Study of Tuned Mass Damper for Attenuating Skyscraper Oscillations Through Project-Based Learning

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Abstract

The intention of the project was to introduce a complex real-life engineering problem in an easy manner to sophomore students, namely, the topic of a tuned mass damper (TMD). Even though TMD is a multiple-degree-of-freedom vibration problem seen only in advanced university courses, the phenomenon of earthquake effects on buildings is easy to understand. In order to ease the complexity, the multi-degree-of-freedom mathematical problem was converted into a single degree of freedom, such as the behavior of a vertical single-mass cantilever beam. Through a do-it-yourself project to be done in home conditions, students are introduced to the topic of mechanical vibrations via seismic action on tall buildings. Two sections of the "Engineering Mechanics: Dynamics" course, with an overall number of 58 students, participated in the project. The project develops critical thinking and inquiry skills by designing and constructing the physical prototype of a building-like structure and its corresponding tuned mass damper; conducting an experiment under certain restrictions to test the stabilizing effect of the damper after an initial displacement; learning a proper software application to graph and measure underdamped oscillations; calculating corresponding vibration parameters; as well as analyzing and discussing experimental results. Students approach the problem of mass-damper tuning by means of trial and error, an on-purpose strategy to add fun and gambling to the process, to enthusiastically compete for the best performance in terms of efficiency of attenuation. Data were collected from direct observation, surveys, reports and presentations. The results showed that students positively and enthusiastically responded at all project stages and with a better understanding of the phenomenon and engagement in comparison with previous students of the same course without project. The impact of the project on students' engagement and implications for engineering education are discussed.

Keywords: STEM education, tuned mass damper, single-mass cantilever

1. Introduction

The purpose of the present article is to provide a project where students can learn new engineering knowledge on vibrations; relate the topic to a real-life situation, such as the effect of earthquakes on tall buildings; apply this knowledge to a do-it-yourself activity at home where students design and construct the physical prototype of a building-like structure; conduct an experiment under certain restrictions to test the effect of a damper to stabilize the structure from an initial displacement; learn a software to measure oscillations, and finally, calculate main parameters. The project aims at developing critical thinking and inquiry skills. This kind of project directly addresses all seven student outcomes recommended by the Accreditation Board of Engineering and Technology (ABET), which are intended to prepare students to enter the professional practice of engineering [1].

Project-based learning (PBL) is a widely used technique in engineering, however, there are still issues in its implementation, such as [2]:

- lack of confidence among engineering faculty members besides its heavy burden on its implementation;
- issues on the sustainability of engineering PBL experiences, since most of these activities are carried out by a single "champion" working in relative isolation. Only few universities in the world have a more structured approach to implementing PBL throughout the engineering curriculum;
- Concerns about funding mechanisms for supporting such activities.

Therefore, it is useful to present cases of PBL design and implementation to be shared with the engineering and science community.

Besides the technical merit of investigating, designing and implementing the present engineering project, the following research questions motivated authors to make changes in the teaching practice: How do students deal with a relatively complex do-it-yourself-at-home engineering problem within four weeks? How do students' engagement in a stage-wise weekly project delivery influence their anxiety and motivation? How does PBL develop students' critical thinking and inquiry skills?

2. Methodology

This project was implemented at MEF University, which is famous for being the first university in the world to fully implement flipped learning throughout all the university curricula [3]. Additionally, the project was implemented using project-based learning, a widely accepted key component of engineering programs, which is generally welcomed by students, industry and accreditors [4, 5].

Through a do-it-yourself project to be done in home conditions, students are introduced to the topic of mechanical vibrations via the effect of earthquakes on tall buildings. Two sections of the DYN 201 "Engineering Mechanics: Dynamics" course, with an overall number of 58 students, participated in the project. The teaching practice of the project consists of delivering four project stages every week (so to not interfere with the start of the first midterm period). This is because the course is a 5-ECTS compulsory theoretical course for both Mechanical Engineering and Civil Engineering students with no additional time for laboratory, so the project was to be done at home conditions in teams of up to 5 members. For this purpose, flipped home videos were reduced during that time to give priority to project activities. Within the project period, only 30 min each week were devoted to explanations and instructions about the project. The project requirements were designed to be as simple as possible to use only simple and inexpensive materials than can be found at home or be purchased from stationery or hardware stores.

Even though a tuned mass damper (TMD) is a difficult multiple-degree-of-freedom vibration topic seen in advanced or elective university courses [6], the phenomenon of earthquake effect on buildings is easy to understand. On the other hand, its mathematical formulation can be approximated to a single degree of freedom for a vertical single-mass cantilever beam [7] to avoid cumbersome theoretical calculations.

Students were asked to design and construct the physical prototype of a building-like structure and its corresponding tuned mass damper; conduct an experiment under certain restrictions to test the stabilizing effect of the damper after an initial displacement; learning a proper software application to graph and measure underdamped oscillations; calculate corresponding vibration parameters; as well as analyze and discuss experimental results. Students approach the problem of mass-damper tuning by means of trial and error, and as a competition among teams to get the best performance in terms of efficiency of attenuation to add fun and gambling to the process.

A short summary of the instructions given at each project stage were the following:

- **Stage 1. Construction of building-like frame** (week 1). Construct a 0.8-1.0 m height wood or plastic-made plane or prismatic frame. Students are given enough freedom to make their own designs. Use Ockham's Razor principle of simplicity in design, where the simplest solution is the best. Creative designs are encouraged. Oscillations can be generated manually by just horizontally displacing the frame top about 10 cm, and then releasing it. Supportive videos even with little children making a shaking table were provided [8-13] to give confidence to students. The list of the team members should be delivered by email the next day after the instruction day. Deliverables for the following week: photo of the frame together with teammates, and respond a survey. Every week delivery of stages 1, 2 and 3 represents 20% of the project evaluation.
- **Stage 2. Design of the tuned mass damper** (week 2). The TMD may be a compound pendulum or a viscous damper cylinder in the top of the frame. Tuning a damper means either adjusting the location of the mass along the pendulum string, or changing the viscosity of the damper liquid or the shape of the movable object inside the cylinder. Creative designs are encouraged, even using eggs as dampers! Trial and error should be used to tune the TMD. Deliverables: Two videos of the system, one without TMD, and the other with TMD (students are warned that adjusting the TMD is a very time-consuming procedure); and respond a survey.
- **Stage 3. Tracking the motion of a point within the frame top** (week 3). Tightly hold the frame base while another student manually displaces the frame top horizontally about 10 cm, and then release the frame to freely generate fading oscillations. A 30-cm ruler in a horizontal position close to the frame will be needed to calibrate the oscillation amplitudes. Shoot two videos of the system: one without TMD (called V1); the second with TMD (V2). The "Tracker" freeware must be used [14,15,16] to automatically track the pixels of a marked dot or edge in the frame top. Apply the software to both videos V1 and V2 to track the mark in the frame top, and obtain the graph of its horizontal position in the *x*-axis versus time. The result should look as a decaying or fading exponential (Fig.1), which should be more attenuated for V2. Take a screenshot of both decaying exponential graph for V1 and V2. Deliverables: Two videos V1 and V2; two screenshots of both decaying exponential graphs (*x* vs time) for V1 and V2; and respond a survey.
- **Stage 4. Calculations, report and presentation video** (week 4). The frame has been approximated to behave as a cantilever beam with significant masses of the beam and the end mass modeled as a single-degree-of-freedom system [17] with a total mass of $m_t = 0.2235\rho L + M_{pendulum}$ $m_t = 0.2235\rho L + M_{pendulum}$ where ρ is frame's material linear mass density, and L is frame's height. Using the logarithmic decrement method [18,19], obtain the damped period τ_d and two consecutive amplitudes X_1 and X_2 from the exponential decay graphs (Fig. 1). Calculate the following for both with/without TMD: damping ratio ζ_d, damped

natural frequency f_d, damped stiffness k_d, and damping coefficient c_d. Obtain the performance of the TMD calculating the relative efficiency of the viscous damping ratio *e = (damping ratio with TMD – damping ratio without TMD)/damping ratio without TMD*. Think critically to provide an explanation about the difference in the values in terms of the influence of the damper and its tuning. Discuss about the efficiency of the damper in attenuating the oscillation. Provide ideas how you could improve the damping effect of the damper in order to get better results. Write a final complete written report following the structure of a template provided. Within the report conclusions, describe your impressions about the project, how the experiment gave you an idea about using engineering to solve a concrete real-life problem to attenuate oscillations, and how the project impacted on your interest in engineering. From the analysis of the results, discuss and write conclusions about the findings. Finally, write what were the skills you developed during the realization of this project. Prepare and edit a final project presentation video including the videos captured from the Tracker software screen showing the oscillating frame with tracking point and its graph for both cases (with and without TMD), and calculations obtained. Deliverables: Final written report (20% of the project evaluation), and final project presentation video (other 20%).

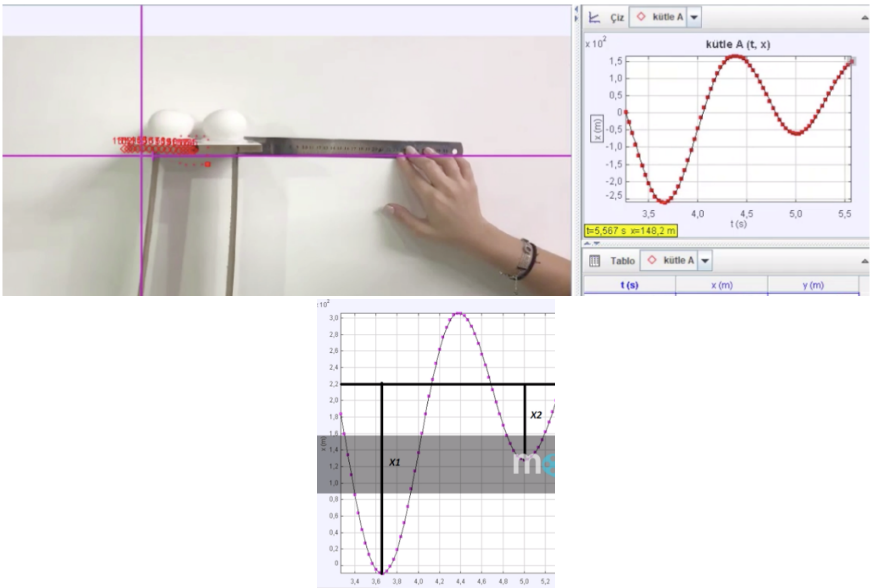

Fig. 1. Screenshot of frame motion tracking using fresh eggs as dampers, and graph amplitudes

3. Results

Data were collected from direct observation, surveys at each stage, reports and presentation videos.

Each survey included the following questions such as: While doing the project so far, what has been new for you or your teammates? Is this project sparking curiosity or any interest toward engineering? Are you enjoying and having fun with your friends while doing the project? What new skills have you learnt during this project stage?

Write any other comment or suggestion that you would like to share, if any. Besides, the reports contained extensive answers and discussions to the questions inquired in stage 4.

Findings from data analysis:

1. Surveys at each stage, final report conclusions, and final presentation videos showed that:
   - students positively and enthusiastically responded at all project stages with a better understanding of the phenomenon and with engagement. This was a change in students' feedback in comparison with students of the same course from previous years without project.
   - Students were even shocked about the fact that a simple pendulum with dampers as such used in the Taipei 101 skyscraper can attenuate seismic oscillations, and that students are able to understand and make and study of such mechanism.
   - For the first time, students learned in practice such concepts as stiffness, viscous damping, damping ratio, natural frequency, free oscillations, degree of freedom.
   - Students learned that the principle of the TMD consists of just equating the period of oscillation of the damper with the period of oscillation of the structure.
   - Students learned that a damped free response due to an initial condition of displacement in the frame top represents the same response as of a force impulse applied to the base.
   - Students learned how to use engineering approximations in a real-life case.
   - Students were eager to share their experiences and how they got fun in the process.
   - Students acknowledged the acquisition of skills, such as carpentry, using drilling tools, unexpected tools and materials, independent learning of new software to track motion from video pixels through video tutorials. This taught them lifelong learning skills, and made them more confident to face technical challenges.
   - The project topic was interesting for both Mechanical and Civil Engineering students.
   - Students acknowledged a greater true interest and motivation toward engineering.
   - The average grade for all the projects was 82/100 which is quite satisfactory.
2. From direct observation on students' performance, direct interviews, and office hours:
   - The dosage of the project in several stages, its gradual presentation, and the corresponding weekly deliverables didn't overwhelm or scare with lots of instructions or about the complexity of the activities, but instead, helped students, dosed their efforts, and their enthusiasm compensated the additional load.
   - Student were just in the third semester, and they started in the third week of classes, so they didn't know anything about rigid bodies, nor about particle kinetics, nor about vibrations at all.
   - Students were allowed to compare a massive damper frame with their frame with no damper, this was to dramatize the improvement of the TMD with even a heavier structure.
   - Students acknowledged developing critical thinking and inquiry skills every time they asked questions during class or office hours.
   - Most of student teams used a pendulum TMD, but some used a big scotch tape

rolling in the top, and others even fresh eggs. Every time a team presented a creative design, the instructor showed to the whole class to acknowledge creativeness and best ideas, this acknowledgment in public grew their ego and confidence. Creativity and fun went together.

- It was found that it is possible to measure the performance of completely different frames and TMD's through one single criterion, the relative efficiency of the viscous damping ratio, or in other words, the efficiency of attenuation.
- The gambling feeling of competition to get the best performance in terms of efficiency of attenuation boosted student competitiveness. They were able to attain very high attenuation efficiencies up to 910%. Acknowledging best teams in public grew their ego and confidence.
- Not all student teams obtained good results, there were efficiencies of 910%, 523%, 473%, 404%, 216%, 175%, 86%, but also worsening the performance with negative values: -23% and -85%. Indeed, it was not easy to tune the damper by trial and error, but students really had big fun and appreciated the real-life learning experience. Even negative attenuations were useful to learn new knowledge and skills.
- There were no comments or complains about expenses or difficulties in getting materials, so we can say that the sustainability of the activities was not an issue. The average cost of materials in every team was about 30 Euro.

Other comments and recommendations:

1. The measuring technology was free of charge just using freeware, instead of expensive accelerometers and Arduino boards presented by experts in YouTube videos such as in [8].
2. Students made their project at home, the instructors even didn't physically see many of their projects, they also didn't need laboratory for their construction, it was a do-it-yourself home project, and this is a change in the teaching practice.
3. Besides some videos in YouTube, there is not so much information about this topic in internet, so it required the authors to be creative and brave when defining the scope and specifications of each project step.
4. Writing project instructions is challenging, since the description should be complete enough, but at the same time, easy to understand and succinct.
5. Instructors recommend to ask questions during every class about the advances and their experiences, give recommendations, and encourage them to come to office hours to ask more questions or clarify their doubts.

Due to all the aforementioned findings and reasons, the impact of the project on students' engagement was significant. The project is easy enough that it can be conducted even with high-school students. To this respect, the best frames were donated by the teams to use them during open days with high-school students.

Conclusions

The article aimed at sparking curiosity and interest toward engineering; learning software tutorials for tracking motion from video pixels; learn to approximate complicated structures with multiple degrees of freedom to a single-mass cantilever beam with end mass, both with significant masses; learn how to use engineering approximations in real-life cases; and develop lifelong learning skills. Through the implementation of this project, authors were able to realize that sophomore students were able to deal with a complex do-it-yourself-at-home engineering problem under student background constraints, and accomplish it within four weeks. Focusing on a single project stage every week it is possible to create and sustain motivation and enthusiasm levels, developing not only critical thinking and inquiry skills, but also encourage creativity.

The project successfully sparked interest in engineering education in students, showing that the change in the teaching practice was worthwhile. The project is easy enough to be conducted even with high-school students. Future research will continue on the implementation of different complex engineering projects.

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