THE INVERTED/INTEGRATIVE/OPEN LAB COURSE: A MECHANICAL ENGINEERING LAB EXAMPLE

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Abstract –Based on the CEAB investigation attribute requirements, the Laval University Mechanical Engineering department has entirely modified its philosophy regarding the lab course. This course is now based on teamwork projects that take place throughout the semester. Different experimental setups are available to accommodate up to 20 teams of three students on a 24h/7d schedule. This paper offers some examples of lab benches and problems designed for this approach. To begin, student teams must describe the apparatus on which they will conduct an investigation and propose a problem they intend to study. Next, teams present theoretical background and a literature review. They determine the physical quantities to be measured and describe the measuring instruments to be used. Then, they plan and prepare a test campaign, including development of their own data acquisition, control and processing programs using LabVIEW. Finally, teams conduct their test campaign, analyze the results (including detailed uncertainty analysis) and report on their findings.

Keywords: lab course, inverted course, integrated course.

1. INTRODUCTION

Mechanical engineering (ME) is an engineering discipline characterized by an extremely wide range of applications. Many ME applications require control of parameters or mechanisms based on measurement and analysis of various physical quantities. From factories to home environments, from airplanes to video game controllers, from magnetic resonance imaging devices to ear thermometers for babies, our everyday life is full of problems requiring measurement, analysis and control. This is why experimentation is so important in the curriculum of a mechanical engineering program.

In the early 2000s at Laval University, we implemented a new course in our four-year undergraduate program in mechanical engineering. This required third-year course, called “Introduction to measurement technique and mechatronics”, explores the physics of active sensors, static and dynamic calibration processes, basic electronics,

uncertainty analysis, data acquisition and processing. It also focuses on the measurement of physical quantities such as temperature, pressure, flowrate, force, torque, deformation, position and vibration. Its structure is 50% classical lectures (based on [1]) and 50% basic hands-on labs. The labs are designed to build a strong and structured knowledge base covering LabVIEW programming, data acquisition, some electronic basics, static and dynamic calibration methods, and use of temperature, flowrate, position and force sensors. On completion of this course, students are well prepared for the lab courses to come in fourth year.

Before 2010, our ME program included two fourth-year lab courses, one in the domain of thermal-fluid sciences and the other on mechanical systems. Each course was worth two credits and included seven different experiments. These were based on the usual formula asking students to follow the steps of a provided lab protocol, gather data on an existing experimental system (under the supervision of a teaching assistant), analyze these data according to given instructions, interpret the results and report their conclusions. From a training point of view, the classical lab structure is not considered to be terribly rewarding for students – a bit like watching a travel video instead of going on a backpacking trip. Once the third-year measurement course had been implemented, we decided in the early 2010s that we would completely revamp our fourth-year labs.

At the same time, the CEAB [1] implemented the 12 graduate attributes for evaluation of Canadian engineering programs. Among these, the third and fifth attributes are *Investigation* and *Use of engineering tools*, which the CEAB defines as follows:

Investigation: An ability to conduct investigations of complex problems by methods that include appropriate experiments, analysis and interpretation of data, and synthesis of information in order to reach valid conclusions.

Use of engineering tools: An ability to create, select, apply, adapt, and extend appropriate techniques, resources, and modern engineering tools to a range of engineering activities, from simple to complex, with an understanding of the associated limitations.

Our new fourth-year course is designed to target these two CEAB attributes. The following sections present how the new fourth-year lab course is structured, what experimental facilities are used, how the course flows and how students are evaluated in order to assess their competence in the two attributes defined above.

2. DESCRIPTION OF THE LAB COURSE

2.1. A New Course Structure

As mentioned above, undergrad lab courses can be a bit like watching a travel video instead of going on a backpacking trip. But after completing the required measurement course in the third year of their ME program, we consider our students to have packed their bags with enough basic knowledge to equip them for a much more interesting voyage. Our goals in designing our new lab are to allow fourth-years to get deeply involved in the preparation and execution of a project so that they can trek through the different stages of their own well-planned journey and then enjoy the excitement of recounting their expedition to fellow students. With these goals in mind, the new lab course has the following characteristics:

- 1- It is a 4-credit course based on a semester-long, 3-member team project;
- 2- The working load is defined as 12h/week per student, or 36h/week per team;
- 3- Each team works on the same experimental setup for the whole semester;
- 4- There are no classroom lectures and facilities are available on a 24h/7d schedule;
- 5- A team of consultants (including 1 professor, several graduate students, 2 mechanical engineers, 1 electronic technician and 1 mechanical technician) are made available throughout the semester to guide the teams and to answer questions;
- 6- Each consultant interacts through a forum (a private forum for each team) when students seek their advice; the consultant can directly answer on the forum or visit the team at the facility;
- 7- The first task for the team consists of making a technical description of their setup and apparatus, to propose a problem they intend to study using the experimental approach and to present theoretical background and a literature review;
- 8- The team must determine the physical quantities to be measured, describe the measuring instruments to be used and plan the appropriate calibration method for the different sensors;
- 9- The team must plan and prepare a test campaign which includes the development of their own data acquisition, control and processing programs with LabVIEW;

10- The team must conduct their test campaign, analyze the results (including detailed uncertainty analysis), and report their findings.

The originality of the present course concept relies on the fact that the teams themselves propose the problems they intend to investigate. Further, they must advance on their own and ask for support when they need it. The workload is significant (a total of 36 h/week per team or 12 h/week per member) and the projects are defined in that respect. The course flow presented in section 2.3 will illustrate in more detail how teams conduct their projects.

2.2. Development of the Experimental Facilities

The implementation of this course structure is very demanding on human and material resources. Human resources include each semester's team of consultants. Material resources include development of the assemblies, electro-mechanical components, PC and DAQ boards, instruments and sensors. The experimental facilities specifically developed or adapted for this purpose are listed in Table 1.

The 15 facilities used in the lab course are all mounted and set up the same way: equipped with a dedicated PC, a DAQ board, necessary sensors and instruments. The instruments are mounted on a panel specifically designed to show all of the electronic components and their corresponding wiring. The facilities are built in such a way that the mechanical assemblies are as visible as possible in order to allow the students to make a detailed description of their experimental setup.

Fig. 1. Control of the load oscillations on a tower crane model.

Table 1: List of the 15 experimental facilities and the physical quantities that can be measured at each facility.

Facility	Physical quantities
Performance of pumps in serial or parallel	Angular velocity, flowrate, weight, torque, temperature, pressure
Design and testing of centrifugal pumps	Angular velocity, flowrate, weight, torque, temperature, pressure
Design and testing of aircraft propellers	Angular velocity, pressure, force, torque, air velocity, temperature
Minor pressure loss evaluation in pipe systems	Flowrate, weight, temperature, pressure, position
Race car aerodynamics	Linear velocity, pressure, force, air velocity, temperature
Diesel motor testing bench	Angular velocity, pressure, torque, temperature, weight
Brake testing bench	Angular velocity, pressure, torque, temperature
Vibration control of a beam	Acceleration, position, time (real time processing)
Performance of a parallel heat exchanger	Flowrate, temperature
Control of load oscillations on a crane model	Position, strain, acceleration
Dynamic balancing of a rotating shaft	Acceleration, position, weight
Performance of a vehicle radiator	Flowrate (air and water), pressure, temperature
Drag measurement of a cylinder in a wind tunnel	Pressure, force, air velocity, temperature, position
Sort, pick and place bench	Position (computer vision)
Control of a rotational inverted pendulum	Position, acceleration

On each PC is a dedicated directory containing pdf files of the spec sheets for all instruments, sensors and controllers used in a given facility.

As a first student project example, Figs. 1 and 2 illustrate a tower crane model. This facility was created to test different strategies for controlling load oscillations while the trolley and/or the jib are moving. The crane can be operated either by use of joysticks or by addressing the controller with various commands specified by a computer program. As shown in Fig. 2, four micro servo motors are used to control the moving parts of the crane as follows: 1- the turntable mechanism at the top of the tower allows rotation of the jib, 2- the drum and winch mechanism at the end of the counter-jib allows lifting of the load, 3- the counterweight mechanism along the counter-jib allows nulling of the bending moment at the tower base, and 4- the trolley mechanism along the jib allows travelling of the load in the radial direction. The hook is instrumented with

a 3D wireless accelerometer and gyroscope, allowing study of load oscillations in real time.

An important issue related to the crane integrity is the fact that a bending moment is generated when a load moves along the jib away from the tower. To fix that problem, a load cell, specifically designed to support the jib and counter-jib suspension cables, is located at the top of the apex. Use of this load cell allows nulling, in real time, of the bending moment at the tower base. The bending moment is nulled by translating a counterweight along the counter-jib as the load moves. This is accomplished through programming a PID controller based on the load cell signal.

Fig. 2. Tower crane details: instrumented hook, turntable mechanism at the top of the tower (motor 1), drum and winch mechanism at the end of the counter-jib (motor 2), counterweight mechanism along the counter-jib (motor 3) and trolley mechanism along the jib (motor 4).

When the tower crane can be operated securely (i.e. the students have implemented a good PID controller for the counterweight), the students can investigate the different strategies for control of load oscillations.

A second student project example is shown in Fig. 3. This facility was created to investigate minor pressure loss in a series of pipe components and fittings. The three-member team seen in Fig. 3 were interested in the determination of pressure-loss coefficients K_L through elbows, a sudden contraction, a sudden expansion, ball, globe and gate valves. They calibrated an orifice flowmeter using the classical weight and time method and compared their results to those obtained from ISO specifications and guidelines. They fixed the pump angular velocity through

an electronic controller, in order to study the influence of Reynolds number on K_L results. The weighting system used two load cells which were calibrated by the team members using traceable weight sets. This allowed performance of a detailed uncertainty analysis, a crucial part of any experimental process, as presented by [2] and [3].

Fig. 3. Experimental setup used for the evaluation of minor pressure loss in pipe components and fittings.

Fig. 4. Sorting and pick-and-place experimental facility.

A third example is shown in Fig. 4. This facility was created to perform sorting and pick-and-place with different objects. A 3D positioning table with four step motor controllers (x, y, z directions and rotation of the

grabber) and a vision system composed of two video cameras offer possibilities for building a wide variety of experiments. This facility offers students a great opportunity to get familiar with the world of computer vision.

Another example is shown in Fig. 5. This facility was created to investigate the aerodynamics of a race car.

Fig. 5. Race car aerodynamics: model mounted on an aerodynamic sting balance over a moving belt inside the test section of a wind tunnel.

A race car model (3D print of a FSAE made by the students) is mounted inside the test section of a wind tunnel. The model is located over a moving belt representing the road. From the reference frame of the car, the belt moves just like the road, travelling backward when an observer looks at it through the window. This is an important feature for studying ground effects underneath the car. The wheels are entrained by the moving belt and are carefully positioned to avoid any contact with the car (Fig. 5). This ensures that the model is only supported by the aerodynamic sting balance and that, apart from aerodynamic forces, there are no other external forces acting on it. Drag force and downforce are measured simultaneously to evaluate the effect of different add-ons. The students involved in the FSAE project are very interested in this facility. They can use their experimental results to validate CFD simulations often conducted in their FSAE project.

A last example is presented in Fig. 6 with a brake test bench. This facility was developed to investigate the performances of brake discs and pads. A rotational inertial load is entrained by an electric motor and a disk brake can decelerate it. The idea is to impose acceleration and inertia with the motor controller in order to simulate the behavior of a small race car on a given track. The brake disc and pad performances can be investigated through various measurements such as brake torque, caliper pressure, and pad temperature. Here again, many different configurations can be tested, and students involved in the Baja and FSAE projects are very interested in this facility.

Fig. 6. Experimental setup used for the evaluation of brake disc and pad performance

2.3. Course Flow and Evaluations

Evaluation of the lab course is based on a midterm report (20%, week 7), an individual presentation (20%, week 12), a final team presentation (20%, week 15), a final report (35%, week 15) and four follow-up meetings (5%, weeks 3, 6, 10 and 14).

The 15 weeks of the semester (plus 1 week at the end called “exam week”) are typically structured as shown in Table 2. Description may vary from one project to another.

Each Friday, a two-page activity report must be filled out and submitted. On the first page of the report are two tables. The first table describes tasks accomplished by the three team members that week, including the number of hours spent on each task. The second table describes the tasks to be accomplished in the week to come. On the

second page of the report, the team includes an up-to-date Gantt diagram of the whole project. Each team can expect to invest a total of about 36 hours per week (12 hours per week per team member). For the project, this totals about 540 hours of time investment. The Gantt diagram should always reflect this fact. These activity reports are analyzed by the professor during the follow-up meetings scheduled for each team.

Table 2: Typical weekly activities of the lab course.

Week	Activities
1	Start of the project: team formation, facility assignment and visit, reading of the different documents on the course web site, exploration of the spec sheet directory, first Gantt diagram.
2	Project proposal, description exp. setup (mechanical assemblies and electronic setup), literature review.
3	Follow-up meeting Literature review (cont.), description exp. setup (cont.), list of all physical quantities to be measured, preparation of the exp. protocol, list of sensors to be calibrated, reading of spec sheets, LabVIEW prog. sensor calibrations.
4	LabVIEW prog. sensor calibrations (cont.), reading of spec sheets (cont.), sensor calibrations (data acquisition)
5	Sensor calibration processing and analysis, writing of the midterm report, list of all the equations used.
6	Follow-up meeting Sensor calibration processing and analysis, LabVIEW prog. experiments, writing of the midterm report (cont.)
7	Midterm report LabVIEW prog. experiments (cont.)
8	LabVIEW prog. experiments (cont.), experiments.
9	Experiments (cont.).
10	Follow-up meeting Experiments (cont.), data processing and analysis.
11	Experiments (cont.), data processing and analysis (cont.), uncertainty analysis.
12	Individual presentation and visiting team Experiments (cont.), data processing and analysis (cont.), uncertainty analysis (cont.), writing of the final report.
13	Experiments (cont.), data processing and analysis (cont.), uncertainty analysis (cont.), writing of the final report.
14	Follow-up meeting Data processing and analysis (cont.), uncertainty analysis (cont.), writing of the final report (cont.).
15	Data processing and analysis (cont.), uncertainty analysis (cont.), writing of the final report (cont.). End of the project
16	Final presentation, final report

At week 12, a session of individual presentations is scheduled. At this time, the projects are sufficiently advanced for the students to make a presentation. Each student must present the project in situ (i.e. in the lab, running the experiment live, in the facility) to visiting teams. Several presentations run in parallel in different rooms for two days. Each team member must give an individual presentation as well as attending five different presentations in the role of visiting team member. This exciting session gives students the opportunity to see the work accomplished by their colleagues and the nature of the different projects. It is not unusual to see students visiting seven or eight facilities.

3. CONCLUSION

The structure implemented for this new lab course offers several advantages:

- 1- Since it is the students themselves who choose their project, they embrace the work and master the use of their experimental setup; the outcome is that they possess the CEAB *use of engineering tools* attribute.
- 2- Since the projects are always different, the probability of plagiarism is clearly reduced.
- 3- Students must advance on their own and ask for support when they need it; the outcome of this philosophy is that the *investigation* attribute plays a crucial role in the project progress.
- 4- Professor and assistants are highly stimulated by the results of the investigations and by novel solutions proposed by students during their projects.
- 5- At the end of their project, students are excited about the opportunity to share their experience and to visit the other teams to see their accomplishments.

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