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Teaching Vibration and Modal Analysis Concepts in Traditional Subtractive Machining to Mechanical Engineering Technology Students

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Abstract

Vibration, in traditional subtractive machining like milling and single point turning, is an undesirable effect. Light vibration causes poor surface finishes, leading to the rejection of machined parts. Heavy vibration causes poor surface finishes as well but can also lead to catastrophic tool failure. To avoid vibration, machinists will adjust spindle speeds and feed rates whenever tool chatter occurs. Since vibration is an inherent reality in milling and turning, it is necessary for mechanical engineering technology students to learn how to analyze vibration in manufacturing processes.

Finite Element Analysis (FEA) is an analysis tool that has been used in mechanical engineering courses for quite some time. Mechanical engineering technology students, however, do not typically get exposed to more in-depth courses of vibration and modal analysis. To assist mechanical engineering technology students into concepts of vibration and modal analysis in a manufacturing environment, FE modeling serves as an excellent learning tool. An FE model of an extended long milling cutter enables students to visualize the properties of a vibrating system and relate the natural frequencies back to spindle speed. Forced vibration models help them understand the resulting cutter displacements from the input force excitation. Modal analysis and forced vibration exposure help students understand the characteristics of vibration and how to mitigate this undesirable effect from traditional machining methods.

The assessment results from a student self-reflection survey for exposing vibration and modal analysis support the need to expose mechanical engineering technology students to these concepts. Student responses to open ended questions indicate they are able to grasp some concepts of vibration analysis using FEA as an analysis tool.

Introduction

It is understood that undesirable vibrations in mechanical structures can potentially lead to excessive deflections and system failures. When the natural frequency of vibration of a structure coincides with the natural frequency of excitation, resonance occurs, leading to excessive displacements [1]. These excessive displacements can cause an annoying oscillation in minor cases or can cause catastrophic failures in other cases. Vibration analysis has been a topic in mechanical engineering courses for quite some time, however, mechanical engineering technology students don’t always get exposed to vibration analysis.

In introductory mechanical engineering vibration courses, students take prerequisite courses in dynamics, calculus, and differential equations [2]. These prerequisite courses are found in all mechanical engineering programs. Mechanical engineering technology students do not always take a course in differential equations, which typically excludes them from being exposed to vibration analysis. Courses in vibration analysis require differential equations to derive the equations of motion and calculate the corresponding solution with specified initial conditions. Without this background in mathematics, mechanical engineering technology students are at a disadvantage of understanding what causes vibrations and the potential risk that can be a result.

Depending on the industry, FEA can be used for different purposes. Most often, FEA is used to evaluate the structural integrity of a component before it is produced, shortening the time it takes to experimentally test multiple prototypes. The Finite Element Method (FEM) uses numerical computation to predict the effects of force, pressure, heat, fluid flow, vibration, or other physical effects on products. FEA is generally performed by computer programs using the NASTRAN solver originally developed in the late 20^{th} century for NASA now integrated into many software platforms. Using FEA can shorten the product design process by indicating how a product can fail prior to the building of a prototype. Building a prototype and testing that prototype is required for validation, but predictions using FEA software before anything is built is a powerful tool. FEA is a tool for the engineer or designer that can be used during most phases of the product development process. FEA can be used for feasibility of initial design ideas, evaluation/testing phase to measure the worthiness of alternative designs, and during the final stages of design to optimize the design solution [3], [4].

To help mechanical engineering technology students gain some exposure to vibration analysis, Finite Element Analysis (FEA) is used as a learning tool into the concepts of vibration and modal analysis in a manufacturing environment. A manufacturing environment that mechanical engineering technology students are very familiar with is subtractive machining; especially single point turning and milling. In traditional single point turning and milling, vibration is an undesirable effect. Machining tools are expected to be sturdy enough to handle recommended cutting speeds and feeds thereby producing a quality surface finish in the final part. Light vibration, however, can cause poor surface finishes leading to the rejection of machined parts. Heavy vibration can also cause poor surface finishes but can potentially cause catastrophic tool failure [5].

CAE and FEA Methods Course

The technical elective course, Computer Aided Engineering (CAE) and FEA Methods, is a 3-credit course, with 2 hours of recitation and 2 hours of lab during a 14-week semester. The course topics are as follows:

- Introduction to the Finite Element Method and Elements of the Finite Element Method
- Introduction to the Stiffness Method
- Development of Truss and Beam Equations
- Development of the Plane Stress and Plane Strain Stiffness Equations
- Two and Three-Dimensional Stress Analysis
- Natural Frequencies of Simple Structures

- Heat Transfer and Mass Transport
- Rigid Body Dynamics

The ABET student outcomes demonstrated and/or reinforced in this course are as follows:

1. an ability to apply knowledge, techniques, skills and modern tools of mathematics, science, engineering, and technology to solve broadly defined engineering problems appropriate to the discipline; (d)
2. an ability to design systems, components, or processes meeting specified needs for broadly defined engineering problems appropriate to the discipline; (d)
3. an ability to apply written, oral, and graphical communication in broadly defined technical and non-technical environments; and an ability to identify and use appropriate technical literature; (r)
4. an ability to conduct standard tests, measurements, and experiments and to analyze and interpret the results to improve processes; and (r)
5. an ability to function effectively as a member or leader on a technical team. (r)

Although this course has topics ranging in many CAE analysis tools, this paper is restricted to an effort to make use of FEA for mechanical engineering technology students to expose them to a vibrating system with visual responses in a manufacturing application. The manufacturing application that was chosen is a standard milling operation using a long 4-fluted endmill. This is used to show how running a milling cutter a specific speed can potentially cause a catastrophic tool failure when the natural frequency of the endmill lines up with the excitation frequency of the cutting operation.

Early in the course, the students are taught how to formulate a stiffness matrix, for simple models using truss, beam, shell, and solid elements. This knowledge helps them look at a problem and understand why a geometric model is broken up into individual elements so the software can calculate a global stiffness matrix. They also learn how boundary conditions are treated, loads are applied, and what degrees of freedom are available for a specific model. This is essential for setting up and solving any FE model.

Before the modal analysis and frequency response analysis exercise, the fundamental equations for natural frequency are taught during recitation, so the students learn what is required for input in the software and how the software calculates the mode shapes and natural frequencies. Basic Single Degree of Freedom (SDoF) spring systems are used to demonstrate the reason for stiffness matrix calculations and mass density values in material cards [1].

The laboratory portion of the class is set up using a series of instructional labs and assignments. The instructional labs are designed to expose the students to finite element software. Students import geometry, mesh the model, define properties, apply boundary conditions, create a solution set, and then solve the model. Once the model is solved, the students learn how to display the results properly. Laboratory assignments are assigned to reinforce the instructional labs and help students learn how solve a given problem by displaying their results in a logical manner and writing a lab report.

The Laboratory Problem

The first portion of the vibration lab exercise is to perform a modal analysis on a finishing endmill. Standard 1/4-inch and 3/8-inch diameter, 6-inch long, 4-fluted endmills were selected. A 1/4" endmill is shown in Figure 1. Solid models were downloaded from the McMaster-Carr website [6], so accurate geometric models were used. The models were meshed with 2nd order tetrahedral elements, and boundary conditions were applied to 1.25 inches of the far end of each endmill, to simulate it extending a significant amount from a milling collet.

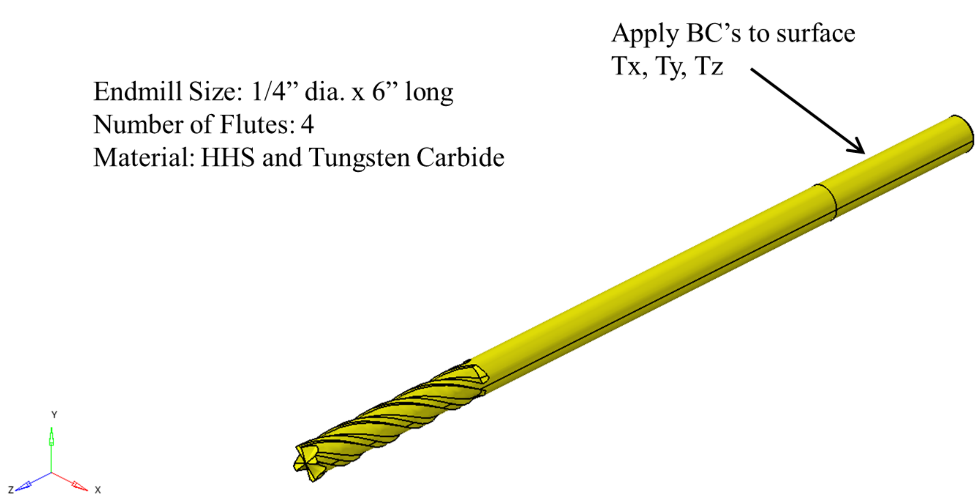

Figure 1 Solid Model of 1/4" Diameter Endmill [6]

Two different materials were used for each endmill, High Speed Steel (HSS) and Tungsten Carbide, as these endmills are available in both materials. Once the solutions were obtained, the students were required to display the first ten mode shapes to see the predicted bending modes, or eigenvectors, and at what frequencies these mode shapes occur, or eigenvalues. The students were instructed to pay particular attention to the first bending mode of the endmill.

The next task was to take the first bending mode frequency and relate it to a spindle speed for a milling operation. The objective of this task was to calculate an equivalent spindle speed that aligns with the first bending mode frequency for each endmill diameter and each endmill material. First, the students considered the number of events per revolution that the endmill produces. Since the endmill has 4-flutes, there are 4-events per revolution. They then calculated the spindle speed for the lower and upper ranges for the different cutter materials. Once they calculated the spindle speed that corresponds to the first bending mode and natural frequency, they were instructed to calculate the recommended feeds and speeds for milling a block of 6061-T6 Aluminum and determine which operating speed aligns with the first bending mode frequency. Table 1 shows modal results and calculated spindle speeds for the 1/4" and 3/8" in cutters, for HHS and Tungsten Carbide. The analysis results and hand calculations were intended to show how closely the first bending mode for the 1/4” HHS endmill and the 3/8” Tungsten Carbide endmill are to the recommended upper ranges for spindle speed for the cutting operation. The students were then asked to reflect on the potential outcome, for using either type of cutter close to its natural frequency, whether the operation will result in poor surface finish or a broken tool.

Table 1 Modal and Cutting Speed Results for 1/4" and 3/8” Endmills

1/4 x 6" – 4 Flute HHS Endmill						
Bending Mode	Frequency (Hz)	Calculated Spindle RPM	Recommended SFM range	Cutter Dia. (in)	Calculated Spindle RPM (low)	Calculated Spindle RPM (high)
1	325.8	4887	200 to 300	0.25	3056	4584
2	326.3	4895				
3	1903.5	28553				
4	1905.6	28584				
1/4 x 6" – 4 Flute Tungsten Carbide Endmill						
Bending Mode	Frequency (Hz)	Calculated Spindle RPM	Recommended SFM range	Cutter Dia. (in)	Calculated Spindle RPM (low)	Calculated Spindle RPM (high)
1	343.5	5153	500 to 750	0.25	7639	11459
2	343.9	5159				
3	2008.3	30125				
4	2010.4	30156				
3/8 x 6" – 4 Flute HSS Endmill						
Bending Mode	Frequency (Hz)	Calculated Spindle RPM	Recommended SFM	Cutter Dia. (in)	Calculated Spindle RPM (low)	Calculated Spindle RPM (high)
1	494.5	7418	200 to 300	0.375	2037	3056
2	494.6	7419				
3	2718.5	40778				
4	2719.0	40785				
3/8 x 6" – 4 Flute Tungsten Carbide Endmill						
Bending Mode	Frequency (Hz)	Calculated Spindle RPM	Recommended SFM	Cutter Dia. (in)	Calculated Spindle RPM (low)	Calculated Spindle RPM (high)
1	515.0	7725	500 to 750	0.375	5093	7639
2	515.1	7727				
3	2836.2	42543				
4	2837.0	42555				

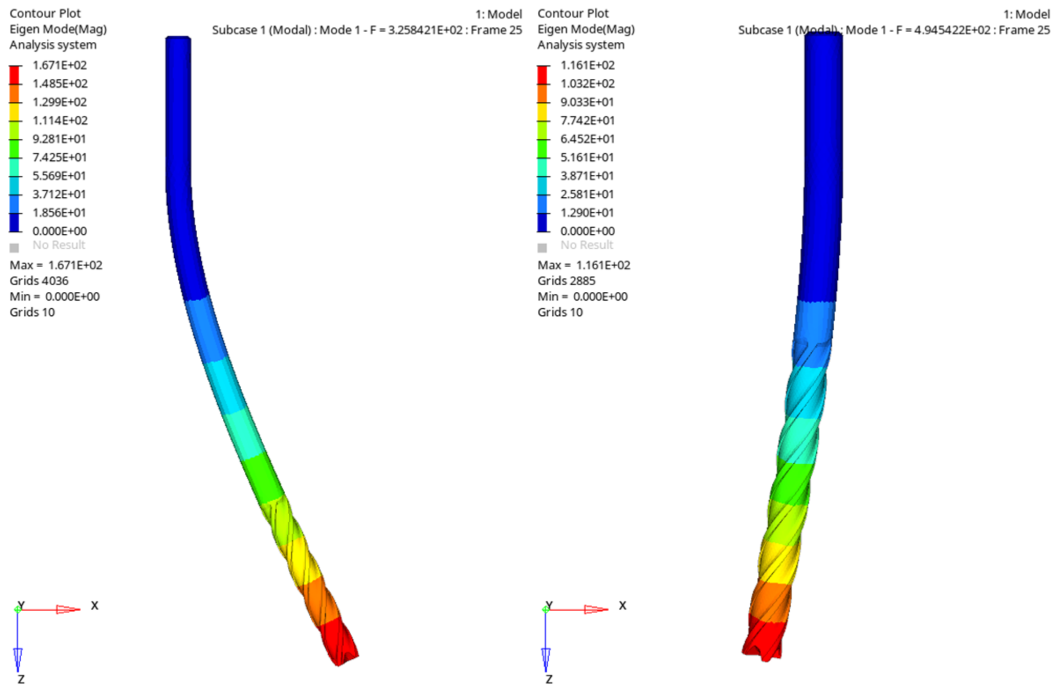

Figure 2 First Bending Mode of 1/4" HHS (left) and 3/8" HHS Endmills (right)

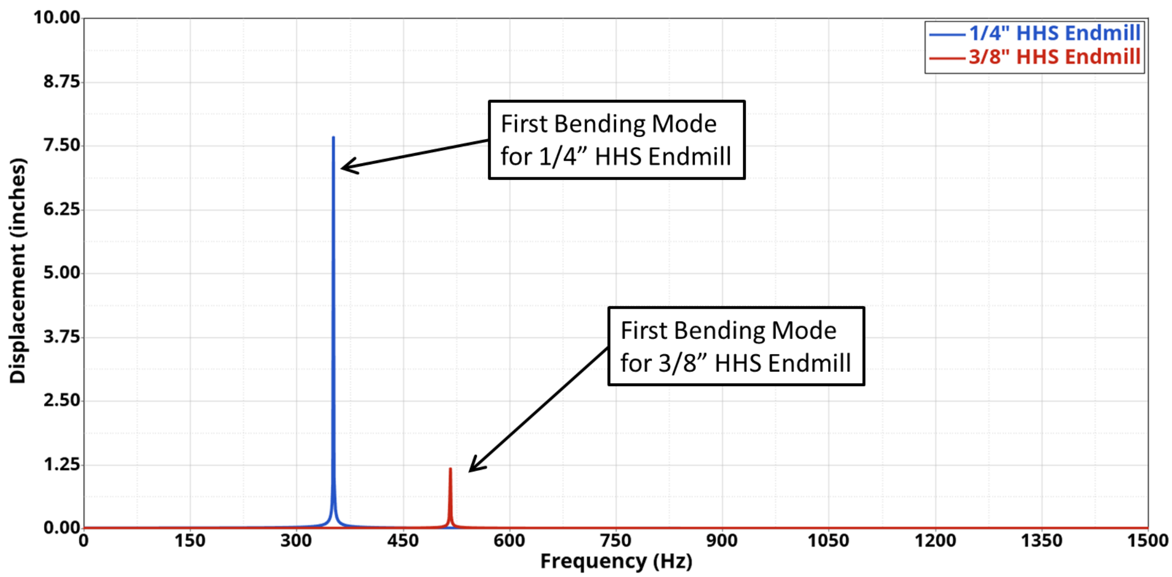

Figure 3 Frequency Response for 1/4" and 3/8” HHS Endmills

To have an appreciation for what amount of bending can be expected on each of the endmills, a frequency response model was then generated. A unit load, across all modal frequencies was used as the forcing frequency to determine the amount of displacement that could be expected. Although this didn’t take into consideration the actual cutting force experienced, this did give the students an understanding that the modal model will only tell them how the endmill wants to bend and at what frequency. The frequency response model will then give them an expected amount of deflection for a given load. The displacement observed was excessive, however, this effort was intended to help them understand the risk of running these endmills close to the 1st bending mode natural frequency.

Student Self-Reflection Survey

To provide feedback for the vibrations lecture and lab exercise, a survey of the students enrolled in the fall 2022 class was conducted. The survey was administered by email to 10 students, which was the total number of students enrolled in the fall course. The survey was sent to the students at the completion of the course. The number of responses was 100%. Even though this is a small sampling, this was the first time this exercise was used.

The survey instrument consists of six questions, three indication type questions and three open-ended questions. The survey was sent via email to students at the conclusion of the course. The indication questions were intended to determine the level of math the students had taken, if they were exposed to vibration analysis, and how familiar they were with a milling operation. See Table 2. The open-ended questions provide the students the ability to expand on how well they understood the exercise.

Results of the Student Survey

- Question 1: Indicate if you completed a course in differential equations. Use the scale: "Completed the Course = 1', "Enrolled and then Dropped the Course = 2", "Did not Enroll in the Course = 3".
- Question 2: Indicate your previous exposure and/or familiarity to vibration analysis. Use the scale: "Very Familiar = 1", "Somewhat Familiar = 2", or "Not Familiar = 3".
- Question 3: Indicate your previous exposure and hands-on experience with machining processes: "Very Familiar and Can Operate a Mill = 1", "Somewhat Familiar and have Operated a Mill before = 2", "Not Familiar and have Not Operated a Mill = 3".

Table 2 Student Survey Questions

Student	**Question 1**	**Question 2**	**Question 3**
1	Completed the Course	Somewhat Familiar	Very Familiar
2	Did not Enroll in the Course	Not Familiar	Very Familiar
3	Did not Enroll in the Course	Not Familiar	Very Familiar
4	Did not Enroll in the Course	Not Familiar	Very Familiar
5	Did not Enroll in the Course	Not Familiar	Very Familiar
6	Did not Enroll in the Course	Not Familiar	Very Familiar
7	Dropped the Course	Not Familiar	Very Familiar
8	Did not Enroll in the Course	Not Familiar	Very Familiar
9	Dropped the Course	Not Familiar	Very Familiar
10	Did not Enroll in the Course	Not Familiar	Very Familiar

From the results of the first three questions, it was observed that only one of the students surveyed took a course in differential equations and had some exposure to the topic of vibration analysis. The rest of the students had not taken differential equations or had dropped the course before completion. The other observation was that all the mechanical engineering technology students were very familiar with machining and could operate a milling machine.

The three remaining questions were open ended. The questions asked:

4. Explain what results you get from a modal analysis.
5. Explain what results you get from a frequency response analysis.
6. Which analysis model was easier to interpret, the modal analysis model or the frequency response analysis model?

Table 3 Student Survey Open-Ended Questions

Question No.	Common Responses	Frequency
4	"show how the endmill wants to bend", "calculates the natural frequencies"	8 out of 10
5	"shows how far the endmill will bend"	5 out of 10
6	“the modal analysis model”	10 out of 10

The results for the open-ended questions indicate most students understood what results can be observed in from each type of analysis, however, they grasped the modal analysis far better than the frequency response analysis. See Table 3. As indicated in the final open-ended question, they thought the modal analysis was easier to interpret than the frequency response. Further discussions during recitation also indicated the frequency response analysis was an obscure topic and they really didn’t understand what was going on. They mentioned it would be nice to have more examples. In addition, the students thought this should be taught in other mechanical engineering technology courses, or to have a dedicated course on vibration.

Conclusion & Recommendations

The student survey results revealed anticipated results for the majority of the response questions. For instance, students in the mechanical engineering technology curriculum do not have to take differential equations as a requirement. Therefore, students starting in the department as a freshman will not be exposed to this level of mathematics. Students transferring into the mechanical engineering technology curriculum from mechanical engineering, in some instances, may have taken differential equations or have been exposed to topics on vibration. In this evaluation, however, the majority were not familiar with this level of math.

One result from the response questions that helped solidify this being a worthwhile exercise was the fact that all the mechanical engineering technology students were familiar with machining. Since the students all take a course in Machine Tool Fundamentals by the sophomore year, the students learn how to machine components on a manual lathe and milling machine. In this course they are not only taught how to operate the equipment, but also taught how to calculate proper cutting speeds and feeds for a variety of different materials using both HHS and carbide cutting tools. With this background, the students were able to relate common occurrences observed in machining operations to vibration.

The responses from the open-ended question responses also provided some helpful information for future exercises. With the students being able to understand the modal analysis easier than the frequency response analysis, more emphasis will be placed on future exercises as they relate to manufacturing processes covered in the mechanical engineering technology curriculum. Being able to relate a vibration concept to an actual process helped to solidify the usefulness of the analysis tool.

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