve the governing differential equation of the system.

The governing differential equation for dynamic equilibrium is

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F_0\, f(t) \tag{1}$$

where m, c, k are the mass, damper, and stiffness (in tons, kN-sec/m and kN/m, respectively) of the structural system, while $x(t)$ (in m) is its response to a dynamic load of magnitude F_0 (in kN) and dimensionless time variation $f(t)$. Note that overdots denote derivatives with respect to time t. Furthermore, the natural frequency and fundamental period of the SDOF system are $\omega_0^2 = k/m$, $T = 2/\omega_0$ (in rad/sec and sec, resp.). It is standard practice to define a dimensionless damping ratio $\zeta = c/2m\omega_0$ in lieu of damper values. Finally, the closed form solution of the SDOF is given by Duhamel's integral as

$$x(t) = x_0 \cos(\omega_0 t) + (\dot{x}_0/\omega_0)\sin(\omega_0 t) + x_{ST}\,\omega_0 \int_0^t f(t) \sin\left(\omega_0(t-\tau)\right) d\tau \tag{2}$$

where x_0, $\dot{x}_0$ are initial displacement and velocity of the system, while $x_{ST} = F_0/k$ is its equivalent static displacement. For ground accelerations $\ddot{x}_g(t)$, the forcing function becomes $F(t) = -m\ddot{x}_g(t)$ and the SDOF kinematics are understood to be relative to the ground motion. Solution is accomplished through numerical integration of Eq. 2 using the Newmark beta algorithm, with the time interval of interest subdivided into N increments of size equal to or less than $T/10$. The structural response is given in a simple text area. Finally, the user may visualize the motion of the system in the graph area of the GUI by selecting as abscissa and ordinate variables in combination: time, external force, displacement, velocity and acceleration.

3 RESPONSE SPECTRA "ESPEC"

This application produces elastic response spectra from ground motion recordings, defined as the plot of maximum response (for either kinematic or force variables) versus frequency (or period) of all possible SDOF systems under a specific type of external force (usually a seismically-induced ground motion). More specifically, response spectra are parametric in terms of damping (e.g., $\zeta = 0 - 10\%$) and are computed from Duhamel's integral of Eq. 2 by varying the natural period of an SDOF system so as to sweep an acceptable range that corresponds to real structures, i.e., $0 \le T \le 3.0$ (in sec). Following computation, the results may be presented as absolute pseudo-acceleration, relative pseudo-velocity or relative displacement related as

$$S_A = \omega S_V = \omega^2 S_D \tag{3}$$

The above an exact relation for a damping ratio of zero and approximate otherwise. Module "espec" utilizes the Newmark-beta numerical integration algorithm for integrating the equation of motion in time.

4 3-STORY FRAME "JFRAME"

Application module "jframe" does modal analysis of a simple three story plane frame that translates into a three DOF system, whose properties are user defined as the elastic and inertial characteristics plus the geometrical configuration. Upon entering the input parameters, this program module computes and presents in simple text area the following fundamental data: stiffness matrix, mass matrix, period and frequency associated with each eigenmode, the components for each eigenvector, plus the participation factor, generalized mass and effective mass corresponding to each eigenmode. The underlying computation procedures are based on the finite element method, but this does not require any detailed knowledge from the part of the students. Finally, there is an option to specify an acceleration response spectrum, in which case the program proceeds to calculate the spectral pseudo-acceleration, relative pseudo-velocity and the relative displacement for each eigenmode. More specifically, the governing equation of motion for a multiple DOF system is Eq. 1 again, except that the quantities of interest are now matrices and vectors (of size N, the number of independent DOF) in lieu of scalars. Of course, the number of eigenvalues (natural frequencies) and eigenvectors (corresponding modal shapes) recovered is again N.

5 1-STORY 3D FRAME “JSISMA”

Module “jsisma” focuses on a single story, 3D building that comprises an arbitrary number of vertical stiffness (column) elements, whose position and mechanical properties are specified by the user, plus a heavy floor slab. The column elements may be inextensional or may have zero resistance to torsion. The floor slab is considered to act as a rigid diaphragm in the horizontal plane. There are also two options concerning its out-of-plane rigidity, namely flexible or rigid. The set of output parameters computed by this module are stiffness and mass matrices, the coordinates of elastic centre and the inertial radius, the period, frequency and coordinates of each eigenvector, and the coordinates of modal poles. The difficulty with space frames is the correct definition of their stiffness and masses, once the dominant mode of deformation motion has been defined.

6 PLANAR FRAME “JTFRAME”

Application module “jTframe” examines a three story plane frame with base isolation which translates into a four DOF system, whose properties are user defined: elastic and inertial characteristics plus the geometrical configuration. This module computes and presents in simple text area the following fundamental data: stiffness matrix, mass matrix, period and frequency associated with each eigenmode, the components for each eigenvector, plus the participation factor, generalized mass and effective mass corresponding to each eigenmode. Next, there is an option to specify an acceleration response spectrum, in which case the program proceeds to calculate the spectral response for each eigenmode. Up to this point, module “jTframe” is similar to module “jframe”, except for the fact that the user may define a variable number of stories and incorporate base isolation. Next, the user may define time-dependent loads at each story level, either as analytical functions of time or from an external ASCII file. Also, the transient loading may be given in terms of a base acceleration file. After specifying the discrete time step and the total time of duration, the transient response of the frame is computed and results are presented through use of a GUI application. In here, the animation option has been utilized and the frame motion is shown in real time, in parallel with a conventional plot for time history at a specified point on the structure. These last plots allow the user to define parameters for the two axes chosen from the set of time, displacement, velocity, acceleration, and external load at each story level.

7 NUMERICAL EXAMPLES

In this section some illustrative examples using modules of EDUSOFT follow to show the use of educational packages.

7.1 Computation of SDOF Response

In here, we will use application module “jesdof” to illustrate the use of these web-based educational packages. More specifically, the input parameters requested by this module are (i) stiffness, mass and damping ratio of the SDOF system, (ii) initial conditions, (iii) description of the external force (analytical function of time or from an external ASCII file), and (iv) integration parameters for Duhamel’s integral (default values are recommended). Output is (i) natural period and (ii) graphical representation of the response (displacement, velocity, acceleration) as functions of time. For an SDOF system with properties

$$m = 10 \text{ tons}, \quad k = 200 \text{ kN/m}, \quad \zeta = 5\%$$

under a unit harmonic load of the type

$$f(t) = \sin(1.1\omega_0 t), \quad 0 \leq t \leq 10\text{sec}$$

and zero initial conditions, a sample output screen is given in Figure 1 for the displacement time history. For the same system with initial conditions

$$u_0 = 0.001\text{m}, \quad v_0 = 0.01\text{m/sec}$$

the computed phase space projection on the displacement-velocity plane is plotted in Figure 2. Similar examples can be worked out for various types of loading functions in combination with the initial conditions.

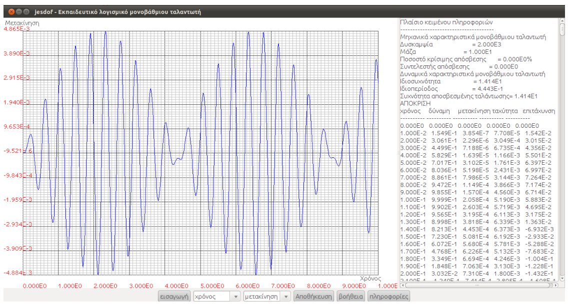

Figure 1: Module “jesdof” screen depicting the SDOF displacement time response $x(t)$ (in m) for an external harmonic loading.

7.2 Transient Response of a Planar Frame

The structure here is understood to be a simple, fixed base, single-bay, three-story frame. What is required

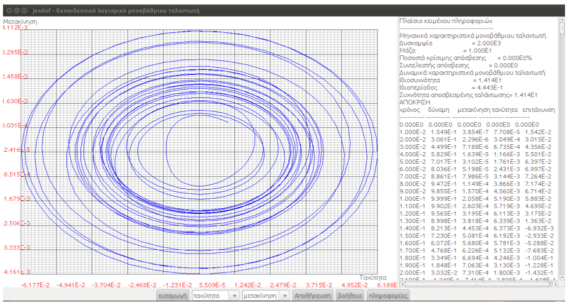

Figure 2: GUI from module "jesdof" depicting an SDOF computed response to initial conditions as a phase space projection in terms of displacement versus velocity.

as input is (i) lateral dimension and story heights (in m), (ii) story masses (in tons), (iii) cross-section lateral stiffness of the columns (in kN/m) and their modulus of elasticity (in kN/m^2) (beams are assumed rigid), and (iv) the input response spectrum (either from use of "espec" or from an external ASCII file). Output comprises (i) graphical representation of the frame's modal shapes and associated natural frequencies, (ii) generalized mass values and participation factors, and (iii) the resulting spectral displacements, velocities and accelerations for each mode of the structure. Figure 3 depicts the input dialog for a three-story frame and in Figure 4 we present the respective input dialog for the forces. Finally, output regarding this example is given in reference to module "jTframe" in Figure 5 .

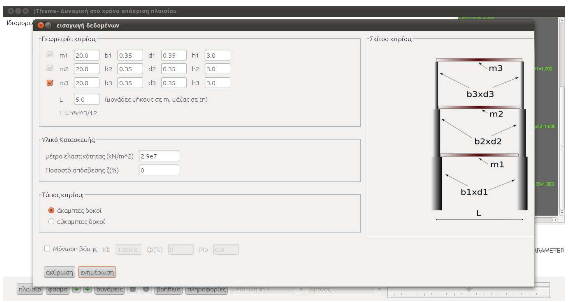

Figure 3: Module "jTframe" input dialog box defining the geometrical and material properties of the three-story frame.

8 CONCLUSIONS

Regarding actual use of the present educational package for structural dynamics analysis, we conclude that the teaching experience accumulated during the first two years of use in actual classroom environment has been most positive. Three modulus ("jesdof", "espec", "jframe") were taught to 4th year undergraduates after the first five weeks of instruction, in groups of 35 students, for a two hour period in a computer laboratory. These sessions were preceded by lectures summarizing basic structural dynamics concepts and the relevant material was accessible through the electronic address http//:blackboard.lib.auth.gr. They were then followed up by two more lectures on the semester project, for which the students could utilize the tools available to help complete it. Course evaluation results indicated a favourable reception of this type of classroom activity by the students involved.

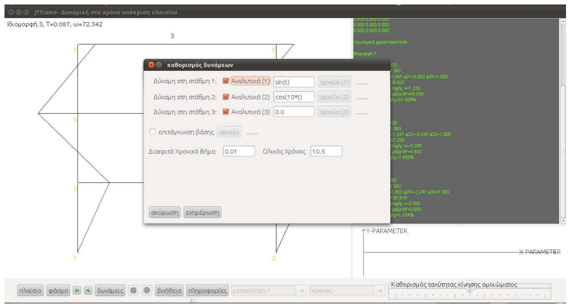

Figure 4: Module "jTframe" input dialog box defining the external time-dependent loads, the total time interval of interest plus the time step, followed by output of modal information.

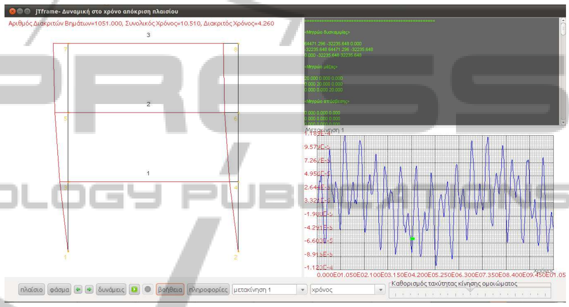

Figure 5: Module "jTframe" screen depicting a time history animation of the three-story frame motion plus its displacement response as defined by the user; the green box marks current state information.

ACKNOWLEDGEMENTS

The EPEAEK II project entitled *"Upgrading Civil Engineering Studies at AUTH"*, 2007-2009, is acknowledged.

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APPENDIX

In terms of programming, a minimum prerequisite for a modern educational-type development is use of the graphical user interface (GUI). Another aspect to be considered is the “open source” policy for software. The philosophy behind this type of policy arises naturally in an academic environment, where free sharing of information is crucial for the development and dissemination of technology in the context of both research and education. Furthermore, we opt to use here the Java Web Start technology instead of the Java Applet technology that is common in the majority of applications.

Finally, we mention here the extensibility of such applications, in order to be modified in several languages, using the internationalization feature of Java. It is also relatively straightforward to include more advanced topics, as for example non-linear response in the case of “jframe” or “jTframe”, that would be of considerable interest in postgraduate study courses in advanced structural dynamics.