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Challenges and Logistics in Flipping a Large Classroom for Junior-year Mechanical Vibrations

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Challenges and Logistics in Flipping a Large Classroom for Junior-Year Mechanical Vibrations

A junior-year Mechanical Vibrations course with 110 students was "flipped" to increase student engagement and learning outcomes. Each week, a gapped notes handout was created. Theory and derivation videos were generated using open-source software and a tablet PC. A qualitative comprehension quiz was administered using the online course shell through which the students accessed the videos. The homework assignment was posted at the same time as the videos, and was due one week later. During the first of two 75-minute lecture slots, the instructor completed examples related to the video topics. The second lecture slot was for student-directed homework problem solving. As a partial control, the final course module was delivered in the traditional manner. Students reported a strong preference for moving the theory and derivations out of lectures, and an overall preference for the flipped course format.

The biggest challenges were 1) instructor's perception of diminished connection to the class through not being physically present for the motivational and explanatory material, 2) finding optimum complexity for worked examples, 3) higher workload to generate content during the first offering, and 4) student perceptions of increased workload. Recommendations include incorporating small worked examples into the videos, to allow for more complex examples to be done live by the instructor for each topic; and for the student-directed problem-solving lectures to be somewhat structured, with 1-2 common homework problems worked simultaneously by all. Additional recommendations for generating flipped course content are given. Overall, the instructor's experience and student feedback confirm that a flipped format is compatible with, and has impact on student engagement in, high-enrollment, mathematically-intensive upper-year engineering courses.

Introduction and Motivation

Traditionally, engineering education has been characterized by one-way information flow from an expert faculty member to a passive classroom audience. Gauging student understanding is difficult, especially in large classes, due to the relatively small number of students who ask questions. Lecture time remaining after delivery of theory is usually devoted to instructor-worked examples, with the expectation of students following the explanations in real time. Missing from the lecture experience is the students attempting to solve problems with the instructional team present for coaching. In the interests of time, we leave the students to work on harder problems after hours, subject to a deadline. Students often leave homework until the last minute, resulting in a large gap between the associated lectures and the first attempts to work an example independently.

Students need the instructor the most, and the instructor can add the most value to their learning process, during late study nights when they are trying to get started on problems for the first time[1], or trying to move beyond the template of less-involved worked examples from lecture. Assuming instructors are not available then, how can they inject their expertise into the student learning process, given the limited contact time?

The author feels that he does most of his teaching during office hours, to people who have gone to lecture, re-read their notes, and tried a problem unsuccessfully. Then they ask targeted questions, and in the ensuing discussion they learn something. Office hours, and small-group problem solving in extra tutorial periods if the course schedule permits, reveal specific sources of student confusion. Given the potential for instructors to have an "expert blind spot"[2], it is critical for us to hear from the students exactly why, for example, drawing the relative acceleration vector of two points on a rigid body is confusing - we *may* remember that we found it hard, but likely we don't remember exactly why. The shift from "sage on the stage" teaching to "guide on the side" student-centred learning[3] requires observation of student struggles - not only to help the affected student, but also to tailor subsequent lectures to the real-time needs of a specific class.

A Winter 2015 mechanical engineering undergraduate student symposium at the author's institution unearthed widespread student desire for faculty to reduce the amount of lecture time spent on theory, and to increase the number of worked examples. This is a contentious issue with faculty who are motivated by their professional standards (as well as by accreditors) to equip students to synthesize solutions to unfamiliar real-world problems, and to engage in life-long learning after graduation[4].

The answer to these challenges lies in the "flipped" lecture format[5,6,7], in which students gain technical knowledge through readings and/or online videos (often with an assignment to verify watching and understanding of the video), and then actively participate in class through problem solving, discussions, and field trips.

As at many institutions, the majority of engineering courses at the author's university follow the traditional format, and students expecting to sit passively in lectures. When the author has used flipped tutorial periods within a passive lecture course, or attempted to flip a single lecture or small subtopic, approximately 20% of students actually participate. While that minority can provide valuable information about class-wide struggles, the majority do not benefit from the proximity to the instructor during a problem-solving opportunity. Students often confuse the ability to read and understand worked examples (especially from increasingly-common pirated solution manuals) with having depth of understanding sufficient for independent problem solving. The inherent motivation to solve problems on their own prior to an evaluation instrument is missing. As a result, the author was strongly motivated to flip an entire course, with the new format being applied consistently, and expectations stated clearly, from the first lecture onwards.

Foreseeable Challenges

The flipped course would be the first such offering in the authors department, and as such would be disruptive to student expectations of the lecture experience. In "testing the waters" for student attitudes towards a flipped course, the author conducted a Winter 2012 survey of junior-level machine design students. The survey, to which 58 of 80 students responded, assessed their satisfaction with the traditional lecture format. The last concept in that course was taught in a flipped manner, with student participation bolstered by an agreement that the material would not appear on the final exam if the students demonstrated proficiency through solving examples in class in small groups. The survey results relevant to flipped lectures are provided in Appendix A, and the following conclusions were drawn:

1. Students self-report understanding material as it is presented in lectures, but admit to having to re-read their notes later to understand what was done (Appendix A, Questions 1, 8). This suggests a need for theoretical explanations to be accessible for students to “rewind” and absorb at their own pace.
2. There was disagreement that lectures should focus on theory rather than worked examples (Question 2).
3. Students are not dissatisfied with passive lectures, with no strong agreement that copying examples in lecture is burdensome or an impediment to understanding (Questions 3, 4). However, students indicated an interest in working on examples in lectures (Question 7).
4. Students were polarized on the issue of having to do assigned readings, so lectures could focus on asking questions and doing problems. This foreshadows student resistance to a flipped course that becomes “a course and a half” (Question 9).
5. There was agreement that the template for all topics should follow the flipped machine design course module: introduction and theory, followed by simple worked examples, and ending with students doing problems on their own, with guidance (Question 11).

The primary challenges prior to a new flipped course offering were identified as

1. Student resistance to a new format due to entrenched attitudes surrounding the lecture experience.
2. The fact that the course would be the only flipped course in the students’ 5-6 course load.
3. Creating a problem-solving session that would allow students to work at their own pace.
4. Timing videos and apportioning lecture time so that students would not feel that the course content was going beyond what was appropriate for a 3 credit-hour course.
5. Recognizing that some students simply do not need to avail of problem-solving sessions or instructor assistance.
6. Motivating students to watch the videos, in an institutional culture where pre-lecture assigned readings (or assigned videos) are unusual.

Choice of Course

Mechanical Vibrations is a compulsory fourth year course taken by approximately 80 Mechanical and 30 Ocean and Naval Architectural Engineering students in their sixth of eight academic terms in a co-op program. Lecture slots were 9:00-10:15 Tuesdays and Thursdays, with no extra tutorial period. A laboratory slot was scheduled from 2:00-5:00 Tuesdays. This was the author’s first time teaching the course. The previous instructor, one of the department’s most senior and respected teachers, reported an unprecedented lack of student engagement, interest and effort in Fall 2014 compared to his multiple previous offerings. Here, then, was a course where innovative delivery methods to increase active learning were motivated, and for which the author did not have existing traditional course materials that he was tempted to recycle. There is little prior reported work on the flipped classroom in Vibrations, with most mechanics-stream implementation of the method having been done for Statics[1,6], with some reports of partial implementation in Dynamics[8,9].

Infrastructure

The author's institution has adopted the Desire2Learn® ("D2L") online teaching and learning platform, via which most courses have "D2L shell" web pages for instructor postings, gradebooks, homework submission, quiz administration, and discussion boards. Students are accustomed to logging into D2L for other courses, so use of this tool does not introduce any overhead from a student perspective.

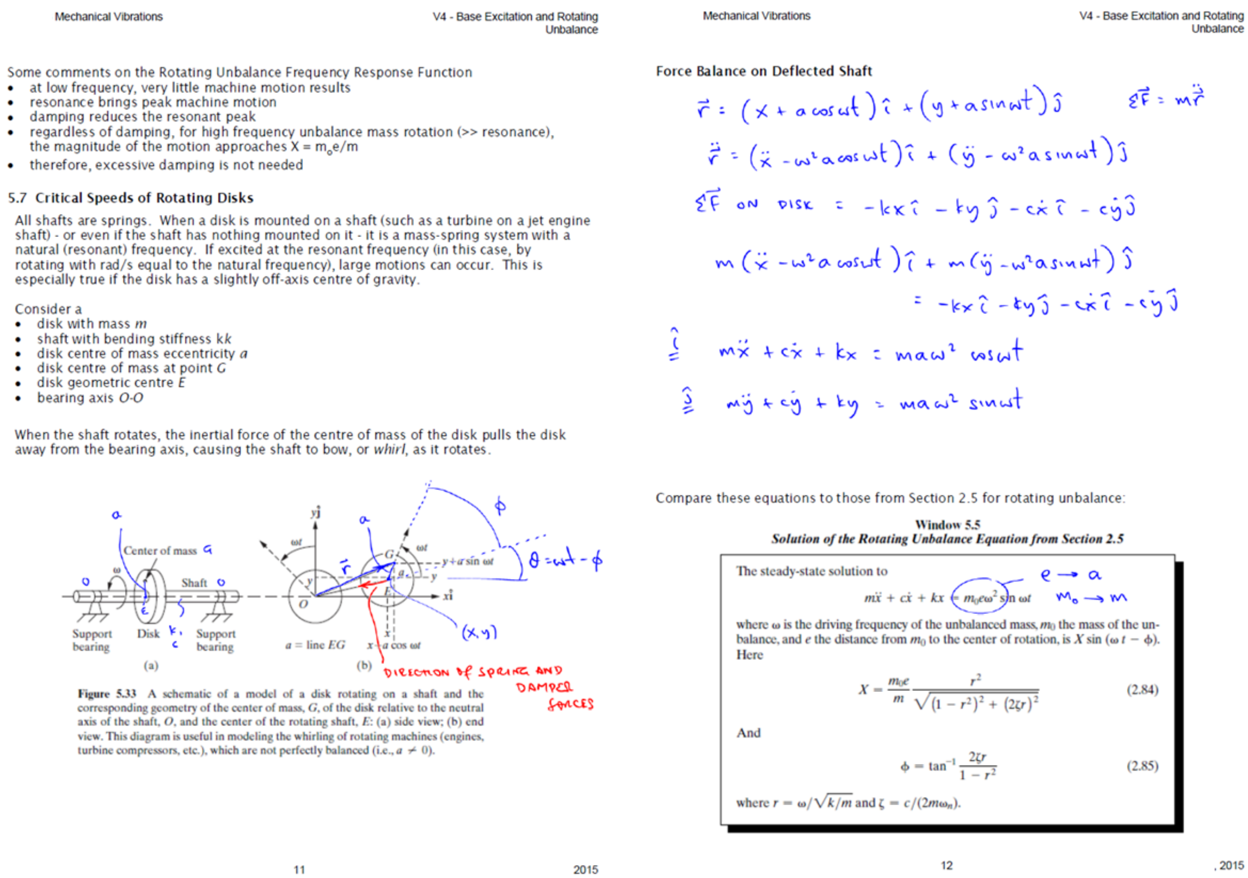
To generate explanatory videos and fill in gapped lecture notes for easy web posting, the author uses a Windows-based tablet PC with open-source CamStudio® and PDF Annotator® software. PDF Annotator allows the user to write directly on PDF documents with a variety of pen colours and thicknesses. CamStudio overlays voice narration with screen recording of any open application. The author prepared gapped handouts as PDF documents, and then recorded narrated annotation of the document. The gapped handouts, with and without annotations, were posted on the D2L shell along with a link to the video, which was uploaded to YouTube as an unlisted but public video with viewer comments disabled. Students could print out a gapped handout and fill it in while watching a video, or simply watch and absorb the video material with the annotated handout in front of them.

Notes handouts were done in Mathcad® v. 15, which allowed equations to be entered as math objects, so that they could be cut and pasted when generating new problems and their solutions; or cut and pasted into the instructor-provided formula sheet prior to the test and exam. The Mathcad files were converted to PDF and printed. Before making the videos, the gaps were filled in roughly, by hand, as a final proof-reading for flow, and to determine which gaps needed to be resized. This "dry run" for the narrated videos allowed most videos to be done in one take. Microsoft Windows Movie Maker® was used to cut out and/or insert video clips for any portions requiring a second take. Figure 1 shows a sample of gapped handout pages after annotation.

The laboratory session was devoted to solution and numerical simulation of practical vibration problems using Matlab's *ode* suite of numerical integrators. Laboratory instructions, sometimes with YouTube videos, were posted prior to the session. Students, if they desired, could complete the lab outside of school, and come to the lab session with questions.

Delivery and Scheduling

Total scheduled lecture time was 2 x 75 = 150 minutes. Therefore, total video time was restricted to approximately 75 minutes, so that students watching on their own time would be spending the equivalent of one lecture slot doing so. Given previous studies showing that students are more likely to prefer watching videos to live lectures if the videos are shorter[7], the target video segment length was 10-15 minutes. Appendix B summarizes the subtopics and video lengths for the course. This resulted in a typical assignment of 4-5 video segments per week.



Mechanical Vibrations — V4 - Base Excitation and Rotating Unbalance

Some comments on the Rotating Unbalance Frequency Response Function

- at low frequency, very little machine motion results
- resonance brings peak machine motion
- damping reduces the resonant peak
- regardless of damping, for high frequency unbalance mass rotation (>> resonance), the magnitude of the motion approaches $X = m_o e/m$
- therefore, excessive damping is not needed

5.7 Critical Speeds of Rotating Disks

All shafts are springs. When a disk is mounted on a shaft (such as a turbine on a jet engine shaft) - or even if the shaft has nothing mounted on it - it is a mass-spring system with a natural (resonant) frequency. If excited at the resonant frequency (in this case, by rotating with rad/s equal to the natural frequency), large motions can occur. This is especially true if the disk has a slightly off-axis centre of gravity.

Consider a

- disk with mass *m*
- shaft with bending stiffness k*k*
- disk centre of mass eccentricity *a*
- disk centre of mass at point *G*
- disk geometric centre *E*
- bearing axis *O-O*

When the shaft rotates, the inertial force of the centre of mass of the disk pulls the disk away from the bearing axis, causing the shaft to bow, or *whirl*, as it rotates.

Figure 5.33 A schematic of a model of a disk rotating on a shaft and the corresponding geometry of the center of mass, *G*, of the disk relative to the neutral axis of the shaft, *O*, and the center of the rotating shaft, *E*: (a) side view; (b) end view. This diagram is useful in modeling the whirling of rotating machines (engines, turbine compressors, etc.), which are not perfectly balanced (i.e., $a \neq 0$).

11 — 2015

Mechanical Vibrations — V4 - Base Excitation and Rotating Unbalance

Force Balance on Deflected Shaft

$$\vec{r} = (x + a\cos\omega t)\hat{i} + (y + a\sin\omega t)\hat{j} \qquad \Sigma\vec{F} = m\ddot{\vec{r}}$$

$$\ddot{\vec{r}} = (\ddot{x} - \omega^2 a\cos\omega t)\hat{i} + (\ddot{y} - \omega^2 a\sin\omega t)\hat{j}$$

$$\Sigma\vec{F} \text{ ON DISK} = -kx\hat{i} - ky\hat{j} - c\dot{x}\hat{i} - c\dot{y}\hat{j}$$

$$m(\ddot{x} - \omega^2 a\cos\omega t)\hat{i} + m(\ddot{y} - \omega^2 a\sin\omega t)\hat{j} = -kx\hat{i} - ky\hat{j} - c\dot{x}\hat{i} - c\dot{y}\hat{j}$$

$$\hat{i}: \quad m\ddot{x} + c\dot{x} + kx = ma\omega^2\cos\omega t$$

$$\hat{j}: \quad m\ddot{y} + c\dot{y} + ky = ma\omega^2\sin\omega t$$

Compare these equations to those from Section 2.5 for rotating unbalance:

Window 5.5
Solution of the Rotating Unbalance Equation from Section 2.5

The steady-state solution to

$$m\ddot{x} + c\dot{x} + kx = m_0 e\omega^2 \sin\omega t \qquad e \to a \quad m_o \to m$$

where ω is the driving frequency of the unbalanced mass, m_0 the mass of the unbalance, and e the distance from m_0 to the center of rotation, is $X\sin(\omega t - \phi)$. Here

$$X = \frac{m_0 e}{m}\frac{r^2}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}} \qquad (2.84)$$

And

$$\phi = \tan^{-1}\frac{2\zeta r}{1-r^2} \qquad (2.85)$$

where $r = \omega/\sqrt{k/m}$ and $\zeta = c/(2m\omega_n)$.

12 — , 2015

Figure 1 - Samples of Gapped Handouts (with Narrator Annotations)

Videos were posted on Fridays. To ensure students watched the videos, the "Quiz" feature of D2L was employed. Quizzes with approximately 6 qualitative questions were posted along with the videos, with a completion deadline of Tuesday, 9AM - the beginning of the first scheduled lecture slot. These quizzes were worth a small percentage of the total overall course grade, and this was likely responsible for the high uptake of the videos[6]. The homework assignment for the week was also posted on Friday, with a deadline of the next Friday.

The 75-minute Tuesday lecture slot was devoted to the instructor working examples. The "Worked Example Lecture" began with a call for questions on the theory videos, and a brief recap of the concepts and figures that would be referenced during the subsequent examples. A document containing several problem statements was posted in advance of the Worked Example Lecture. The author worked through as many as possible (depending on student questions and resulting sidebar discussions), with increasing complexity. The solutions to all examples were posted on the D2L shell, including those that were not worked in lecture.

The other scheduled (Thursday) lecture slot was used for student-led problem solving, with three teaching assistants (TA's) present along with the instructor. Students who attended the "Problem Solving Workshop" were simply prompted to begin working on the homework problem of their choice. Students were also given the option of working on, and asking questions about, their laboratory exercise (also due on Friday). This is in contrast to some other delivery methods[6] in which the instructor works problems after which the students work on specific problems chosen by the instructor.

These sessions were "attendance-optional", given that the students had already participated in 150 minutes of course material. Normally students would work on homework after hours. Moving homework facilitation into the class time gave students a scheduled, yet optional work slot that was attractive because their peers and the instructional team would be available. Attendance was varied (Figure 2), but strong overall except for one session where the problems were not related to graded homework. Students seemed to realize that time spent in the Workshops would save work later, given that the homeworks were worth a significant portion of the course grade. The weighting applied to the homeworks was higher than the typical department norm, to ensure student participation in the new format. The assignments were consistently due each week at the same time. Table 1 gives the course grading scheme.

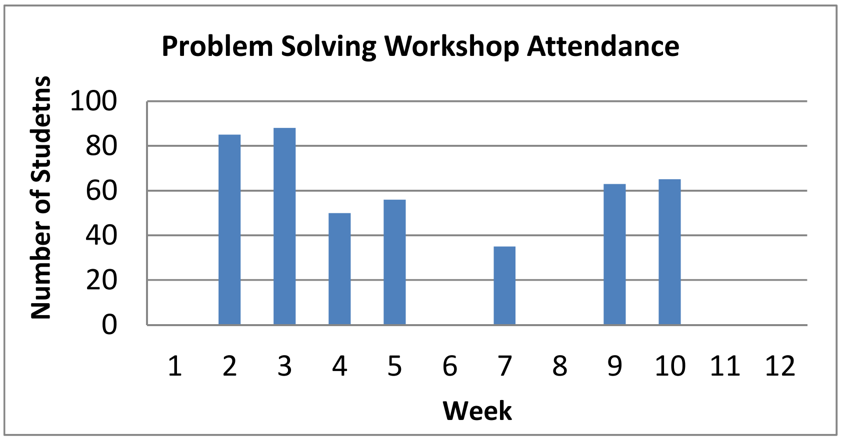


Figure 2 - Problem Solving Workshop Attendance (Total Enrollment 110)

Week 1 consisted of only one introductory lecture. Weeks 6 and 8 saw the Workshop replaced with a term test and an industry guest speaker. Week 11 did not have a Workshop because the final topic was delivered in the traditional manner. Week 12 was devoted to a classroom demonstration related to the author's research.

Table 1 - Grading Scheme

Assessment	Scheme A	Scheme B
Video Comprehension Quizzes	5	5
Homework Assignments	15	15
Labs	10	10
Term Test	25	10
Final Exam	45	60

Office hour traffic revealed that many students began the homework after the Worked Example Lecture or before, so that by Thursday they were working on the few remaining (typically most challenging) problems and could ask targeted questions of the instructor and TA's. Also, the homework due date ensured there was no overlap with the next topic. Homework deadlines were therefore firm. Figure 3 shows the weekly schedule. Office hours (1.5 hours) were held Monday mornings to address questions in the immediate aftermath of the videos, and to help those beginning the assignment. An additional 1.5 hour office hour session was held on Thursdays to help those not reached in the Problem Solving Workshop.

Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
				Quiz n closed			
			Office hours	Worked Example Lecture		Problem Solving Workshop	
Homework $n-1$ due							Homework n due
Laboratory n-1 due							Laboratory n due
Video n posted							Video n+1 posted
Homework n posted				Laboratory n		Office hours	Homework $n+1$ posted
Quiz n posted							Quiz $n+1$ posted

Figure 3 - Weekly Schedule

Challenges, Mid-Term Feedback and Adjustments

The author found the time commitment in developing the course to be even greater than anticipated. As there was not time to generate a significant portion of the content prior to the semester, a typical week consisted of

- reading the text and generating notes handouts Tuesday through Thursday (4-8 hours)
- generating videos Thursday and Friday (2-4 hours)
- developing comprehension quiz Friday (1-2 hours)
- office hours (typically 1.5-2 hours of student traffic per week)
- selecting and generating solutions to Tuesday worked examples (2-4 hours)
- conducting Tuesday and Thursday sessions (3 hours)
- web posting (1 hour)
- course-related email (1-3 hours)
- laboratory sessions (total of 4 labs + two-week analysis project)
    - content development (4-6 hours per lab)
    - facilitating lab session (2.5 hours)

A worst-case scenario week would then involve in excess of 30 hours. The lecture preparation time will not be required in future offerings, leaving more time to evolve the assessments and in-class examples.

Despite the instructor's efforts to work the most multi-faceted text examples, and to add additional parts to the questions, there was widespread student concern that the worked examples did not prepare them for either the more difficult homework problems or for the test. The instructional team noted a difficulty in the TA's answering all student questions in the Workshops, and in transitioning between student questions. While the TA's understood the solutions, it was difficult to help Student A who had done partial incorrect workings on Question 1, move on to Student B at an arbitrary stage of Question 7, and so on for the entire session.

A small-group feedback session[10] was held after the term test. The videos were positively received, as was the opportunity to work on problems in scheduled lecture time. Negative feedback focused on overall course workload, and the complexity of the worked lecture examples. Some students were frustrated in trying to get sustained help on Thursdays. There was class-wide consensus for focusing on a small number of specific homework problems in the Workshops. After the test, the difficulty of the homework problems was maintained; however, the number of questions to be submitted for credit was reduced. This allowed Thursday sessions to be devoted to 1-2 problems, facilitating TA preparation, peer interaction (there was a better chance of a student's neighbours having the same difficulty), and grading.

Students later in the semester reported spending a disproportionate amount of time on Vibrations, at the expense of other courses, early in the term. This was originally thought to be due to an accelerated pace of delivering course modules; however, the normal number of topics was covered by the end of the course. The schedule of course topics is given in Appendix B. When surveyed, 80% of students agreed that the video lectures "present[ed] a reasonable amount of information at an appropriate pace." Of their 5-6 courses, Vibrations was the one most likely to require sustained early student effort, in contrast to courses without graded problem sets. If all courses followed the same format, it is possible that students would have managed their time differently. In addition to the small-group feedback, questions about the course experience were worked into the on-line comprehension quiz just after the test, with the results shown in Figure 4.

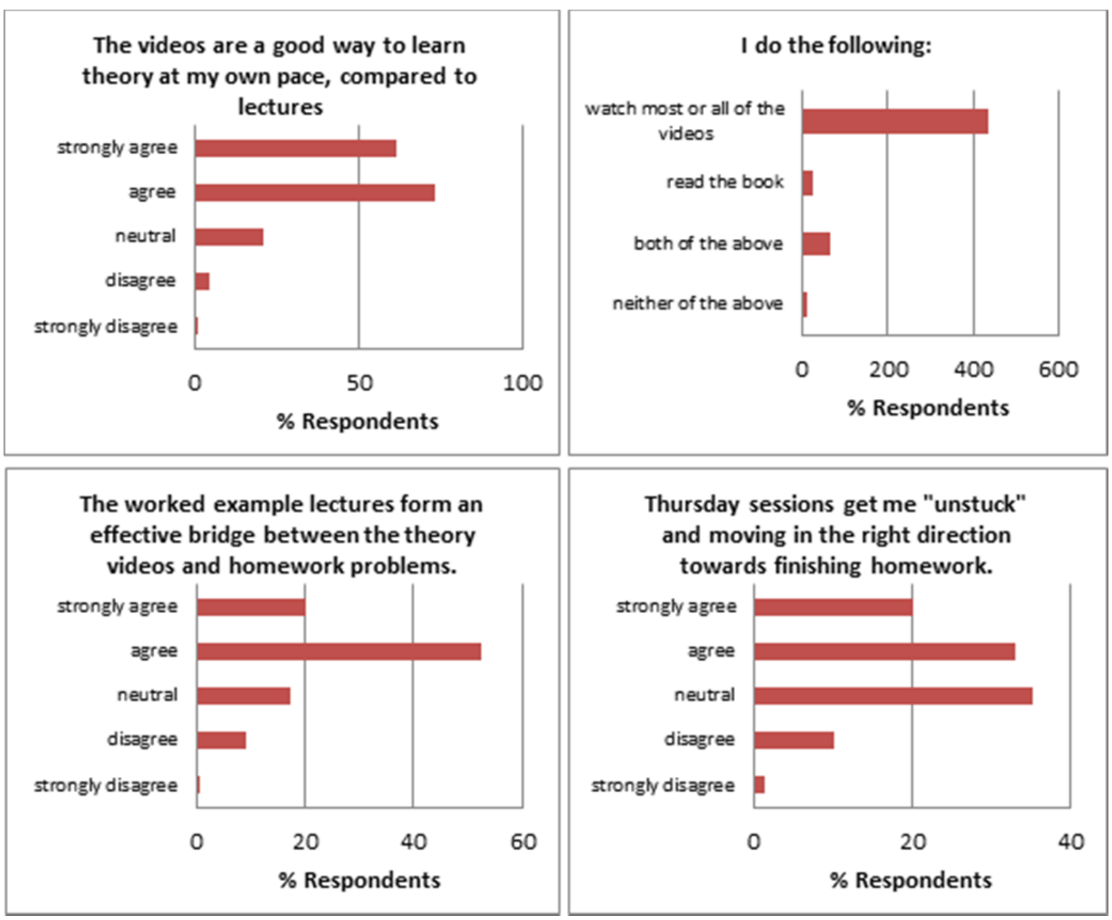


Figure 4 - Mid-Term Survey Results

Despite anecdotal evidence of student frustration with the level of test preparation, the mid-term survey shows a positive student attitude towards the format. Video uptake was very high. A moderate proportion of students did not feel they benefited from the Thursday sessions.

At the end of semester, the final on-line quiz was used to gather more feedback on the overall experience and on the efficacy of mid-term adjustments. Students were more satisfied that Tuesday worked examples were representative of test-calibre questions (3.49 on 5-point Likert scale), and largely neutral about the homework problems being more representative of test questions (3.11). The results from questions directly related to the flipped format are shown in Figure 5. The least satisfying response from the author's perspective is for the lower left question in Figure 5, indicating that students did not miss the problem-solving workshops in solving the final homework. The final homework was largely Matlab-based, closed-ended, and somewhat formulaic from a theoretical point of view. Students may not have required as much coaching as for earlier assignments. Flipping the classroom has reinforced for the author the critical role of assessment selection in exciting student passion [2], and in maximizing the opportunities for coaching in the instructor-student relationship.

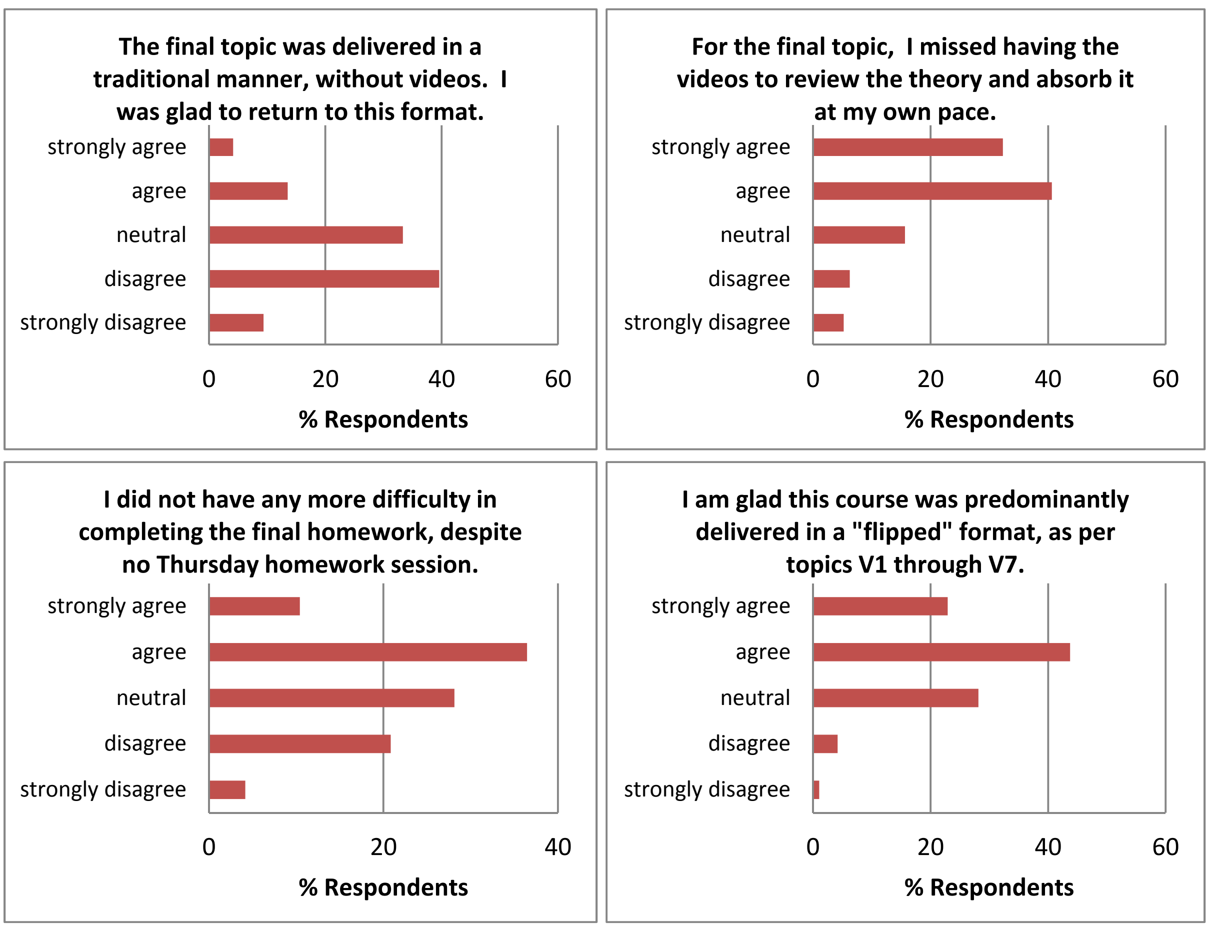


Figure 5 - Pre-Final Exam End-of-Semester Survey

Recommendations and Future Work

Given that the Mechanical Vibrations course is offered only once per year, with one lecture section, it is not possible to run a control section in the traditional manner to quantitatively assess outcomes. One possibility under consideration is to administer a concepts inventory test to students from the previous offering, and then offer the same test to the Fall 2015 students in one year. Such a test would measure the effect of the flip on depth of student learning. The flipped course average was 74.8, up from a previous 4-year average of 72.0, and the percentage of A grades was 35.0, up from 24.2 historically. While not proof of improved outcomes, this is promising given that the previous instructor has had similar grade distributions and course evaluation scores in two other courses that both instructors have taught. The 2014 instructor reported widespread student disengagement in that year, which was not apparent in the flipped 2015 course.

For departments with an entrenched culture of traditional "sage on the stage" lecturing, it is extremely important to clearly state expectations to students at the beginning, including being open about the motivation for the novel format. Consistency is important, so that the schedule for each week looks the same and things like watching videos, completing on-line quizzes, and completing homework by a certain day become habitual. Assigning marks to participation components will be a necessary extrinsic motivator as long as the problems are "textbook-style" or "exam-type" problems. Students must practice the fundamentals, and this is best done with closed-ended problems of manageable scope. However, students may not perceive that such problems are deeply meaningful or inspirational, even if effort is made to relate the problem to industry. The author is optimistic that student engagement in unstructured active problem-solving sessions would be higher in a course where the instructional team acted as coaches for larger, open-ended, societally impactful problems (ideally sourced by the students)[11].

When generating the videos for the first iteration of the course, the instructor was not cognizant from the very beginning of the need for modularity and independence of the video segments. A typical topic contained 3-5 videos (Appendix B), each 10-20 minutes in length. Summarizing the important points of the previous video at the beginning of the next seemed natural, given that instructors typically do this in live lectures. However, if the video needs to be replaced, or the subtopics rearranged, those references will be obsolete. Given the time required to create the videos, it is desirable to ensure that individual videos can be changed without causing a "domino effect" of having to edit all or portions of surrounding ones. The author offers the following video creation recommendations:

1. Use gapped handouts that do not reference other handouts or topics by specific name or number.
2. Avoid verbal reference to, for example, "the last video" or "Video 4a", and also avoid concluding the video with a foreshadowing of the material in the next.
3. If there is a need to reference another video, refer to it generically, e.g., "As seen in the Rotating Unbalance video..."
4. If you make a mistake or are unhappy with a derivation or explanation, do not stop the video recording and restart. Instead, pause briefly, erase any unsatisfactory annotations on the tablet, and resume. Then, during editing, a *deletion* of a portion of the video is all that is required instead of a potentially choppy *insertion*.

5. Worked examples should appear as separate short video files. If the example library grows, students are likely to appreciate this, especially if it does not make it appear that the “compulsory” theory videos are increasing in length.

In future, D2L quiz will allow the students to express the “muddiest point” so that the instructor can anticipate, prepare TA’s for, and address any widespread student confusion “just in time” for the next lecture[7]. Simulation-based visualization tools are motivated, where students can pause a video, open a relevant simulation, adjust parameters such as support stiffness, and see the effect on vibration response. A library of short worked-example videos will be built up to supplement lecture videos, thereby removing rudimentary examples from the classroom sessions. The homework examples will evolve to reflect more real-world situations, with more open-ended problems. A flipped format alone, without meaningful assessments, does not necessarily mean the instructor is doing “less of the doing and thinking for the students”[12] simply by moving the solving of closed-ended analysis problems from the home into the classroom.

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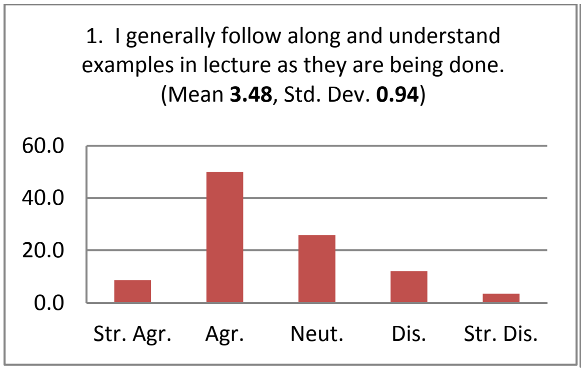
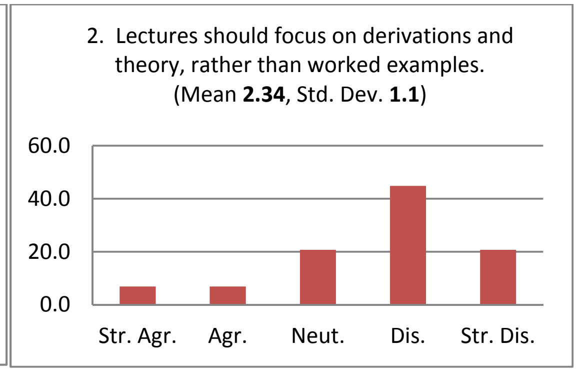
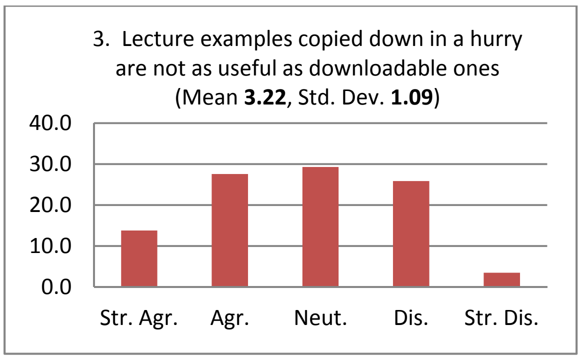
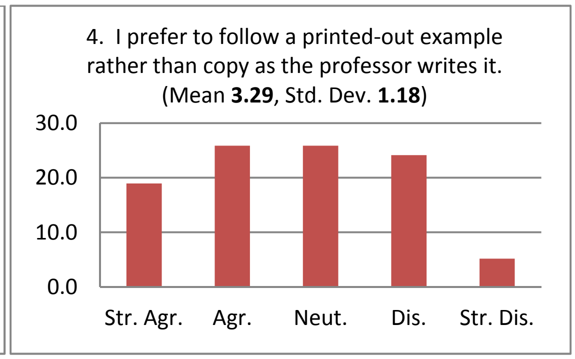
Appendix A - Survey of Student Satisfaction with Traditional Lectures

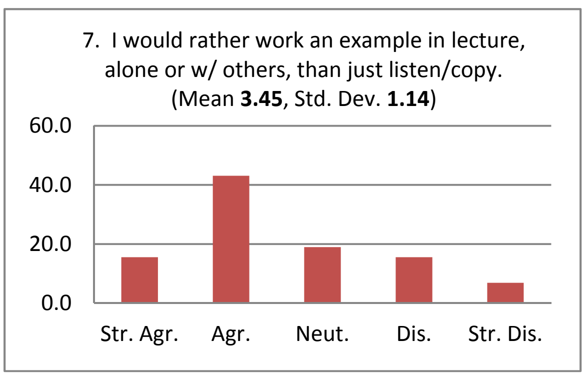
(excerpted from a 2012 survey of third-year machine design students)

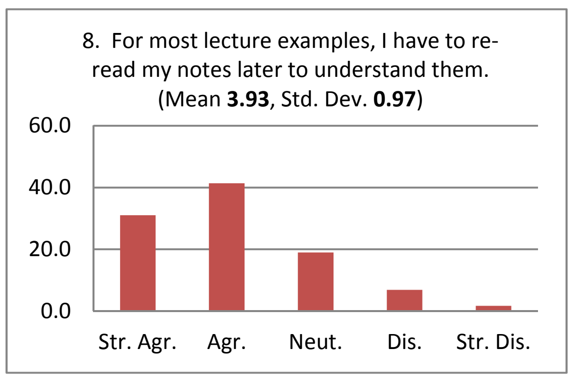


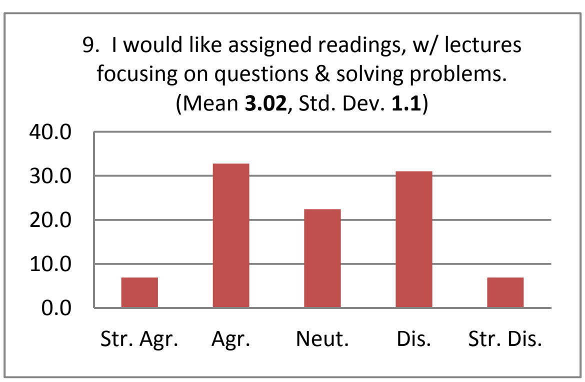


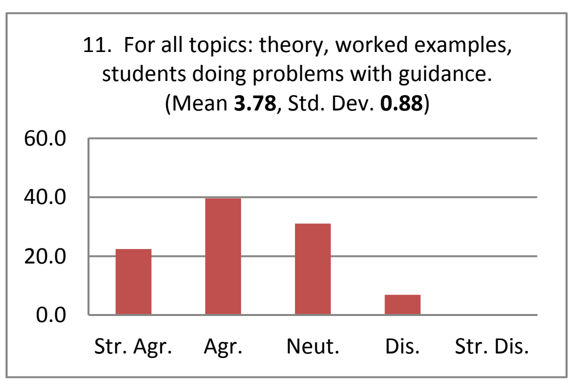












Appendix B - Course Schedule with Topics and Video Lengths

Week	Topic	Content / Remarks / Video Lengths
1		One introductory lecture; **Explanation of course format**
2	1	Free Undamped Vibration (13:57) Solution of Undamped Free Vibration Equation of Motion (11:11) Equivalent Stiffness (13:56) Alternate (Complex) Form of Undamped Free Vibration Solution (16:03) Equivalent Forms of Undamped Free Vibration Solution (16:05)
3	2	Introduction to Damping (13:44) Solution of Damped Free Vibration Equation of Motion (13:46) Expressions for Magnitude and Phase Angle (13:50) Critical and Overdamped Motion (13:53) Logarithmic Decrement (13:54)
4	3	Introduction to Harmonic Forced Vibration - Undamped (21:05) Resonance and Beat Frequency (21:10) Damped Harmonic Forced Vibration - Particular Solution (20:57) Damped Harmonic Forced Vibration - Initial Conditions (21:12) Frequency Response Function (21:00)
5	4	Base Motion - Equation of Motion and Particular Solution (11:50) Base Motion - Frequency Response Functions (11:53) Rotating Unbalance (12:15) Shaft Deflection and Critical Speed (14:14)
6		Term test
7		Worked examples and extra practice: Topics 1-4
8	5	Human/Machine Tolerance to Vibration (16:16) Vibration Isolation (16:20) Shock Isolation (16:23) Vibration Absorber Design Chart (16:26) Accelerometers (16:30) Industry Guest Speaker from Apple, Inc.
9	6	Forced Vibration with Constant Forcing Function (14:58) Total Response / Superposition (15:00) Example (14:14)
10	7	Impulse Response (12:31) Impulse Response Example (12:34) Convolution (12:35) Matlab Implementation (12:26)
11*	8	Two Degree-of-Freedom Systems (undamped)
12*		Demonstration - measuring natural frequency; intro. to beam vibration
13*	9	Modal Impact Testing (demonstration)

* Material in weeks 11-12 was delivered in a non-flipped traditional format. Week 13 activity was a demonstration of the application of current and future course concepts.