ROAD VIBRATION SIMULATION EXPERIMENT: PROGRESS REPORT OF FINAL DESIGN

DESIGN AND DEVELOPMENT OF A ROAD VIBRATION SIMULATOR FOR THE MIAMI UNIVERSITY VIBRATIONS LABORATORY

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EXECUTIVE SUMMARY

The problem objective developed by the Road Vibrations Simulator Team was to design and implement a versatile device and corresponding classroom experiments for use in the Miami University Vibrations Laboratory to simulate road vibrations felt by vehicles during normal operation.

During EGR 448, the team began their work on this project in three major areas: hardware, software, and experiments. To begin, the team researched, selected and purchased components for the sensing, actuating and model of the system, specifically accelerometers, a shaker, and a 1/5 scale car. The team also selected Matlab to use for the data acquisition and analysis of the experiment. Overall goals for the design of the GUI, as well as mini working GUI components, were also developed. Finally, the importance of researching vibration in design was researched, and the team devised goals for 2 experiments that were to be written for the MME 315 vibrations course.

To begin EGR 449, the team developed a contract that established the major deliverables they were to accomplish by the end of the semester. This included a road vibrations simulator experimental setup, a user manual, two laboratory experiments, a GUI for data acquisition and analysis, and a website. Throughout the semester, the team updated their GUI and experiments in a continuous improvement process. Further research, user tests conducted on the MME 315 students and readings by faculty (Dr. Bailey Van Kuren and Dr. Amit Shukla) provided a means of feedback for what improvements could be made to improve the accuracy of the data, the wording and appearance of the experiments, and other issues related to the experimental setup and documentation. The website was used as a means for documenting this entire design process, as well as displaying the results for Miami engineering students and faculty, as well as others outside Miami University.
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OVERVIEW

PROBLEM

In order to look at the design project more effectively, the vibrations design team identified an overall objective, several important constraints, and some general tasks within their problem definition. The problem that faced the design team was that the Miami University School of Engineering and Applied Science did not have a lab to reinforce the topics learned in the Mechanical Vibrations Course (MME 315). The team formed a project objective which was: to design and implement a versatile device and corresponding classroom experiments for use in the Miami University Vibration Laboratory to simulate road vibrations felt by vehicles during normal operation.

The constraints of the project include physical laboratory space, time, and funds. The design team has identified funding as an important constraint limiting many aspects of design including the components used, specifically the types of actuators and data analysis software. The main tasks, agreed upon in the team contract, include:

- Road vibrations simulator experimental setup
- User manual
- Two lab experiments
- GUI for data acquisition and analysis
- User test feedback from EGR 315 students
- Website
THE FINAL DESIGN

TEST COMPONENTS

At the beginning of the semester, the team had in its possession most of the necessary components for the experimental setup. This included the shaker and accessory kit, the scale model car, the amplifier, the computer software, the accelerometers, and the signal conditioning box. This enabled the team to begin testing of experimental components at the first meeting of the semester (1/20/04). Testing of components is necessary early on to ensure all equipment is working properly. This allows the team to catch possible present or future errors in the experimental setup. Testing of the road vibrations simulator equipment consisted of the following:

- **Hardware**
  - Assembling components of shaker not assembled prior to shipment
  - Testing shaker, amplifier, and cooling system to ensure proper operation
  - Using temporary support structure to suspend car and test shaker on car

- **Software**
  - Writing and troubleshooting software to ensure code was correct and free of errors
  - Running computer software to establish correct connections between data collection components, shaker and amplifier
  - Checked accuracy of shaker using the SignalCalc Ace software and a laptop
SUPPORT STRUCTURE

The support structure has one main function: to support the weight of the car in a manner that will isolate it from outside disturbances and yet be able to vibrate freely in response to the stinger touching the car. The team came up with three potential options for the support structure. Each of these preliminary ideas involved suspending the car using bungee cords. The main benefit to bungee cords was that the cords would have a minimal impact on the natural vibration response of the car. The first idea was to purchase an engine hoist. This would have been a very expensive option, but it could have future applications for the engineering department beyond this project that could potentially justify the cost. It would also be the easiest option to manufacture, since the structure could simply be purchased. The next idea was to purchase sawhorses as the basis for our support structure. Once again, the sawhorses could have additional value to the department beyond this project. The final option was to build a support structure entirely out of materials available in the machine shop. Although this would require the most work from the team, it would be free of cost and would allow the team to design the support structure to the exact necessary specifications. This final choice was found to be the best option for the team. The selection matrix can be seen in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Functionality</th>
<th>Cost</th>
<th>Ease of Use</th>
<th>Ease of Production</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Hoist</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Sawhorses</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>Build Our Own</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 1: Support Structure Selection Matrix

After much deliberation between team members and the machine shop expert, Jeff Peterson, it was decided to first build a temporary structure based on the same principles
desired in the permanent structure. This would allow the team to begin testing until the final structure was designed. Two posts from an old chalkboard stand were found in the scrap pile. They were made of wood and had steel cross iron brackets already in place. The team measured the distance needed to have between the shaker and the bottom of the car chassis. Based upon this distance, the brackets were moved up on the posts. A strong steel iron corner bar was found in the scrap pile that was long enough for the car to be suspended below it and between the posts. The iron corner bar already had a couple holes in it that were large enough for the bungee cord hooks to go through. The team used two C-clamps and clamped this iron corner bar to the brackets. A pack of bungee cords was acquired from the machine shop. The team then began to experiment with which length of bungee cords to use and how many. The fewer bungee cords used, the better, because this meant fewer factors influencing the vibration of the car.

Three bungee cords were tried and various holes in the car were used to attach them to. The team decided that the best place for the cords to attach were on the metal chassis. There were not many options for this type of attachment, however. The car needed to be level, and the holes available could not be paired with bungee cords of appropriate length. So, with Jeff Peterson’s aid, four C-brackets were fashioned from thick scrap aluminum. Two of these C-brackets would be attached with spacers in the rear of the car and the other two attached to the car chassis in the front. To attach them in the front, holes were drilled in the chassis on the angled part. The angled part was drilled because this would not lessen the amount of places the shaker stinger could reach; the shaker stem could only reach the level parts of the car.
While the team was making the C-brackets with the bending machine, drill press, and grinder, the team also worked on making the permanent support structure. This used the same basic parts from the temporary structure. To make the permanent support structure, holes were drilled with a hand drill in the iron corner bar as well as the cross iron brackets. Holes were also drilled in marked locations so that the bungee cords could be attached to the iron corner bar directly above their attachments on the car chassis. Bolts, nuts, and lock washers were then used and the iron corner bar was permanently attached to the cross iron brackets. The car was then put underneath the structure and hung from four bungee cords of equal lengths.

After hanging the car, it was discovered that it still was not completely level. The team went back to the machine shop and found two long bars of unistrut-type steel. They were then attached to the iron corner bar with nuts, bolts, and washers. After locating the proper location for the bungee cords hanging from these steel pieces, they were cut so that they were not unnecessarily long. These were then permanently attached to the corner iron with spacers. The final support structure can be seen in Figure 1.

Figure 1: Final support structure with car attached
EXPERIMENTAL SETUP

Figure 2 shows the final flow of information for the experimental setup. The only major change that was made between this proposed design and the final design was to use a second computer, a laptop computer with SingalCalc Ace software, to drive the excitation of the shaker. This change was necessary because the Matlab software currently available in the vibrations laboratory did not have Analog Input capacity.

Figure 2: Final Flow of Information
Figure 3 shows an actual picture of the experimental setup designed.

The team’s design for the road vibrations simulator setup accomplishes their original goal of being a self-contained, intuitive experimental setup that is educational and easy to use. Because the setup is self contained, it can easily be moved to a new location in the future engineering building. The electrodynamics shaker provides a very intuitive actuating force for exciting the road vibrations felt by the vehicle. The realistic nature of the 1/5 scale model car, specifically in terms of components such as the real springs and shock absorbers, also helps in the improve the intuitive nature of the experiments.
The costs associated with the team's project include the cost of the car, shaker, amplifier, cooling system, and accessories kit. These costs are outlined in Table 2 in the team's Bill of Materials.

<table>
<thead>
<tr>
<th>Bill Of Materials [$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
</tr>
<tr>
<td>Shaker</td>
</tr>
<tr>
<td>Amplifier</td>
</tr>
<tr>
<td>Cooling System</td>
</tr>
<tr>
<td>Accessories Kit</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
</tr>
</tbody>
</table>

**Table 2:** Bill of Materials

The costs are justified because in order to build the desired road vibrations simulator some type of car is needed as well as some type of device to shake the car. The team did research into the least expensive model car, and found the cheapest one was $530.00 with all the necessary parts. The team did receive an educational discount on the car as well, also justifying the amount that was spent. In order to shake the car, the team could have chosen a shaker like they did, or could have used hydraulics. Due to the large size of hydraulic shakers as well as the high costs, the team opted for the electrodynamic shaker listed on the table above. This shaker requires an amplifier and cooling system as well as an accessories kit (that includes tools for use with the shaker as well as necessary components of the shaker such as the stinger). Overall, with the actual shaker itself, the required amplifier, cooling system, and accessories kit cost a total of $8,214.00. This is justified, even though expensive, because the team received a large educational discount on these items as well, and some type
method to shake the car, and this was the least expensive method available. Overall, the cost of the car and shaker with components was $8,744.00.

Because of the high costs mentioned above, the team looked for ways to reduce costs in other parts of their experiment. One way to do this was to use scrap materials from the departmental machine shop to build a support structure. Also, the use of equipment already in the lab such as accelerometers, computers (with correct Matlab software and DAQ hardware), and the signal conditioning box eliminated costs associated with purchasing these necessary components.

So overall, though expensive, this experiment was built at the lowest possible cost.

GUI AND RELATED PROGRAM LOGIC

Figure 4 shows the final design for the graphical user interface.

![Figure 4: Final Design of GUI](image-url)
There were a few changes made to this design from the original model proposed. Since the team decided to focus the second experiment of changing system design parameters instead of data accuracy improvements, the on/off windowing capability and averaging capability were never added to the experiment.

Another improvement to the GUI was to add a zoom capability. Through research the team found a matlab m-file online called zoompls.m. This included code for creating a mini GUI with zoom functions. The team then changed this file accordingly to match their current code. When the GUI is run, a mini ‘Zoom’ pop-up menu will be displayed in the corner of the GUI transfer function graph. This pop-up menu can be used to zoom in and out of the GUI graphs. Figure 5 displays this pop-up menu.

In order to zoom in, the user can click on the ‘in’ button of the pop-up menu. The user can then use the mouse and click on the desired locations for the lower left and upper right corners, respectively, of the plot that is to be generated. Next, in order to zoom out, the
user can click on the ‘out’ button of the pop-up menu. The graph will automatically zoom out to an appropriately expanded set of axes.

Addition of this zoom capability allows the user to more closely look at individual peaks on the output graph as well as make sure they are actually looking at one peak, rather than several peaks that are close together. Because analyzing the peaks of the transfer function graph is the main task of the users of the team’s experiment, it is important to have this zoom capability to allow them to do this better.

**Figure 6** list the five Matlab files used in the final design of the development of the GUI, along with a brief description outlining their role within the data analysis and acquisition logic.

**Figure 6: Program logic**
Some specific changes in code were also made in order to improve the accuracy of the data being displayed.

To improve the accuracy of the GUI, the team did research into proven methods of improving the accuracy of transfer functions. It was important to focus on transfer functions in their quest for methods to improve accuracy because the transfer function graph is the key graph on the team’s GUI. Through research, the team found that the Auto Power Spectra is a proven method of improving transfer function accuracy. According to Vibrations: Experimental Modal Analysis by Dr. Randall J. Alleman from the University of Cincinnati, the idea behind the Auto Power Spectra method is to multiply the data by its complex conjugate. This tends to minimize noise on the output.

Another way the team improved the GUI was to change the dynamic range of the graphs. This means that the GUI code was adjusted such that each time data is taken, the range of the y-axis of the graphs changes to correspond to the data that is taken. For example, if the maximum value of the data is 0.04 Volts, then the maximum value of the y-axis on the graph will be 0.04 Volts. Also, the team changed the GUI code such that the x-axis range was smaller to effectively spread out the data. This allows students to more easily see the difference between the peaks of data and analyze them accordingly.

Windowing is another method that the team used in improving the GUI. According to Experimental Modal Analysis: A Simple Non-Mathematical Presentation, “leakage occurs from the transformation of time data to the frequency domain using the Fast Fourier Transform.” The code of the GUI includes this transformation, and thus, “in order to minimize the distortion due to leakage, weighting functions called windows are used to cause the sampled data to appear to better satisfy the periodicity requirement of the FFT.”
team chose to use a Hamming (or Hanning) Window, which is a common window used to
in increase the accuracy of random signals, weights the function in a way that forces the
beginning and end of the sample data interval to go to zero. This smoothes out the overall
function, and reduces noise, thus making the graph more accurate. A picture of a Hamming
window can be seen in Figure 7.

One of the largest strengths of the GUI, experimental setup, and user manual is that all
three are very flexible to be applicable for vibrations testing on any object, not just the 1/5
scale model car used in the experiments designed. Consequently, the deliverables of this
senior design project have not only provided two labs for the MME 315 course, but have
also provided an experimental setup and data acquisition and analysis tool for final design
projects and any similar vibrations testing experiment.
EXPERIMENTS

In order to provide future students in the Mechanical Vibrations class with actual lab experiments to perform with the vibration simulator, the team developed 2 lab reports, as well as a corresponding lab manual. Once the final support structure (hardware) and user interface (software) was completed, the team set out to determine the best lab experiments to create for the class. The team concluded that a good first experiment would be an introduction to the fundamentals of experimental vibrations and the experimental setup, and the best follow-up lab would have students change certain experimental parameters in the setup and analyze the effects of these changes.

The hardware used in the experiments is very fragile and expensive, and also can generate dangerously high voltages. Therefore, the team decided to create a user manual, found in Appendix A to explain the proper way to handle the hardware to ensure safety of both the hardware and the students. Before the students would perform either of the laboratory experiments, they would need to read the user manual, which contained an extensive safety section. To ensure the safety of the students, the team added safety notes throughout each of the lab manuals, in case the students did not remember important aspects of the user manual.

The first lab manual is titled Introduction to Small Scale Road Vibration Experimentation can be found in Appendix B. The objective of this laboratory is to introduce the user to several important fundamentals of experimental vibrations: accelerometer use, actuator use, force response graphs, and transfer functions. Also, this laboratory will introduce the student user to the functions and use of the small scale road
vibration experimental setup. This first lab manual also included an extensive background section to introduce the students to such concepts as:

- Importance of Road Vibration Experimentation
- Electrodynamic Shakers
- Accelerometers
- Data Acquisition System
- Graphical User Interface
- Analysis behind GUI code

The objective of the second laboratory, found in Appendix C, is to analyze changes in the parameters of the system. The changes made in this experiment include using multiple accelerometers as well as adding weight to the system. By using multiple accelerometers, the user can compare the vibrations felt in different parts of the car, specifically in terms of the transfer function. By adding weight and changing the mass of the car, the user can explore the effects of a design change that could be implemented in a real world situation.

In order to ensure that the students understand and retain the information from the labs, the team also included post lab discussion topics for the students to include in their lab write-ups. These topics would help enhance the students’ knowledge of the labs, and give them a framework to discuss the results of their data analysis.

After writing the first drafts of the user manual and two lab experiment manuals, user tests were conducted, surveys were filled out by the users conducting the user test, and a faculty member read through the user manual and lab manuals. The process of updating the lab manuals and user manual was very iterative because changes would be made and another test run and then more subsequent changes would be made. So, the lab manuals and user manual were constantly being updated. The user test criticisms were collected through
immediate on-site feedback. To enable immediate feedback, the Road Vibration Simulation Team members were present during the lab sessions. The team members also video recorded the student user tests for future use and demonstrations. The users spoke comments and the team wrote notes to themselves to address the comments in future revised versions of the labs and user manual.

The user test users were the students of the EGR 315: Mechanical Vibrations class. This class was used because the students are in the midst of learning about vibrations theories and the importance of them, so the team felt they would be the best candidates for the user test. Most of the feedback from the user tests had to do with small details being left out as to when to turn on a component, where to place something such as an accelerometer or the stinger, and how to dismantle a certain part of the experimental set-up. Dr. BVK was the faculty member who read the labs and user manual and provided feedback. Dr. BVK was chosen due to his extensive laboratory experience. The point of having a faculty member read through the documents was so it could be read for format and flow errors. His main comment was that all three documents lacked pictures and figures. So, the team added pictures and figures with arrows referencing specific aspects of the pictures for clarity.

In Appendix D, a compilation of all of the comments taken into account throughout the iterative process to produce the most current Lab Manuals and User Manual can be found. It is noted that there are no specific Lab 2 Flow and Format Criticisms because those types of errors were taken care of in the User Manual and Lab 1 Manual. The main criticisms received on Lab 2 were about the lab itself rather than the flow and format.

Surveys were also handed out to collect criticisms and to ensure certain goals were met. In revising the Lab Manuals and User Manual format and flow, these answers to the
questions were taken into account. The main comments and questions addressed in the survey dealt with how effective the background information was as well as how clear the goal of the lab was. Generally speaking, the students felt the background information was important and that the goal of the labs was apparent. The students also felt that vibrations experimentation was very important. The specific questions asked and the results of the surveys can be found in Appendix E. The format of these results is the question and then the student answers in a, b, c, etc. The first survey had all five student responses; the second survey had only three student responses because not all of the surveys were filled out by the students.

While going through the iterative process of revising the Lab Manuals and User Manual, all changes were recorded. The list of all the changes made can be found in Appendix F. As mentioned, the final copies of the Lab Manuals and User Manuals can be found in Appendix A-C.

TEAM WEBSITE

The team made a comprehensive website detailing the project work. The website can be found at www.users.muohio.edu/shuklaa/vibrations.html Figure 8 below shows the organization and contents of the website.
The team feels this website is an excellent resource that will serve to update future teams on progress made by this team. Also, it can be used by other schools for use and reference on small scale road vibration experimentation.

**CONCLUSIONS AND FUTURE WORK**

The team’s final design has several advantages. First, the team has kept a continual focus on enhancing pedagogy. They feel it is important to consider the enrichment of education in every step of the design and implementation of the experimental setup. A second advantage of the final design is its mobility. The team has considered mobility in every aspect of the experimental setup. This includes a mobile cooling system, a mobile support structure, and a shaker that can be easily moved by one or two people. This is an advantage for the future since the engineering department will soon be relocated. A final advantage is user friendliness. The team realized early on that its target user was the student. Because of this the team has focused on making the setup as well as software and soon the experiments
themselves easy to use. This is important since lab time will be limited and the student should not have to spend time assembling components or experiencing errors.

The team has noted some tasks that could be completed by future design teams or those working with the experiment. This list is as follows:

- Add additional capabilities added to GUI
  - On/Off Windowing Capability
  - Averaging Capability
- Create additional lab manuals (corresponding to additional GUI capabilities)
- Enable experiment to be run from a remote location

The GUI has several accuracy improvement capabilities (on/off windowing and averaging) that could be added to it by future teams. This team did not choose to focus on these things because they wanted to develop two fundamental experiments that did not deal with accuracy. With changes made in the GUI to improve accuracy the team recommends lab manuals be written to accompany these changes. The team also recommends the same iterative user testing process be used with each new lab manual. Finally, the team recommends future teams look into running the experiment through a remote location. An example of a vibrations experiment in which remote use is enabled can be found at www.reallabs.net/Vibes/.
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ABOUT THE TEAM

There is a wide variety of engineering background within the group, with Manufacturing,
Management, Mechanical, and Environmental majors represented. This variety of
backgrounds has led to a wide array of skills, and many different approaches to problem
solving. Each member of the group shares the same feeling regarding learning style. The
group has been able to take advantage of the shared learning styles by taking a hands-on
approach to the project. An example of this is when the team scheduled a trip to see a full scale road vibration simulator at the University of Cincinnati. Two of the group members, Sarah Brady and Mandy Frederick, have taken a Vibrations class at Miami University. Mandy also spent last summer at Miami University assisting in vibrations research. Sarah and Jessica Irons also have had professional experience in the engineering industry. Their prior knowledge and ability to share this knowledge with the rest of the team has greatly benefited the group.

Each member of the group was interested in the subject matter behind this project, and the team wanted to be able to help improve the Engineering Department at Miami University. In order to simultaneously proceed with different segments of the project, the team divided into subgroups, but continued to meet as an entire group at least once a week. This ensured that every member of the group was aware and educated of all aspects of the project. In EGR 448, the group divided into 2 main sections. Due to their experience with Matlab, software development, and vibrations software, Jessica, Mandy, and Sarah focused on software development for the group. Due to their experiences as Engineering Management majors, Carolyn and Matt worked primarily on the selection and acquisition of hardware for the experiment. In EGR 449, Sarah joined Carolyn and Matt to work on the hardware segment of the project. By doing this, the group was able to maximize the skills of each member and increase the overall productivity of the group.

Once the user testing ensued, all team members joined together to do different parts to complete the whole user test. Jess and Mandy wrote a lot of the background for the lab manuals. Carolyn made a lot of the corrections suggested through the user tests and faculty feedback. Jess and Mandy also adjusted the GUI as per the comments and suggestions. Sarah, Carolyn, and Matt all made changes to the structure and set-up as per the comments
and suggestions. Sarah complied all of the suggestions and Carolyn compiled all of the changes made in the lab manuals and user manual.