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Reversing the Roles of Experiment and Theory in a Roving Laboratory for Undergraduate Students in Mechanical Vibrations*

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Product manufacturers are carrying out far fewer, more deliberate experiments than ever before to cut costs and compete in the marketplace; however, many undergraduate engineering students enter the workforce with the false perception that 'experiments are just data-taking.' The roving laboratory discussed here can be set up wherever interesting test specimens are found and aims: to give students more control of the learning process through inquiry-based, collaborative teaching; to provide a better introductory education in vibrations and experimental mechanics; to promote lifelong self-learning and an appreciation of experimentation; and to strengthen the link between industry and academia. By reversing the roles of theory and experiment, the new course lab and lecture empower students to discover theories on their own. Comparisons between formative and summative surveys indicate that: student perceptions of experimental practices changed as a result of the course; students were more engaged than in traditional laboratory courses; and students felt more prepared to enter the workforce. Other assessment results are also discussed.

INTRODUCTION

DETAILS OF THE development and assessment of a roving laboratory for undergraduate students in the context of a new undergraduate engineering vibrations course at Purdue University in the School of Mechanical Engineering called *ME 497A: Practical Experiences in Vibration* are provided here. The course was offered for the first time in the spring of 2003 to 15 students and is intended to eventually serve as a permanent elective for students interested in pursuing careers related to mechanical vibrations. During the course, students design, set up, carry out and interpret their own experiments in the roving laboratory, which can be set up wherever interesting test specimens are found. These experiments are used by students to anticipate each theoretical discussion in class, to learn how to plan and conduct their own experiments, and to explore emerging areas of experimental mechanics such as nondestructive evaluation and prognosis.

In order to effectively teach this course, a dynamic inquiry-based, collaborative learning environment has been established where the teacher engages students more like a 'coach' and less like an instructor. Strong industrial partners of the course with a vested interest in promoting education in experimental mechanics donate meaningful projects and test specimens for use by the students and also help to evaluate the student project reports. By reversing the roles of theory and experiment, the laboratory, course notes and lectures empower students to discover theories on their own. Instead of using experiments to validate theories, students use theories to validate experiments. The overarching goals of the project are: to give students more control of the learning process; to better educate students in vibrations and experimental mechanics; to encourage life-long self-learning and an appreciation for experimentation; and to create a stronger and more direct link between industrial partners and the classroom.

Included in the paper are discussions of the following topics: why such a course is needed, both from an industrial perspective and a university perspective; the format of the roving laboratory and lectures, which both implement inquiry-based and collaborative pedagogy; the assortment of instrumentation used to offer the course for the first time; individual student projects for orientation in the laboratory as well as capstone group projects; and a discussion of the formative and summative student evaluations of the course and laboratory.

BACKGROUND

There is a disturbing trend in colleges and universities towards less education and training in experimental practices for mechanical systems

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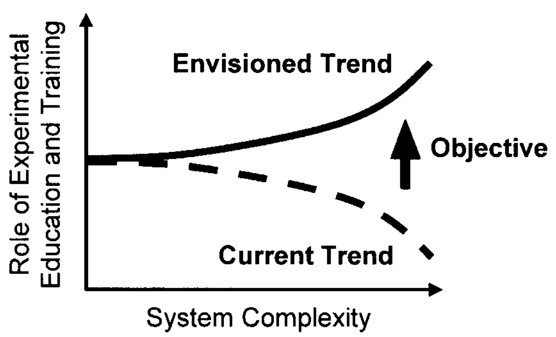

Fig. 1. Illustration of downward trend in the role of experiments and training with increases in system complexity compared to the desired trend, which is the objective of this project.

at a time when industry needs engineers who can more quickly design and interpret far fewer experiments on increasingly complex systems. Figure 1 illustrates that, in the current educational environment, students spend little or no time conducting and interpreting experiments on the most complex engineered systems. When these same students enter the workplace, they are thrown into a product manufacturing environment and asked to design and interpret their own experiments to validate analytical models and product performance. Although hands-on laboratory courses are increasingly being offered to undergraduate engineering students, experiments in these courses have prearranged procedures and outcomes that guide students in verifying theories rather than the other way around, leading to student leaps of faith during lectures. In addition to circumventing the discovery process and reinforcing student perceptions that experimentation is 'just data-taking,' as noted by Coleman and Steele [1], this approach to experimentation is aggravating the downward trend in Fig. 1 given the state-of-the-art in model-based simulation. Students often carry out 'proof-by-simulation' with advanced software in more complex engineering systems and do not get the opportunity to carry out physical experiments and develop their experimental planning and data interpretation skills.

The theme of this project in instructional adaptation and laboratory improvement is that 'experiment is the sole source of truth' [2]. We believe that students might accept theories more readily if they could discover them for themselves rather than taking them on faith during lectures. Furthermore, experiments are powerful tools of science and engineering, because one experiment can completely dismiss or divulge an entire theory; therefore, engineering students should be taught to design their experiments carefully and to glean as much information as possible from those experiments, which will lead to greater insight and discovery. The course and laboratory described here aim to make experiments as important in teaching as they are in research, so that opportunities in education and discovery are not overlooked like chaos was for so many years. In so doing, these educational materials and methods respond to needs in engineering education as expressed by Doderer and Giolma [3] and others to stimulate formal thinking, or 'thinking out of the box' as discussed by both Pavelich and Piaget [4–5]. Moreover, the roving laboratory adheres to the principles of the National Science Education Standards (Standard A) [8] and the National Research Council [7] by emphasizing hands-on, experiential learning as described by Wankat and Oreovicz [8–9] and student-driven investigation and inquiry of the kind described by McConnaughay [10].

CHALLENGES AND APPROACH

There are three main challenges that have been overcome to achieve the objectives of this educational project. First, 'experimentation is not just data-taking' [1]; however, the majority of students think it is, probably because the majority of lab assignments follow specific procedures and have prearranged outcomes. Although these traditional laboratory exercises serve an important role in the curriculum by enabling students to verify theories in a reasonable period of time, they only promote two types of knowledge: information-based (the 'what') and skills-based (the 'how') knowledge. As Gorman discusses at length in his overview of different categories of knowledge relating to the ABET criteria [11], two other types of knowledge, judgment-based (the 'when') and wisdom-based (the 'why'), are critical for developing the tacit knowledge that students need to succeed as professionals. The inquiry-based educational format in the course and roving laboratory described here underscores a need in engineering education to expose students to the wonders and pitfalls of experimentation beyond just data-taking, especially where vibrations are concerned, to promote the acquisition of knowledge by students in the form of judgment and wisdom. Furthermore, ABET criterion 3 (b) speaks directly to this need for experimental skills as discussed by Shooter and McNeil [12]. In the roving laboratory, undergraduates design, set up, carry out and interpret their own experiments, which are never easy tasks but always packed full of good engineering lessons. These lab experiences are very different from traditional prearranged laboratory exercises, in that the roving lab does not follow a fixed format and gives students an opportunity to develop their own experimental planning and design skills. Students who are capable of thinking on their feet in this way in an industrial setting have a distinct advantage when seeking many types of engineering employment. Students in the inquiry-based roving laboratory work together in teams to solve specific capstone engineering vibration problems by first developing their own experiments and then developing analytical engineering models, which can be used to generalize those experimental results and make recommendations

Fig. 2. Two student experimental set-ups showing an inexpensive, custom-built data acquisition system (left) and a battery-powered portable data acquisition system (right).

for addressing the given problem. Many other educators also find this type of project-based learning very effective because it forces diverse groups of students to work together to provide a deliverable [13].

The second challenge to overcome in this project was to develop a roving laboratory that is flexible enough to grow over time, mobile enough to be used for on- and off-campus testing, sustainable enough to evolve with the needs of industry, and interactive enough so that students get timely responses to their questions and concerns. Each of these elements of the roving laboratory is now described in more detail. First, custom-made equipment was designed and fabricated for use in this project in order to meet the flexibility requirement and an additional durable mobile acquisition system was purchased to provide the means to carry out remote experiments. Figure 2 shows two typical student set-ups featuring each of these data acquisition systems. Both systems are modular with eight to sixteen channels for filtering and sampling analog signals from external voltage mode or powered sensor or actuator arrays. The system on the left includes an IBM laptop computer and data acquisition box (described later) and is being used to make an impact vibration measurement on a test specimen. The system on the right is portable, includes a laptop computer and acquisition module and is being used to make impact measurements on a gymnasium court with seismic accelerometers.

The roving laboratory has been made sustainable by forming a strong industrial advisory committee for the course. These industrial partners, who range from practicing engineers to researchers at national laboratories to directors of engineering in major R&D firms, donate test specimens for student projects, provide engineering problems of practical importance on which students can work and evaluate the project results by grading student team presentations and final reports. By forming an industrial advisory committee, this project recognizes that researchers, professionals and instructors can better educate engineering students by establishing educational partnerships between academe, industry, and government laboratories as discussed by Wankat and Oreovicz, Hoots and Denton [14–16].

In order to provide students with the right amount of student–instructor interaction in the roving laboratory, the pedagogical approach follows two recently successful trends in inquiry-based engineering education whereby teachers act more like learning coaches and less like instructors and students serve as teachers for one another in collaborative learning environments. In inquiry-based learning environments, students are given compelling problems to solve, the resources to solve them, and the freedom to fail [17]. This latter characteristic of inquiry-based learning emphasizes the fact that successful outcomes are sometimes but not always guaranteed. In the roving laboratory, we have worked to manage failure throughout the semester so that in the end students leave the course with a sense of accomplishment after having overcome small failures along the way that do not prevent them from achieving their ultimate objective.

Regardless of the particular adaptation of inquiry-based learning being considered, the essential ingredient in all like-minded programs is student frustration, which leads to revelation when instructors intervene at the right times. Although instructors must give up a certain amount of control [18] to teach this way, inquiry has proven extremely effective for preparing students to practice engineering [19]. For example, Professor Mosch [20] at the Colorado School of Mines has developed a hands-on mining safety course inside Edgar Mine. In this course, students perform simple experiments with mining tools to demonstrate analytical concepts directly while instructors work like coaches to field student questions as they arise. This format has been very well-received by the students. As a second example, Professor Arce at Florida State University [21] has implemented a set of soccer coaching principles akin to the inquiry-based teaching methodology as discussed by Keefer. Arce hopes to transform the way students are taught the physics of transport in continuous media. There are many other good examples of where students and faculty interact in an experimental setting. For example, 'test-trips' have been used for decades by engineering graduate student advisors to successfully train their research assistants in experimental methods on research and development projects for industrial sponsors. These tests are filled with engineering lessons that expose students to everything, from failed sensors to misapplied engineering assumptions.

We believe that the collaborative element of the roving laboratory and course is in large part the key to its success. Collaborative, or 'team', learning has been shown to be very effective in enhancing an individual's tacit knowledge of a subject. In particular, Gorman [11] describes the work by Wegner [22], who has further defined the cognitive area of *Transactive Memory*. This type of memory, or knowledge, is formed by a team which is aware of who knows what within the group and who is assigned to which task. This element of the project has been based on the format of the Los Alamos National Laboratory Dynamics Summer School, which was offered for the third consecutive year in summer 2003. Cornwell and Farrar [23] have described this project in detail. Diverse student teams from all across the country come to Los Alamos in the summer to perform focused graduate-level research on emerging topics of interest in experimental structural dynamics with group mentors who coach students along their way.

The third challenge to overcome is that textbooks in vibrations are not written in an observational format, so students often feel as if they are taking giant leaps of faith in lecture from one section to the next when mathematics, calculus and differential equations are involved. To address this challenge, a unique set of course notes has been written in an inquiry-based format to complement the roving laboratory. The technical portions of these notes were adapted from a set of course materials that have been written and revised over the past twenty years by the staff within the Structural Dynamics Research Laboratory at the University of Cincinnati. The adaptation and lecture format are guided by Dale's conjecture [24], as described by Shooter and McNeil [12], that students assimilate information according to a 'cone of learning'. Moreover, students process 20% of what they hear, 30% of what they see, 50% of what they see and hear, 70% of what they say, and 90% of what they experience or practice doing. Clearly, optimal learning is achieved for most students when they are exerting themselves when reading the course notes and attending lectures. By requiring that students carry out a virtual experiment at the beginning of every section and lecture, these adapted notes emphasize that experiments of all kinds, including those that are physical, virtual (computer) and mental, can be used to develop analytical approaches. In this way, the notes aim to help students define the analytical approaches to be used rather than forcing the approaches on them. Numerous case studies from various research projects are also integrated into the lectures to provide students with the impetus to ask questions and engage one another during class. The following sections are included in the course notes.

1. Introduction

The need to study vibrations in the first place is motivated with examples of destructive and constructive oscillation phenomena, ranging from earthquakes to motion simulators to the stock market. Then free and forced vibrations are discussed from a phenomenological point of view using mental experiments that students can perform for themselves using commonly available test specimens (e.g. children's toy ring set). As students read this section, they discover how energy principles can be used to explain these experiments. They also learn about more advanced vibration phenomena in nonlinear systems through a series of experiments on a 'not-so-simple' pendulum. A case study involving a design problem for an offshore oil structure subjected to wave forces is then used to extend these basic principles in vibration to more complicated systems. The fundamental working principles of vibration in linear and nonlinear systems are then summarized in a conceptual format with physical examples at the end of this section.

2. Elements and equations of motion

The basic building blocks of vibrating systems are discussed and equations of motion are formulated using Newton's Laws and energy methods. The emphasis in the notes is on modeling and the physical interpretation of equations of motion rather than on their derivation. Many examples are carried out, with detailed descriptions for a motorized bicycle that bounces and pitches, a laptop computer bag that is dropped, a marine shaft-disk power train system, a blood testing lancet device and a two-story office building. As students read this section, they perform mental and sometimes physical experiments on each of these mechanical systems to develop an idea of which elements of vibration could be involved in the oscillations of interest in given problems. In a sense, they use an 'inverse approach' to develop the equations of motion by finding the solution prior to the equations. By reverse-engineering the equations of motion, students seem to be able to develop insight that is not possible in the more traditional approach to these derivations.

3 and 4. Free and forced vibration analysis

Students carry out experiments to discover when and where free and forced vibrations can occur in common engineering applications (e.g. automobiles, airplanes, civil infrastructure). Once students have performed these mental experiments and interpreted their 'data', they are able to carry out standard engineering approaches to solving equations of motion to verify their experiments. It is worth emphasizing that this approach is much different from the available textbooks in vibrations, which start by solving the equations of motion and then interpret solutions in light of the physical phenomena. Students are asked routinely in the notes to discover vibration theory for themselves, including concepts like resonant frequencies and damping in the context of interesting case studies like vibrating helicopter rotor blades. One of the principle achievements of this section of the notes is that students are not required to make a leap of faith from single to multiple degree-of-freedom vibrating systems. In fact, students carry out experiments in the notes that demonstrate why more degrees-of-freedom do not change the concepts or procedures introduced for single degree-of-freedom systems.

5. *Experimental vibration analysis*
Students learn why theories do not always agree with experiments. Concepts in experiment design, signal processing, measurements and parameter estimation are presented. Once again, the emphasis in this section of the notes is on having students reverse-engineer approaches in each of these areas. For example, the various types of excitation sources for conducting vibration experiments are described only *after* students ask themselves which behavior they are trying to capture in the experiment. By answering questions regarding several different desired measurements (e.g. narrowband response vs. broadband response), students will ideally be better able to define for themselves which excitations they need to use in their projects.

6. *Nonlinear vibrations*
Students are rarely exposed to advanced nonlinear concepts in undergraduate vibrations courses, so this section of the notes aims to give students an appreciation for these issues. The content of the notes is based on a set of interactive lectures and demonstrations delivered over the past two summers at the Los Alamos National Laboratory Summer School to undergraduate engineering students. As in the other sections of the course notes, this section uses experiments to inspire students to discover theoretical concepts on their own. Topics are intentionally covered with a low but sufficient level of mathematics to emphasize physical understanding of phenomena.

In summary, the unique observational instructional approach of the course notes and lecture complement the roving laboratory by reversing the roles of theory and experiment. Instead of using experiments to validate theories, experiments are used to reverse-engineer theories. This pedagogical approach aims to enhance the role that experiments play in and out of the classroom and to give students a better appreciation of the types of questions that cannot be answered without the benefit of mathematical models.

DESCRIPTION OF ROVING LABORATORY

Fifteen undergraduate students enrolled in the first offering of the course. Of these students, 21% were women, 7% were international students and the remaining students were white Caucasian males. A roving laboratory was the centerpiece of this course. As mentioned earlier, the laboratory is referred to as 'roving' because it can be set up wherever students find interesting mechanical, civil or aero-engineering test specimens. Each project established an educational link between university classrooms and industry to foster higher-level learning in vibrations. In the first offering of the course, experiments were carried out in the Ray W. Herrick Laboratories on campus and at remote test sites on campus (basketball gymnasium, machine tool lathe). Approximately three students were assigned to each of the five groups to work on different projects. Each team was required to submit a final report and deliver a presentation summarising their problem, approach and results for the industrial advisory committee and instructor to evaluate. The students met in teams at least once a week for three hours. An initial survey was completed by students in the first offering of the course and the demographic data contained therein was used to assign similarly diverse student teams. More specifically, teams were assigned to normalize the students' background in experimental work, grade point average, comfort level with mathematics, reason for enrolling in the course,

Table 1. Laboratory software and hardware acquired in preparation for spring 2003 offering

Item	Description
QRDC vibration test stand	Two degree-of-freedom vibrating system driven to oscillate by a rotating component with imbalance
SDC003-8H-kit	LanSharc Process Analysis Box kit for data acquisition with eight dynamic input channels, including three IBM laptop computers
IBM A22m laptop computer	Laptop accompanies mobile data acquisition system
IOtech Waveport®	Mobile 16-channel data acquisition system for examining vibrating systems in the field
Twenty T356B18	Tri-axial, high sensitivity, ceramic shear ICP® accelerometers with 1000 mV/g
Twenty T393A03	Seismic, ceramic shear ICP® accel. with 1 V/g
Twenty 012E10	Low-cost, black coaxial cable
One 086D50	Large sledge impact hammer with 1 mV/lb
Three 086C03	Modally tuned hammer with 10 mV/lb
Two 086D80	Miniature modal hammer for 0–50 lbf. excitation
Eight 740B02	ICP® piezoelectric strain sensor
Two T288D01	ICP® impedance head, force/accel. with 100 mV/lb, and 100 mV/g
UC-MRIT and UC-XModal	Software for performing impact testing and carrying out experimental modal analysis

Table 2. Three primary concepts examined in the course using the theory and experiments noted in the table

Concept	Theory	Experiments
Frequency response	$H_{pq}(\omega) = X_p(\omega)/F_q(\omega)$ Frequency response functions, $H_{pq}(\omega) = [h_{pqr}(t)]$, which are the Fourier transform of impulse response functions, are the primary analytical and experimental means for characterizing linear systems. The equation above relates the frequency domain input, $F_q(\omega)$, to the output, $X_p(\omega)$.	All
Transmissibility	$T_{pq}(\omega) = X_p(\omega)/X_q(\omega)$ Transmissibility functions, $T_{pq}(\omega)$, are ratios of frequency response functions and are the second primary analytical and experimental means for characterizing linear systems. The equation above relates the frequency domain output, $X_q(\omega)$, to the output, $X_p(\omega)$. Transmissibility functions are used to study vibration isolation systems, for example.	Golf clubs Power drill Model airplane wing F150 model Ink-jet printer Fishing pole
Modal superposition	$h_{pq}(t) = \sum_{r=1}^{N_r} A_{pqr}e^{\lambda_r t} + A^*_{pqr}e^{\lambda^*_r}t$ Modal superposition is the primary analytical tool for studying linear vibrating systems. The equation above expands the impulse response function, $h_{pqr}(t)$, as a sum of N_r modes, each with its own modal frequency (λ_r) and modal vector (associated with residues, A_{pqr}). Students experimentally extract these modes and then compare their results with analytical estimates.	All including: Fuselage Exhaust system Mackey arena Bicycle brake Lathe etc.

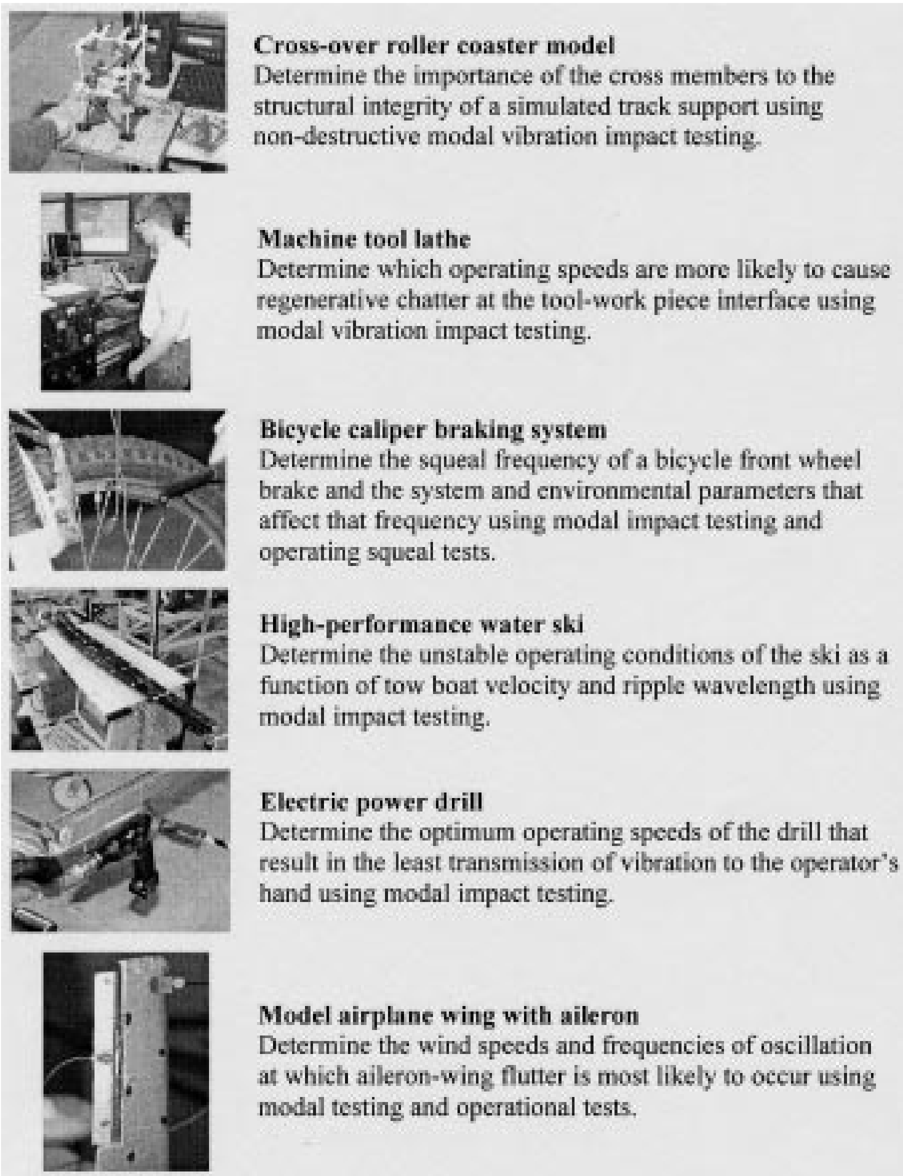

Fig. 3. Examples of individual student projects used for orientation purposes with the objective and approach of each project.

Fig. 4. Examples of group projects used for a capstone course project with the objective and approach of each project.

gender, ethnicity, interest in structural dynamics, comfort level with hands-on activities, and preference for individual or group activities.

Instrumentation for laboratory

The laboratory equipment purchased for the course is listed in Table 1, with the exception of the instrumentation cabling. Included in the list are various types of sensors, data acquisition hardware and educational vibration trainers. An assortment of transducers was required for measuring forces and motions in small (power drill) to medium (exhaust system) to large scale (basketball court) test specimens. The SDC003-8H-kit units (see Fig. 2, left) have eight dynamic channels of data acquisition and were custom designed for use by students in the roving laboratory by the Modal Shop (Cincinnati, OH) of PCB Group using the Analog Devices Sharc chip. The equipment is such that it can be easily expanded to accommodate more measurement channels and is completely network ready to facilitate future over-the-network remote testing by students. The University of Cincinnati Multi Reference Impact Testing (MRIT) and X-Modal software packages were used by students in the course. These programs were developed as educational tools for engineering students, have been updated over the years and are highly flexible to allow for various implementations in the course.

Technical content of laboratory projects

The technical content of all projects in the roving laboratory to date can be categorized as shown in Table 2. The three concepts of frequency response, transmissibility and modal superposition are sufficient to examine and solve a wide range of practical problems in vibrations. The challenges for students are to decide which among these concepts is critical to solving their specific problem, how to make good measurements and how to

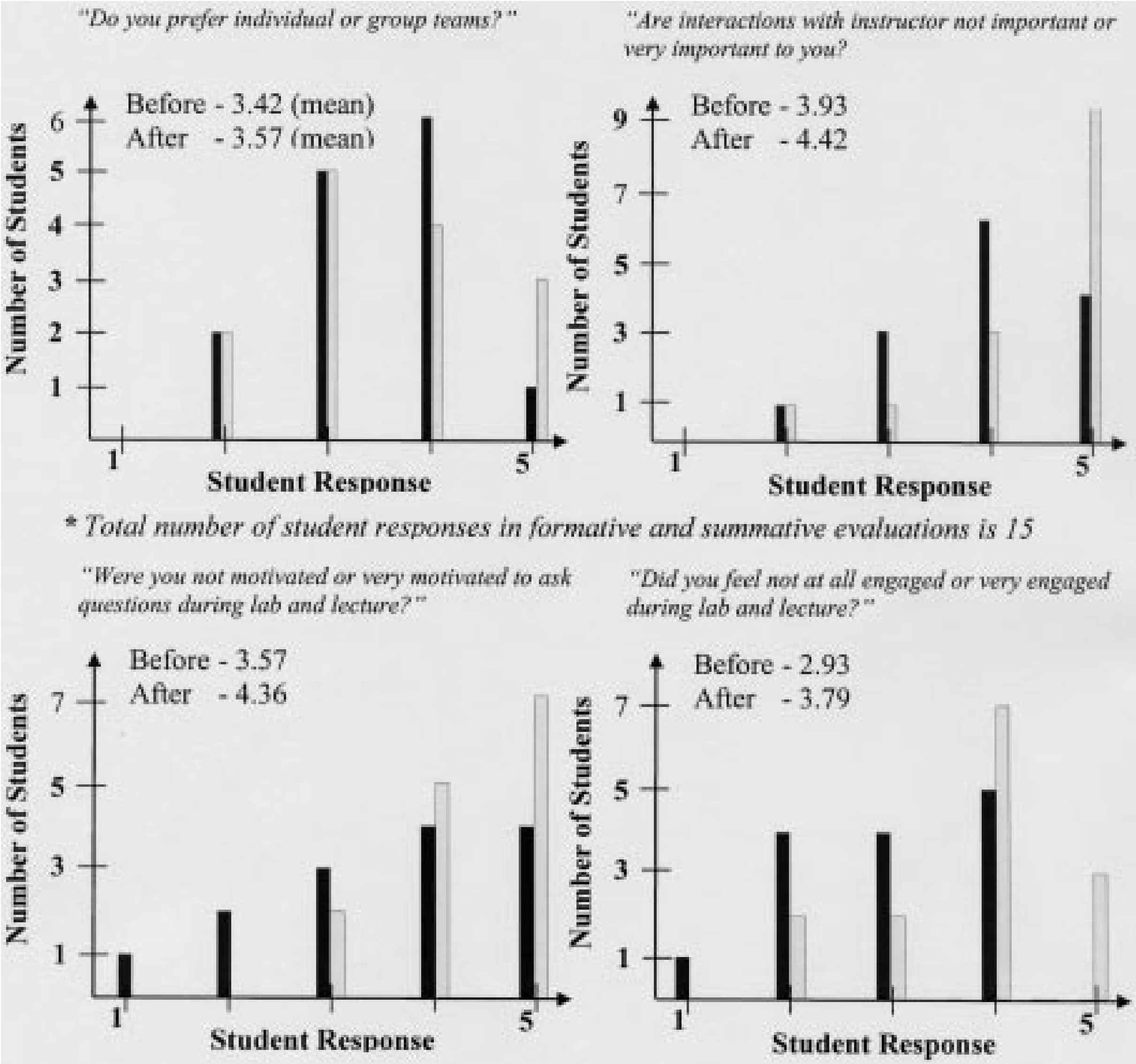

Fig. 5. Group 1 of formative vs. summative evaluation results.

interpret those measurements in light of the physical characteristics of interest.

Student projects—individual and group

Two sets of projects were carried out by the students during the semester-long course. First, individual student projects were used to orient each student in the course to the proper use of experimental hardware and software during the first six weeks. The objectives and approach of six of the 15 individual student projects are summarised in Fig. 3. Note that some of these projects were carried out in a laboratory and others were carried out at other sites on campus.

The five group projects are summarised in Fig. 4. Projects in the first offering were supported by several industrial sponsors including Lord Corporation and ArvinMeritor. In each project, students had a specific problem statement, set of experimental and analytical objectives and approaches, all of which the students defined themselves with limited intervention by the instructor. Students in all of the groups routinely commented that the open-ended requirement to define their own vision for these projects was preferable to having their projects defined for them.

ASSESSMENT

Five assessment methods have been used to evaluate the degree to which the roving laboratory and new course achieved the objectives for this project. First, 15 students in the first offering completed a formative survey consisting of 35 questions to provide a baseline set of responses for evaluating the course. Second, a summative survey consisting of 25 questions was completed by those same students at the end of the semester to

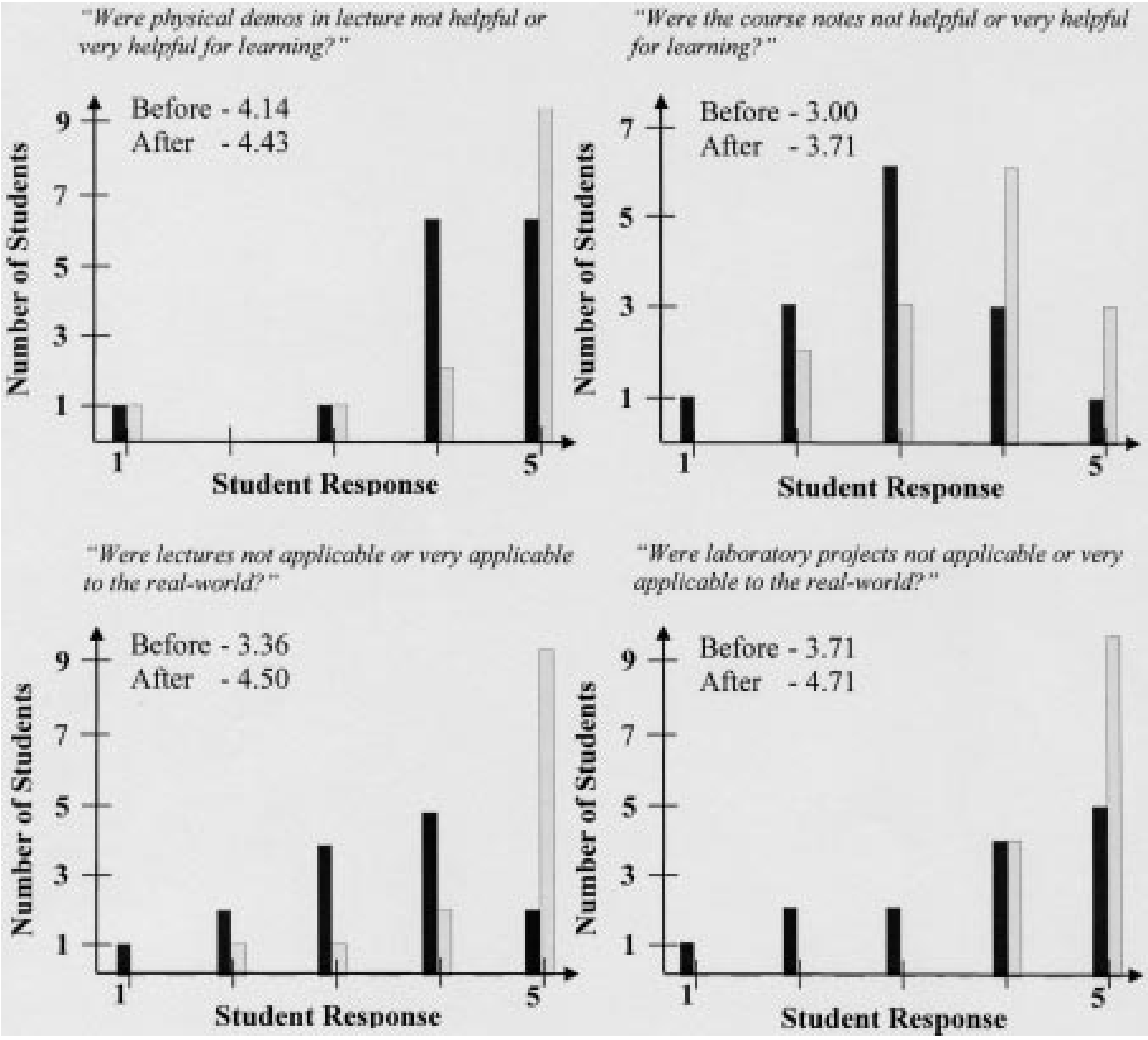

Fig. 6. Group 2 of formative vs. summative evaluation results.

provide data for comparison with the formative responses. Third, a few faculty evaluators graded the student presentations on their individual and group projects. Fourth, Pi Tau Sigma, the Mechanical Engineering honors society, conducted a summative course evaluation survey in the twelfth week of classes. Fifth, the industrial sponsors evaluate the student group project reports, but since these evaluations have not yet taken place, none of these results can be presented here.

Several of the more interesting results of the pre and post student surveys are illustrated in Figs 5–8. These assessment results are presented as histograms, so that the mean and variance among the 15 student responses can be more easily visualized. In each of these graphs, the height of all bars of a similar color must add up to 15. The formative and summative responses are indicated by dark- and light-colored bars, respectively. Student responses range from 1 to 5, with 5 indicating a 'positive' response and 1 indicating a 'negative' response.

Figure 5

The first two survey results in Fig. 5 (top) dealt with questions concerning working in teams and student–instructor interaction. A 5 in the first question indicates students prefer to work in teams and a 5 in the second question indicates that students feel one-on-one student–instructor interactions are very important in helping them to learn. The results in Fig. 5 indicate that students were similarly inclined to work in groups before and after the course (mean before = 3.42; mean after = 3.57); however, there was a statistically significant difference in the way students felt about the role that student–instructor interactions play in helping them to learn after their experience in the roving laboratory. The second two survey results in Fig. 5 (bottom) dealt with questions concerning the students' motivation to ask questions and student engagement during lab and lecture. In both cases, there was approximately a 0.8 positive increase in the average student response to these questions, indicating that, as

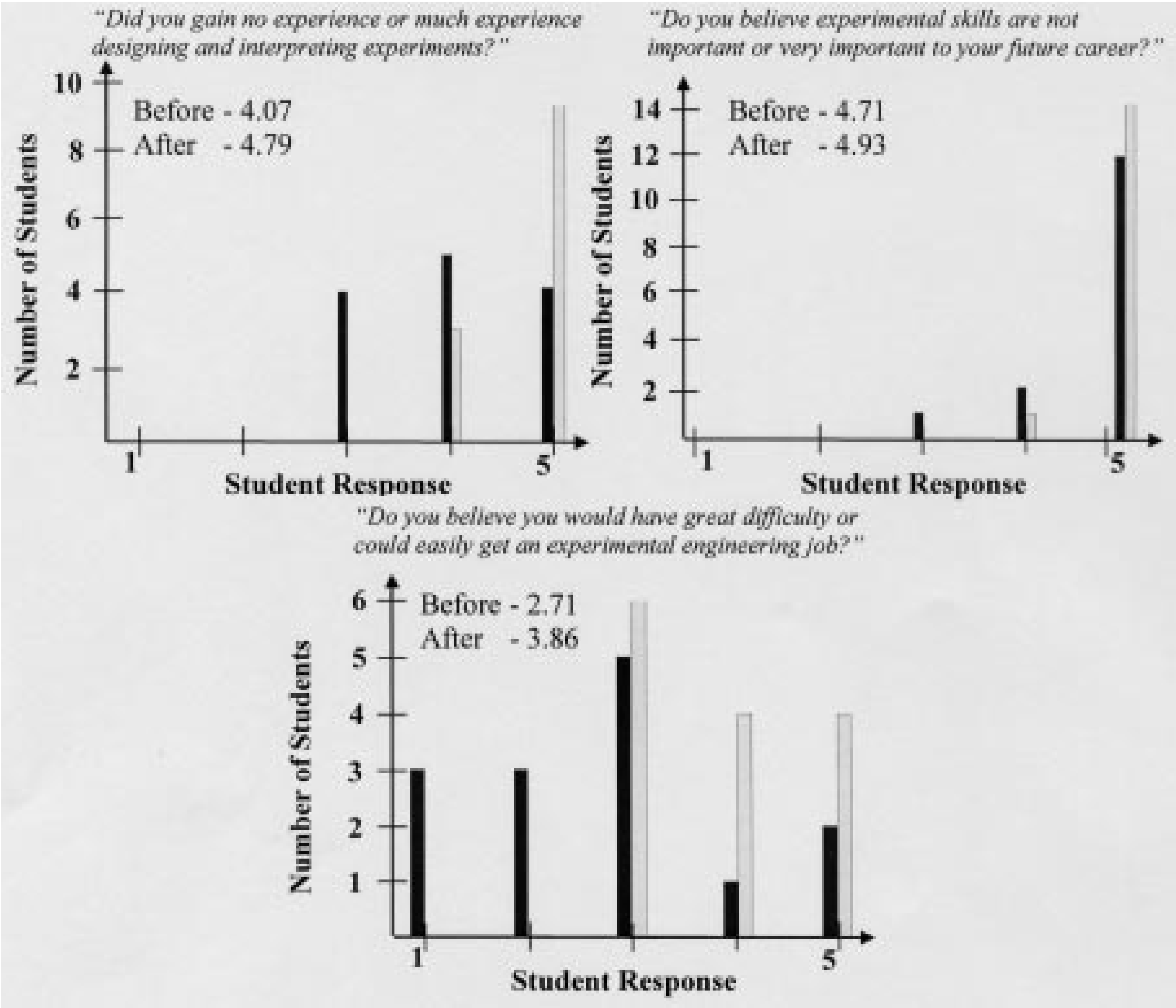

Fig. 7. Group 3 of formative vs. summative evaluation results.

expected based on the interactive nature of the lectures and labs, students felt engaged and were not at all hesitant to ask questions and even argue with the instructor.

Figure 6

The first two survey results in Fig. 6 (top) dealt with questions concerning physical demos during lectures and the course notes. Although there was only a marginal increase in the students' belief that physical demonstrations during lectures were helpful for learning the material, students responded with a 0.7 positive increase that the course notes, which were tailor-made to complement the roving laboratory, aided in learning the course material. We feel that this result is significant because one of the most often heard complaints from students about courses is the inadequacy of the textbook. The second set of questions in Fig. 6 (bottom) dealt with the applicability of lecture material and laboratory projects to the real world. The students uniformly responded with 0.8–1.0 positive increases on both of these questions that this course provided more insight into the practical issues in vibration than other courses have in their curriculum. The second of these results is particularly significant, because the roving laboratory was developed to provide more opportunities to students to develop their own experimental skills in comparison to traditional laboratory exercises.

Figure 7

The first two survey results in Fig. 7 (top) dealt with questions concerning experience with experimentation and perceptions of the need for experimental skills. Although there was only a marginal increase in students' feelings that experimental skills are important to their future engineering careers, a 0.7 positive increase on the first of these questions indicates that students felt that the inquiry-based roving laboratory did provide them with more experience in designing and interpreting their experiments. Comments from students during the laboratory sessions throughout the semester also indicated that the students enjoyed the sometimes frustrating job of interpreting their data. The result of the final survey

Table 3. Pi Tau Sigma independent course evaluation results

Pi Tau Sigma Survey Questions (1 strongly disagree, 5 strongly agree)	Response Mean
Overall course evaluation	4.5/5.0
Enhanced my understanding of fundamental principles	4.7/5.0
Showed me how to apply these principles to practical situations	4.8/5.0
Stimulated me to think creatively	4.4/5.0
Encouraged cooperative learning	4.9/5.0
Lectures contributed significantly to my understanding of the material	4.4/5.0

comparison presented here in the bottom of Fig. 7 is perhaps the most compelling evidence that the roving laboratory and course was successfully delivered in its first offering. It indicates more than a full point increase in students' confidence that they could obtain a job in experimental mechanics in industry.

The questions and answers in the independently conducted Pi Tau Sigma course evaluation results are listed in Table 3. The results in this table are consistent with those presented above and will not be discussed at length. Note that students were in uniform agreement that the course promoted cooperative (collaborative) learning, enhanced their understanding of fundamental principles and showed them how to apply vibration techniques to practical problems.

The objective evaluations of the faculty evaluators indicated that students had done an average of B+ to A− work in their individual and group projects (3.9/5.0 individual; 4.0/5.0 group). In future work, we will carry out multivariate regression analysis to correlate demographic, attitude and evaluative responses. Chi-square statistical hypothesis testing will be used to examine levels of correlation and coupling between the variables. Results of particular interest include differences in male/female responses and coop/non-coop responses.

CONCLUSIONS

Example projects in a roving laboratory for undergraduate students in vibrations and the accompanying observational instruction format and course notes have been discussed. The observational course notes, lectures and roving laboratory reverse the roles of theory and experiment by using theories to validate experiments rather than using experiments to validate theories, as is traditional in prearranged lab courses. The role of an industrial advisory committee for the course has also been described and the merits of teaming with industry to better educate students in experimental mechanics have been given. The goals of the project have been defined and the challenges to achieving those goals and methods for overcoming those challenges using inquiry-based instruction with collaborative learning have been described. The evaluation procedures and assessment results for the roving laboratory and course have also been given. All results have indicated that the first offering of the course achieved the objectives set forth at the beginning of the project. More specifically, the course and laboratory gave students: more control of the learning process; provided a better introductory education in vibrations and experimental mechanics than traditional courses; promoted lifelong self- or inquiry-based learning and an appreciation for experimentation; and strengthened the link between industry and academia through project-oriented learning.

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