2006-984: AN INTERDISCIPLINARY VIBRATIONS/STRUCTURAL DYNAMICS COURSE FOR CIVIL AND MECHANICAL STUDENTS WITH INTEGRATED HANDS-ON LABORATORY EXERCISES

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An Interdisciplinary Vibrations/Structural Dynamics Course for Civil and Mechanical Students with Integrated Hands-on Laboratory Exercises

Abstract

The University of Tennessee at Martin offers a multi-disciplinary general engineering program with concentrations in civil, electrical, industrial, and mechanical engineering. In this paper the author discusses the development of an engineering course that is taken by both civil and mechanical engineering students. The course has been developed over a number of years, and during that time an integrated laboratory experience has been developed to support the unique interests of both groups of students. The course is required for all mechanical engineering students, while the civil engineering students may take the course as an upper division elective. To insure the success of the course, the author has structured the course to attract both groups of students. This paper discusses the course content and laboratory structure. Particular attention is given to developing the course content so that it is clear to the students that the theory applies to both disciplines. The laboratory exercises have been developed so that they immediately follow the appropriate lecture material. The major concepts covered in the lecture are measured and verified in the lab. Custom designed laboratory apparatus has been incorporated into the laboratory, as well as state-of-the-art transducers, signal conditioning equipment, and data acquisition systems using Matlab as the data acquisition software. The laboratory includes both linear and rotational experiments, and the required laboratory reports use several different report formats with emphasize on clear, concise writing style. All experiments include analysis, testing, and simulation, and the students are required to explain any differences between theory and the measured experimental results. The course culminates with an open-ended laboratory based project in which the students must apply the concepts and techniques learned in the course to characterize a ¼-scale three-story building.

Evolution of the Vibrations/Structural Dynamics Laboratory

This course has three hours of lecture and one three-hour lab per week. Prior to 1999 only one laboratory period in the course had been used to perform experiments. At that time a group of important topics from a traditional vibrations textbook[1] were selected and simple experiments to illustrate those principles were developed. Matlab[2] and Simulink[3] were purchased to support the lab portion of the course. A small shake table was also purchased and has been incorporated into the course. Finally, in an effort to entice civil engineering students to become involved in senior projects involving earthquake and wind excitation in civil engineering structures, the course was advertised as applicable to both mechanical and civil engineering students.

Over the next three years additional funds were allocated to purchase linear amplifier/filter units as preprocessing for a data acquisition capability, followed by the purchase of state-of-the-art workbenches with six stations each accommodating four students, and the vibrations lab was moved into a dedicated location. More recently new test equipment has been purchased for each station, including a PC computer with LCD display, a 16-digital and two-analog data acquisition board per station, 60Mhz oscilloscope, DC power supply, frequency counter, power supply, and bench top as well as a handheld multimeter. Finally transducers accelerometers and LVDTs

were obtained which allow measurement of displacement and accelerations. Most recently additional custom built hardware has been incorporated into the laboratory, including several test frames that allow a wide range of experiments, and a ¼ scale three-story structure to attract civil engineering students into the course.

Vibrations/Structural Dynamics Course Content

The vibrations/structural dynamics course is taught by the author every other fall, is required for all mechanical engineering specialty students, and is an upper division elective for civil engineering students. The course has a reputation as being demanding, since the students are expected to be able to apply dynamics, differential equations, Fourier series, and Laplace Transforms. The prerequisites to the course are differential equations and dynamics. To recruit civil engineering students we emphasize that this course will give them a significant advantage for studying structural dynamics in graduate school. This has proven to be the case, as several civil students have continued on to very good graduate programs in this area. Typically the course has 18-24 students, with a maximum of 24 based on the laboratory capacity. This past fall there were eight civil engineering students and 14 mechanical engineering students.

There are five main goals for the course:

1. Derive the differential equations of motion for single and multi-degree of freedom systems (SDF & MDF), for both transitional and rotational motion, and for both linear and nonlinear coplanar systems.
2. Identify, explain, calculate, and experimentally determine the major parameters that describe the response of the systems.
3. Solve the differential equations of motion for both the transient and steady state response using both manual and computer based approaches, when the system is excited by various types of forcing functions.
4. Identify, describe, and apply the various hardware/software components that make up an experimental data acquisition and vibration testing system.
5. Apply various manual, hardware, and computer-based approaches to experimentally determine the response of various structural systems, and present and report the results.

The students are expected to use the textbook as a reference, and all the topics in the lectures are covered in the textbook. However, the textbook is not relied upon heavily in the lecture. The major topics covered in the course are:

- Free vibration of single degree of freedom (SDOF) systems, undamped and damped, linear and rotational
- Sinusoidal excitation of undamped and damped SDOF systems, linear and rotational
- The concepts of damping, stiffness, and mass, as well as the effective values of these parameters for more complex systems
- Derivation of equations of motion using both dynamic equilibrium and energy balance
- SDOF systems under sinusoidal base excitation
- SDOF systems that experience excitation due to rotational unbalance
- Excitation of SDOF systems due to impact loading, general non-periodic loading, and periodic non-sinusoidal loading
- Free vibration of multi-degree of freedom systems, undamped and damped.

- Modal analysis of undamped and damped multi-degree of freedom systems
- Free and sinusoidal forced response of multi-degree of freedom systems

Structure of the Lectures

It is critical to include examples in the classroom that will keep the students' attention. This course has been taught enough times so that heavy reliance on a set of notes is not required. This brings a more interactive atmosphere into the classroom. The lecture topics for the semester are included in the syllabus, and it is made very clear that it is not a good idea to miss class.

The course was developed using many of the concepts presented in the National Teaching Effective Institute[4] sponsored by ASEE. On the first day of lecture a spring and weight are hung from the grid ceiling in the classroom, the weight is pulled down, and the mass/spring system is set loose. The class counts the time for a cycle, introducing period and frequency. The mass is weighed and the spring is experimentally measured using a ruler and a force gauge, yielding stiffness. The relationship between mass and weight is shown to be a special case of Newton's second law. Immediately afterward, the free body diagram is drawn on the board, and the equation of motion is derived. The radian frequency is obtained, and the relationship between radian and angular frequency is derived. The class ends by showing that the measured frequency is very close to the square root of the stiffness divided by the mass, obtained from either the experimentally measured values or the analytically derived quantity. This sets the hook by gaining the interest of each student in the class. Not all lectures can be carried out in this manner, and as the subject material becomes more complex it is more challenging to bring examples into the classroom. But with a little thought it can be done.

The students are provided with handouts so that they can more easily follow the derivation of analytical results, and the board is used to work out examples as the derivation progresses. All examples are carefully selected to correspond to real situations that the students have observed. For example, bringing in a simple model of a one, two, or three story "Popsicle" model of a building, and using the portable small shake table to excite the model, immediately illustrates the concept of resonance. Laterally exciting a small four-legged table illustrates that a building, which is similar to the table, also has a dominant mode. Sharply striking the same table with an object illustrates that the free vibration frequency of the structure is excited. The sounds that are emitted are the resonant frequencies. Simple examples like this help clarify otherwise complex concepts for students who are so easily overwhelmed by the obscure relationship between the mathematical theory and physical phenomenon. As the input excitations become more complex, an automobile suspension system has been found to be a good system to engage the class. A car traveling on a bumpy road is base excitation, the movement of the engine when the fan or flywheel is out of balance is rotational unbalance, driving over a speed bump is an example of a general input, and driving down a railroad bed is a good example of a non-sinusoidal periodic input. All students can immediately relate to these examples, and thus they are able to understand where the lecture is going.

It has been found that students learn best when they work problems outside the classroom that are graded for credit. As the course progresses the problems become more challenging. The early problems are taken from the text, but as the material becomes more challenging problems that address the real-life example situations discussed in class are assigned. The relationship

between the mathematical models and the corresponding analytical responses, and the response from real experimental structures, is illustrated in the laboratory.

Structure of the Laboratories

The students are separated into four-person groups, and these are maintained throughout the semester. They are free to select their own groups, so the groups are often separated by discipline. This introduces some friendly competition between the civil and mechanical students. At the beginning of each lab period each student is provided with a handout that describes the laboratory objectives, the detailed procedures to be followed, the analytical tasks to be performed, and the type of lab report that will be due. These lab handouts have been developed over the past several years, and there are now seven laboratory exercises.

All data acquisition is performed using the data acquisition toolbox in Matlab. The required programs are provided to the students. These programs require the students to input sample rate and duration, as well as dc biases associated with the transducers. The lab uses conditioning amplifiers, which include gain-settable linear amplifiers and anti-aliasing filters. The proper use of this equipment is covered in the early lab sessions. The students are required to hook up all connections, and they must include a block diagram of the system in their lab report.

With few exceptions, each laboratory exercise requires that the students predict the response of the system being tested using analytical tools from the lectures, experimentally excite the system and record the response using the Matlab-based data acquisition system, and determine the response of the system using the simulation package Simulink which is included with Matlab. A major component of the laboratory report requires that each group clearly address any differences between the experimental and analytically derived responses. The students often spend long hours trying to understand what went wrong, and when their simulation and experimental response plots eventually sit on top of each other, they show obvious pride when they turn in their reports. Of course the responses will almost always be different, so they gain a practical understanding of the accuracy that may be expected. This experience is invaluable in clearly demonstrating the difference between the response from a mathematical model, and the experimentally obtained response from the real system, albeit with unavoidable experimental errors which are due to the test equipment and not the system under test.

Integration of the Lectures with the Laboratories

It is important that both the civil and mechanical engineering students see how the material is pertinent to their discipline areas. Feedback from students indicate that even if they cannot immediately see how a rotating machine relates to a civil structure, having it pointed out that an out-of-balance air conditioning system sitting on the roof of a structure is rotational unbalance, their nodding in class or lecture shows that they are involved and see the importance. Taking the effort to find these examples is well worth the effort. The fact that the theory applies to large as well as small structures is constantly emphasized in the lab.

A common complaint from students in laboratory courses is that the laboratory experiment is not related to the lecture material. If the purpose of the laboratory is to emphasize and expand on the concepts in the lecture, then every effort should be made to tie the two together. It has been found that this is best achieved if the instructor of the lecture is also the instructor of the lab, and

optimally the lab exercises should follow as soon as possible after the presentation of the material in the lecture.

Each major area in the course follows this approach:

- Simple example and possible demonstration in the lecture
- Development of the governing mathematical theory integrated with a real example
- A number of practical examples worked out on the board, showing all steps and soliciting student participation
- A lab exercise in which the experiment is as close as possible to the system that was just discussed in the lecture
- Student work outside the lecture and lab, including both assigned homework and a required written lab report. All lab exercises and most homework assignments require that the student perform a simulation as well as the analysis or experiment.
- Return of the graded homework and lab report to the students

In order to accomplish the goal of having a lab exercise that is directly comparable to the models used in the textbook, a set of custom designed and constructed equipment has been incorporated into the lab over the years. This is an ongoing process, and these pieces of equipment continue to be improved.

Description of Integrated Lab Exercises

The current vibrations/structural dynamics laboratory consists on seven lab exercises, numbered 0 through 6.

Lab 0: MatLab Simulink Overview
This lab introduces the students to Simulink. It is presented in a computer lab during the second week of school. There is a detailed handout which leads the students through the development of a simple simulation model to obtain the response of both an undamped and under-damped SDOF system. This ties closely with the lecture, as these topics have just been discussed. Each student is required to build their own model, and use it for the next several weeks, modifying it for different input configurations. It is important to include actual windows from the program in these types of handouts, as shown in Figure 1.

Laboratory 1: SDOF Multi-spring Mass System
This lab introduces the students to performing measurement in the lab, using a very simple vibration setup. The system used for this lab is shown in Figure 2. In this lab the students measure individual spring stiffness and the effective stiffness of the multi-spring mass system, they predict via analysis the effective stiffness, and they calculate the natural frequency of the system. This lab uses very limited instrumentation, and relies on static measurements. One of the goals is to have them appreciate uncertainty in measurement, such as from using a ruler or hand held force gauge. This also allows the opportunity to discuss when a single degree of freedom is appropriate, in this case for small displacements. Detailed steps are provided in the procedure to accomplish the objectives.

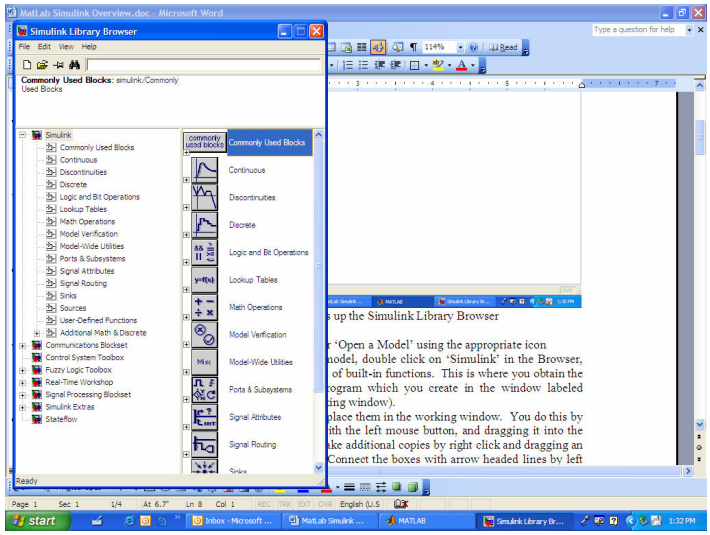

Figure 1 Opening Simulink from the Lab 0 Handout.

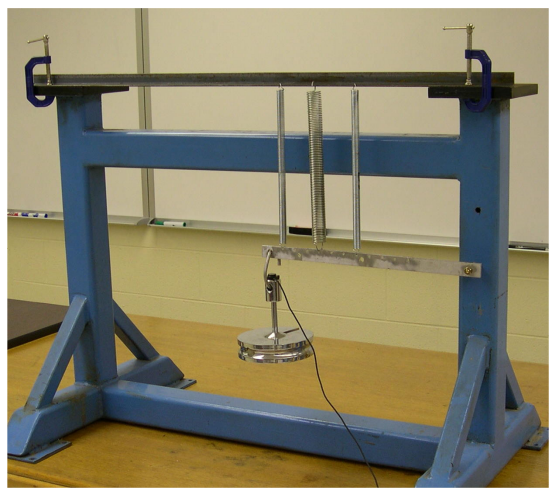

Figure 2 Mass with multiple springs used in Labs 1 and 2

Laboratory 2: Determination of Natural Frequency and Damping

In this lab, using the same setup as the previous experiment, the students measure the natural frequency of the system using an accelerometer and data acquisition system. They then dynamically determine the damping of the system using the log decrement method. Finally, they compare the measured acceleration response from the test to a Simulink generated response of the same system. In the lab report they must compare the results to those obtained in Lab 1, and discuss intelligently any differences. They must answer questions such as: Based on these results, what was the maximum acceleration of the mass? How does this compare to the displacement that you observed? Does it make sense? Emphasis is placed on comparing theoretical to experimental results, and intelligently discussing any differences.

Laboratory 3: Response of SDOF System to Harmonic Excitation

The experimental setup is shown in Figure 3. In this experiment a sliding SDOF system is excited with the shake take being driven by a signal generator. The table motion is measured

with an accelerometer, and the mass motion is measured with an MTS LVDT. They students must experimentally determine the natural frequency of the system, determine the displacement transmissibility curve, and compare the measured transmissibility to the theoretical transmissibility obtained from using Simulink. The Simulink results are plotted as a continuous curve, and the experimental five values are plotted as discrete points.

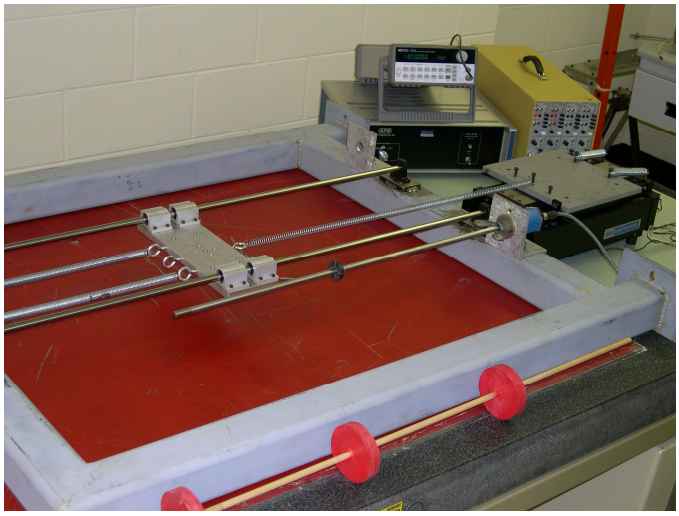

Figure 3 Sliding mass on linear bearings excited with shake table used in Lab 3

Laboratory 4: Rotating Unbalance

The experimental setup is shown in Figure 4. In this experiment a computer fan is attached to the end of an aluminum cantilever beam. One of the fan blades has had a small bolt attached to it, causing significant rotational unbalance. The fan speed is measured using a simple circuit using an infrared transmitter and detector. The students must experimentally identify the natural frequency and damping, determine the vibration acceleration amplitude of the system when the unbalanced motor is rotating at various speeds, convert the measured acceleration amplitudes to displacements, analytically determine the predicted vibration position amplitude of the system for various rotational speeds of the motor using measured system parameters, and verify the experimental and analytical results using a Simulink model. In the lab report the students are required to plot the experimental and theoretical normalized displacement on the same graph.

Laboratory 5: 2DOF System with Sinusoidal Excitation

The lab setup for this experiment uses the same frame shown in Figure 3, with an additional mass added. The students are required to experimentally determine the input frequency that causes the maximum in-phase motion of the two masses for a minimal input motion, and then to experimentally determine the input frequency that causes the maximum out-of-phase motion of the two masses for a minimal input motion. They then take additional data at two frequencies below and above the resonant frequencies. They must build a Simulink model of the 2DOF system, adjusting the damping constants until the experimental and simulated results match. Finally they must derive the equations of motion for the system.

It can be seen that the students are expected to be more sophisticated in their experimental approach as well as their understanding of the concepts being illustrated. They find this lab difficult, and they are given two weeks to complete the report. Often they need to reenter the lab

and take additional measurements. Because there is only a single setup at this time, careful scheduling is required to complete the experimental portion of the lab.

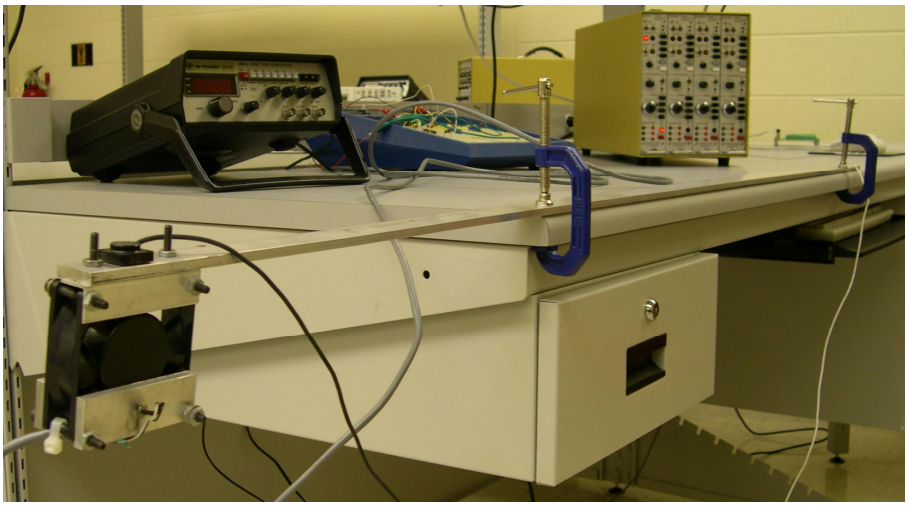

Figure 4 Unbalanced computer fan attached to cantilever used in Lab 4

Laboratory 6 (Parts 1 & 2): Modal Analysis of a 3DOF ¼-Scale Structure
This is a two part open-ended lab exercise that each student must independently perform. The ¼-scale building used is shown in Figure 5. During testing, LVDTs are attached at each floor level, and the shake table is used to excite the structure in the second and third modes. The shake table is then turned off, and free displacement response may be observed. Manually excited free vibration is used for mode one response.

In the first part of the lab each student must derive the equations of motion for the ¼-scale building, assuming a force input at the first floor level. Next, they determine the modal frequencies and mode shapes using the traditional eigenvalue approach, and write the equations of motion in terms of initial conditions on the three coordinates. Finally, they use modal analysis to determine the modal frequencies and normalized mode shapes. Finally they write the uncoupled equations of motion in terms of initial conditions on the three modal coordinates.

To perform this first portion of the lab they must determine the mass and column lengths. For the second moment of area they may either measure the cross-section in the direction of bending and calculate it, or consult the AISC LRFD Code. They must assume end conditions for the columns, and they are referred to their strengths course to determine the actual stiffness values based on these end conditions

In the second part of the lab they experimentally determine the free vibration responses for each mode, determine the modal damping rations, and finally calculate the physical damping coefficients appropriate for the 3DOF model.

This lab takes two to three weeks, and requires that each student experimentally determine the three modal frequencies, build a Simulink model that produces similar frequencies, and measure the damping. They find this lab challenging. However, the civil engineering students particularly enjoy this project.

Figure 5 ¼ scale building used in Lab 6

Lab Reports

Beginning fall 2005 the engineering faculty adopted a standard technical writing textbook[7] to be used in all laboratory courses that require reports. During the most recent offering of vibrations/structural dynamics the students were required to use both short and long narrative reports. All labs except the last required group reports. To ensure that all students were involved in report writing, it was required that each section in a given report clearly indicate the name of the student that wrote that section. All students were required to write all sections before the semester concluded. For example, each student had to write at least one introduction, executive summary, analysis section, discussion, conclusions, and sample calculations.

Trends and Conclusions

A vibrations/structural dynamics course with integrated lectures and laboratories has been developed over a period of seven years. Emphasis has been placed on illustrating the main concepts in the lecture with hands-on laboratory exercises in which the students are required to determine system response using theoretically based analytical approaches, computer based simulation, and experimental approaches using transducers and data acquisition systems. In all cases emphasis has been placed on understanding the differences between the results obtained from these approaches. Since this course is offered for both civil and mechanical students, efforts have been made to bring examples from each discipline into both the classroom and the laboratory setting. The course has been well received by the students. The student evaluations for this course (measured on a scale of 1-5) continue to improve, as shown in Figure 6.

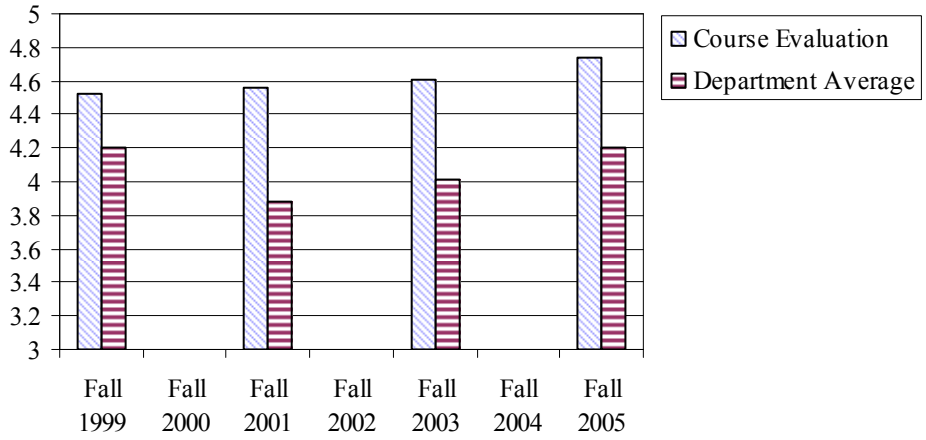

Figure 6 Student Evaluations for Course Compared to Department Average

The students appreciate that the labs are tied closely to the lectures, and they all respond well to the inclusion of a large number of examples in the lectures. However, many still have difficulty with the material when the inputs become more complicated than a single sinusoid, and some students are confused by the differences between forced and transient response. In the lab, they uniformly complain that there is not enough equipment to allow all groups to complete their experiments in a timely manner. The department continues to explore ways by which the needed additional equipment can be obtained. Finally, it is expected that additional rotational related experimental equipment will be purchased and incorporated into the course in the future.

References

1. *Engineering Vibrations, 2nd Edition*, Daniel Inman, Prentice Hall, 2001
2. Matlab, The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760-2098
3. Simulink, The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760-2098
4. Felder, Stice, and Brent," National Effective Teaching Institute", American Society for Engineering Education, 1999 Annual Conference
5. Writing Style and Standards in Undergraduate Reports, Jeter and Donnell, College Publishing, 2004