

An Elective Course on Computational Techniques in Structural Mechanics with a Balance in Theory and Application

John R. Baker
Department of Mechanical Engineering
University of Kentucky

With ever increasing readily available computer power, and more sophisticated commercial structural analysis software, it seems that mechanical engineering graduates who plan to do design work will be much better prepared for the workplace if they have a good background in both theory and application of modern computer-based structural analysis techniques. Various universities offer courses which focus on numerical techniques, which may be applied to structural system analysis. Also, many programs offer courses on finite element analysis, which may include application. Many such courses, at the undergraduate level, may not include much background on dynamic system analysis, or on nonlinearities. This paper overviews a new elective course at the University of Kentucky, “Computational Techniques in Mechanical System Analysis”, for both graduate students and upper-level undergraduates, which seeks a balance between theory and application, and focuses on providing the students with a basic understanding of computational methods in static and dynamic structural system analysis, including nonlinear systems. This course includes significant use of commercial software, such as the ANSYS finite element package and MATLAB. Student work includes some programming, primarily using the MATLAB m-file functionality, for analyzing some relatively small systems. For example, students write programs for employing the Newton-Raphson method in large-deflection nonlinear static analysis, and the central difference method in linear dynamic structural analysis. While the students develop familiarity with the numerical methods through writing short programs and applying them to relatively simple systems, they also gain an appreciation for how these techniques can be applied to analyze more complex “real-world” systems through assignments involving the commercial finite element code, ANSYS.

The course was offered via distance learning for the first time in Spring, 2004. It will be offered a second time in Spring, 2005. This paper discusses course goals, course assignments, lessons learned from the first course offering, and planned modifications for the second course offering.

I. Introduction

The University of Kentucky has an Extended Campus Engineering Program in Paducah, KY¹, offering BS degrees in mechanical and chemical engineering. The course described in this paper originates from the Paducah campus, but is also offered to undergraduate and graduate students on the main campus in Lexington via Interactive Television (ITV).

*“Proceedings of the 2005 American Society for Engineering Education Annual Conference & Exposition
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This is a newly developed course which was offered for the first time in Spring, 2004. The second course offering is scheduled for Spring, 2005. The course was felt to be a useful elective for the students because instruction related to computational techniques and computer-based system analysis is becoming more and more important for engineering students^(2,3), as computing power becomes more readily available, and software tools continue to improve.

Undergraduates take the course as a technical elective. The course can also be taken for graduate credit. It is cross-listed as ME-599/699. Undergraduates take it as ME-599. Graduate students may take it as either ME-599 or ME-699. The difference in requirements is that students taking it as ME-699 must select a research oriented course project which requires a seminar offered to the rest of the class. ME-599 students are assigned a less intensive project, and do not provide a seminar. In the first course offering in Spring, 2004, there were seven undergraduate students enrolled in Paducah, three undergraduates in Lexington, and six graduate students in Lexington.

II. Course Description and Goals

This course includes both theory and application for various computer-based methods for analyzing mechanical systems. The primary software tools used are ANSYS and MATLAB. It is not necessary that a student have previous background in FEA, or in using the ANSYS FEA software. However, it is important that a student have a background in dynamics, and in mathematical modeling of relatively simple structures, such as spring-mass-damper systems. The background should include an understanding of the formulation of coupled differential equations to describe the motion of a mechanical system. For assignments that require a finite element model, the students are provided either with the model or a macro to easily create the model, or with detailed instructions for creating the model and performing the required simulation in ANSYS or MATLAB.

The teaching approach varies with the topic, but the typical approach for studying most topics is to first consider a relatively simple case that does not require a complicated system model, for which the basic mathematics, such as a numerical integration procedure, can be carried out either by hand, or through use of a MATLAB macro (MATLAB “m-file”). The mathematical methods used are discussed in the lecture material. Once the basic mathematical background is understood, the concepts are extended to more realistic system models, with simulation results calculated by ANSYS and/or MATLAB.

While this course is not a computer-programming course, students are required to do some programming in the form of MATLAB m-files and ANSYS macros. Although previous ANSYS and MATLAB experience are not required, some understanding of basic programming concepts is necessary, such as would be gained through a typical introductory course in some standard programming language.

The primary goals of the course are to provide students with an understanding of the types of mechanical system analyses that can be carried out with modern software tools and with an understanding of the basic mathematical approaches used in the analyses. Also, students become familiar with methods for performing analyses efficiently, such as through automating the analysis process by writing macros, which is useful, for instance, in a design optimization study.

III. Course Delivery Issues

The offering via ITV presents some challenges in instruction for a course which requires significant hands-on use of a computer. The students in Lexington were encouraged to contact the instructor as often as needed via email or phone. Also, the instructor was available for weekly ITV contact with the students in Lexington outside of class hours. However, they primarily posed questions via email, and met in-person with the instructor during his visits to the main campus in Lexington. Overall, the feedback from the Lexington students did not indicate significant problems with the course being offered via distance learning technology.

The actual lecture material was primarily presented in PowerPoint slides. There was no required textbook for the course. The lecture slides were either made available before class, or handed out at the start of class, so that the students did not need to take all notes during lectures.

IV. Course Topics

In the first offering of the course, the primary course topics were presented in the following order:

1. Review of lumped mass system equations formulated in standard 2nd order matrix form: $[M]\{\ddot{d}\} + [C]\{\dot{d}\} + [K]\{d\} = \{f\}$
2. Brief overview of simple finite element formulations (link elements, beam elements).
3. Software Overviews – ANSYS; MATLAB.
4. Linear static solutions for multi-dof systems.
5. Nonlinear static solutions using the Newton-Raphson method, including large deflections and material nonlinearities.
6. Stress Stiffening.
7. Contact.
8. Numerical integration techniques for linear dynamic structures: Central Difference Method, Runge-Kutta Method, Newmark's Method.
9. Modal analysis.
10. Harmonic response analysis.
11. Brief surveys of selected topics: Rotating equipment and Campbell Diagrams; nonlinear dynamics of cable-stayed bridge cables and inverted flexible beams; impact analysis using ANSYS/LS-Dyna explicit dynamics solver; Coupled-field finite elements and vibration control using piezoelectric material.

While the above list highlights the primary topics covered, additional discussions related to various other issues, such as damping assumptions and constraint equations, were included where appropriate.

V. Student Work

The student work was broken into the following categories, with the weighting on their grade shown:

Homework	20%
Application Projects	35%
Final Project	20%
Midterm Exam	10%
Final Exam	15%

Example homework assignments are provided in Figures 1 and 2. In the assignment of Figure 1, the students are required to write a MATLAB m-file to use the Newton-Raphson method for a nonlinear solution on a very simple system. In the example homework of Figure 2, the students wrote MATLAB m-files to do central difference numerical integration and Runge-Kutta integration on a simple 1-DOF system.

An example application project is provided in Figure 3 in which the students used ANSYS to model systems with nonlinearities. In Figure 4, another example application project is provided in which the students were required to write an m-file to do central difference numerical integration on a two DOF dynamic linear system.

For a final project, the ME-699 graduate students proposed a topic related to some system analysis pertinent to the class, and for most of them, the topic was related to their thesis research. They made a presentation to the class on their topic. The undergraduates were assigned a torsional vibration analysis of a geared drive train for a final project. They were required to attempt design modification to eliminate interferences between natural frequencies and excitations in the operating speed range.

VI. Student Feedback

Student feedback on the standard university course evaluations from the first offering of the course was overall positive. A summary question on the course evaluation form asks the students to rate the overall value of the course, with the following rating options: Poor, Fair, Good, or Excellent. Of fourteen students who answered this question, ten rated it “Excellent”, while four rated it “Good”.

The students were also given a supplemental survey, and one segment asked them to provide a numerical ranking for each of three statements to gauge how well the students felt the course met some desired learning outcomes. For each of these three statements, the students were asked to provide a numerical ranking as follows: 0-Not Applicable; 1-

Unacceptable; 2-Poor; 3-Acceptable; 4-Good; 5-Outstanding. Fifteen students completed this portion of the supplemental survey. The statements are below, followed by the average numerical ranking:

1. This course provided me with an understanding of the types of mechanical system analyses that can be carried out with modern software tools. *Average Ranking=4.4*
2. This course provided me with an understanding of the basic mathematical approaches used in the analyses. *Average Ranking=4.1*
3. This course helped me become familiar with methods for performing analyses efficiently, such as through automating the analysis process by writing batch input files. *Average Ranking=4.4*

VII. Planned Modifications for Next Offering

It is felt that the course would flow better if all of the dynamic linear system analysis is moved to earlier in the semester, ahead of any discussion of nonlinear analysis. It was originally felt that all discussion of static analysis, including nonlinear static systems, should precede discussions of dynamics. However, it seems that a better approach may be to cover all linear system topics before moving to nonlinearities and covering the Newton-Raphson approach. The students seemed to find the large deflection and material nonlinearity analysis procedures to be somewhat confusing, so it seems that it might be better not to start with that information so early in the semester.

Also, it is planned to provide the students with the lecture material further in advance so they can review it, so lectures should be able to proceed somewhat faster. Since this was the first course offering, often the PowerPoint slides were not available to the students in advance, but in the next course offering, they will be. There may be some short review assignments due at the start of some classes to encourage students to read provided material ahead of lectures. There was not as much time at the end of the semester as would have been desired to survey the topics in Item 11 of Section III, and so some of the lecture material will be shortened to allow for more survey of advanced applications. In particular, somewhat less time in class may be spent on detailed numerical examples, as the students will be asked to review the details in advance of class lectures.

VIII. Summary and Conclusions

A course has been overviewed which was offered for the first time in Spring, 2004. It was designed to provide students with a solid background in the mathematics behind various types of computer-based system analysis, and a good grasp of analysis capabilities available with modern engineering software tools. The course included a balance of theory and application.

It seems that in the first semester of the course offering, the goals for student learning were achieved, for the most part. This assessment is based on overall good student performance in class assignments, and the fact that student feedback on course evaluations was overall favorable.

IX. References

¹Capece, V.R., Murphy, W., Lineberry, G.T., and Lykins, B., “Development of an Extended Campus Mechanical Engineering Program”, Proceedings of the *2000 ASEE Annual Conference & Exposition*, American Society for Engineering Education, (2000).

²Leslie, I., and Garcia, G., “High Level Programming Packages in Undergraduate Mechanical Engineering”, Proceedings of the *2004 ASEE Annual Conference & Exposition*, American Society for Engineering Education, (2004).

³Smith, P., Pederson, R., and Vennes, J., “Computational Education within Mechanical Engineering Programs”, Proceedings of the *2004 ASEE Annual Conference & Exposition*, American Society for Engineering Education, (2004).

JOHN R. BAKER

John R. Baker is an Assistant Professor of Mechanical Engineering at the University of Kentucky Extended Campus Program in Paducah, KY. He received his B.S., M.S., and Ph.D. in Mechanical Engineering from the University of Kentucky in Lexington, KY. After obtaining his B.S., he spent three years working in the Plastics Division of Eastman Chemical Products, Inc. He entered his current position in July 2000.

ME-599 - Homework #3 - Due Thursday, February 5, 2004

Consider the system below. The system equation is $(K)x=F$. Assume $K=20-5x^2$ and $F=10$, in some consistent system of units. Write a MATLAB m-file to perform 5 iterations of the Newton-Raphson method. The output of your m-file should be a vector with entries that are the displacements, x_i , calculated at the end of each iteration, i . Assume the initial displacement is $x_0=0$. You do not need to check for force convergence. If you are unsure how to write an m-file, please review the handout provided in class: "MATLAB M-FILES AND PLOTTING FUNCTIONS". You will need a loop in your file (the loop will start with: "for i=1:5").

By 5:00 pm on 2/5/04, you should email the file, as an attachment, to: jbaker@engr.uky.edu

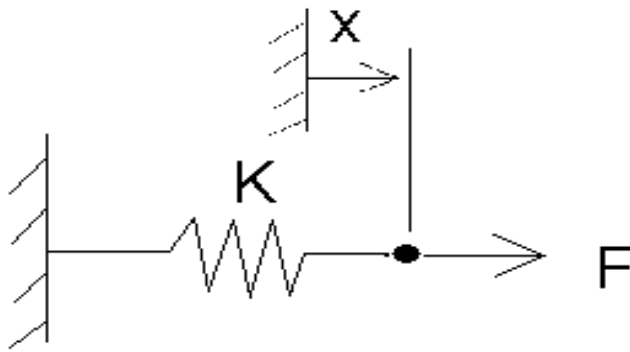


Figure 1: An example homework assignment.

ME-599 – Homework #7- Due Tuesday, March 9, 2004

Consider the system from Homework 5, with the following differential equation:

$$\ddot{x} + 4 \dot{x} + 104 x = F(t)$$

1. Write a MATLAB m-file that will calculate the unit step response using the finite difference method. The m-file should store the response values in an array named "x", and the corresponding time values in an array named "t". The time step should be stored in the m-file under the parameter name "h". In this case, you can assume $F(t)$ is the system input and it equals "1" for all time, including $t=0$. The initial conditions, $x(0)$ and $v(0)$, are zero, where $v=dx/dt$. You do not need to turn in any results or plots; you simply need to email your m-file to jbaker@engr.uky.edu before class on Tuesday, March 9.

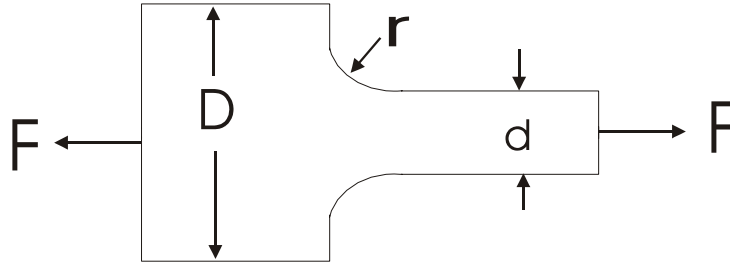
2. Repeat part 1, except create a separate m-file, and in this case, your m-file should solve for the response using Runge-Kutta integration, as discussed in class on Thursday, March 4.

Figure 2: An example homework assignment.

ME-599 – Application Project #1 - Due Friday, February 27, 2004

The reports required should be submitted as email attachments to jbaker@engr.uky.edu before class time on the due date.

1. Consider a rectangular cross-section filleted bar in tension:



Assume the material is steel. Select some grade of steel for which you can find sufficient data to enter a reasonably accurate nonlinear material model in ANSYS.

a) Neglect material nonlinearity. Enter a linear material model in ANSYS, pick some dimensions and determine the stress concentration in the fillet region using ANSYS. Use a plane stress assumption with Plane42 elements. Compare the result to expected results that may be found in a reference book, such as a machine design textbook. Perform the analysis for two force levels. Use one force level for which the peak stress is below the yield point for your material, and one for which it is significantly above the yield point.

b) Enter the nonlinear material model in ANSYS and repeat the analyses in step a.

Write a concise report summarizing and commenting on your results. The report should be written in Microsoft Word with appropriate ANSYS stress and strain contour plots. For the nonlinear material model case, you should include plots showing both elastic strain and plastic strain. Be sure to compare your stress concentration from step a from your reference text to that found in ANSYS.

2. Model a thin cantilevered beam. Use 3-D Solid45 elements in ANSYS. Assume linear material properties with $E=30E6$ psi, $\Delta=(.282/386.4)$ [lb-s²/in]/in³, and ≤ 0.29 . Assume it is loaded by gravity loading only, where gravity acts perpendicular to the beam's axis in the direction that produces the most deflection at the free end.

a) Select your own dimensions, but use dimensions such that deflections due to gravity loading are large enough to require a large deflection nonlinear analysis for accuracy. However, do not include nonlinear effects in the analysis, and compare the deflection at the free end and normal stress near the clamped end to calculations from beam theory. In this case, model the gravity loading as a constant acceleration.

b) Repeat step a, but use a large deflection analysis.

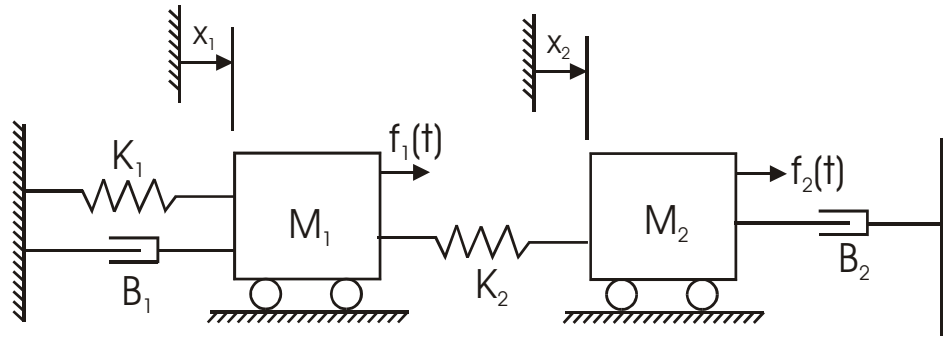
c) Repeat step b, but this time, approximate the gravity loading as a pressure on the top surface of the beam.

Write a concise report summarizing and commenting on your results. The report should be written in Microsoft Word with appropriate ANSYS results, including deflection plots. Be sure for the linear case to compare your results to beam theory, and then compare results from all three cases and comment.

Figure 3: An example application project assignment.

ME-599 – Application Project #2 - Due Tuesday, March 30, 2004

The required information should be submitted as an email attachment to jbaker@engr.uky.edu before class time on the due date. All information should be pasted into a single Microsoft Word document. The student's name should be listed at the top of the first page. All required information should be clearly labeled. See the finite difference equations on the following page. Consider the two DOF translational mechanical system below:



Case 1: Assume $K_1=300$ N/m, $K_2=200$ N/m, $B_1=B_2=0$, $M_1=1$ kg, $M_2=2$ kg, $f_1(t)=f_2(t)=0$, with initial conditions: $x_1(0) = 1$ m; $x_2(0) = \dot{x}_1(0) = \dot{x}_2(0) = 0$. Write a MATLAB m-file to solve for the system response using the finite difference method. The information required is:

- A plot of “ x_1 vs. time”, for a time range of zero to five seconds.
- A plot of “ x_2 vs. time”, for a time range of zero to five seconds.
- A listing of the m-file.

Case 2: Repeat Case 1, except this time, use the following initial conditions:

$$x_1(0) = 0.4495 \text{ m}; x_2(0) = 1.000 \text{ m}; \dot{x}_1(0) = \dot{x}_2(0) = 0.$$

Provide the same information required for Case 1, except a listing of the m-file is not needed. In addition, estimate the frequency of the responses, x_1 and x_2 . The responses should be dominated by one mode corresponding to one of the two system natural frequencies.

Case 3: Repeat Case 1, except this time, use the following initial conditions:

$$x_1(0) = 1.000 \text{ m}; x_2(0) = -0.2247 \text{ m}; \dot{x}_1(0) = \dot{x}_2(0) = 0.$$

Provide the same information required for Case 2.

Case 4: Assume zero initial conditions, $x_1(0) = x_2(0) = \dot{x}_1(0) = \dot{x}_2(0) = 0$. Now, let $B_1=B_2=1.5$ N-s/m. Assume the forces are: $f_1(t)=0$; $f_2(t)=\cos(7.42 t)$. Find the system response. The information required is:

- A plot of “ x_1 vs. time”, for a time range of 0-20 seconds, and a separate plot for 15-20 seconds.
- A plot of “ x_2 vs. time”, for a time range of 0-20 seconds, and a separate plot for 15-20 seconds.
- A listing of the m-file.
- An estimate of the steady-state response frequencies and amplitudes for x_1 and x_2 .

Case 5: Repeat Case 4, except assume the forces are: $f_1(t)=0$; $f_2(t)=\cos(15 t)$. Provide the same information for this case as provided for Case 4, except the m-file listing is not needed.

Case 6: Repeat Case 4, except assume the forces are: $f_1(t)=0$; $f_2(t)=\cos(23.34 t)$. Provide the same information for this case as provided for Case 4, except the m-file listing is not needed.

Figure 4: An example application project assignment.