EGR 448: Senior Design

Road Vibrations Simulation: Preliminary Report

Design and Development of a Road Vibration Simulator for the Miami University Vibrations Laboratory

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Executive Summary

The point of this project is to design and develop a road vibration simulator for the Vibration Laboratory at Miami University. This will test the vibration response of a component of an automobile or an entire automobile scaled down to various potential road conditions. The simulator must be able to generate input and then measure the response of the specimen being analyzed. The vibration simulator will be used primarily for educational purposes and a lab manual will be developed to coincide with the simulator. The final product will be posted to the internet so other smaller schools can mimic the design created by the team here at Miami University. The design of the vibration simulator includes many components. The simulator will be suitable for use with a scale model of an entire car as well as individual car components. The sensors used will force and accelerometers. The actuator will be an electrodynamic shaker and the data acquisition/analysis package used will be Matlab. By implementing a timeline to keep the design team on task, this vibration simulator will be finished and ready for use by students at the end of the second semester of the school year.
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Introduction and Background

Road vibrations simulators are very important in the automotive industry. Before assembling any vehicles, the parts must be analyzed in order to determine their reaction to road vibrations. There are many safety reasons and comfort factors to be considered in road vibrations analysis. While there are theoretical ways to roughly estimate the reaction these components will have to road vibrations, it is necessary to experimentally measure the actual responses to get accurate information. This simulator should be able to measure the responses as accurately as possible, and it should give students an intuitive, hands-on experiment in which to learn about these vibrations.

Problem Definition

Problem definition is a critical step in engineering design. The problem statement should include, “objectives and goals, the current state of affairs and the desired state, any constraints placed on solution of the problem, and the definition of any special technical terms (Dieter, 10).” The vibrations design team identified an overall objective, several important constraints and some general tasks within their problem definition.

Objective

To design and implement a versatile device for use in the Miami University Vibration Laboratory to simulate road noise vibrations felt by vehicles during normal operation. The experiment will be designed for use by all students regardless of their previous experience in the vibrations field.

Constraints

The constraints of the project include physical laboratory space, time, and funds. Kreger is currently home for the School of Engineering and Applied Science. Room 201 is used as not only a classroom, but also a laboratory for many engineering classes. Because of this, the design team feels lack of space is a constraint. In initial meetings it was determined that the space available for building, storing and running the experimental setup could only be the size of a tabletop. The next constraint identified is limited time. EGR 448 and 449 is a two semester series in which research and design should be completed within the first semester, leaving the second for building and implementing the projects. With only a school year, about 8 months, the design team must consider time throughout many aspects of the project. Finally, taking on such a large project requires large 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.
Tasks

The four main tasks of this project include (1) design and build the vibration experimental setup, (2) develop Matlab interface to acquire and analyze the data from the vibration simulator, (3) develop a lab procedure and manual for students and instructors, and (4) make all relevant documentation available to all of academia via Internet.

As mentioned, one aspiration of the road vibration simulator senior design is to enhance the learning experience and future engineering curricula. Education cannot be limited to learning solely from books, because of this, the project team’s primary intentions for the final device is that it be used by future engineering students and faculty at Miami University to supplement the traditional vibrations courses.

Following this idea, all four of the general tasks identified in the problem statement have an end goal of enhancing education. The road vibration simulator must have an experimental focus. Therefore, the first task classifies the device as an experimental setup and designing and building it is of primary concern for the design team. Engineering students use Matlab or other data acquisition devices to collect and analyze data during experimental procedures, thus, it is important for the design team to incorporate Matlab into the experimental setup. This allows students to use the simulator and understand it with ease. The third task listed is also of vital importance when it comes to the education process. The design team must develop a lab procedure for students to use in supplementation of vibrations courses. In addition, the team would like to construct a manual for students and instructors to refer to when using the road vibration simulator.

Finally, with a broader reach in mind, the project team would like to make all design information, data, and documentation available to academia via Internet. The project team hopes to not only enhance Miami University, but also allow other universities with limited resources to improve the learning experience of their engineering students by taking ideas from the team’s research and design to either duplicate or add to the experimental setup.

Actuators

The three primary types of actuators the team debated using in the design of the simulator were hydraulic, electronic, and impact systems. The design team primarily investigated these three types since they are the most commonly used techniques, and information on them is readily available and accurate.

Hydraulic

Hydraulic actuators operate using Pascal’s Law, which states, “when a pressure is applied to a liquid in a sealed container, the pressure is distributed across the liquid, and the pressure is the same everywhere throughout the liquid.” In hydraulic systems, a power source must supply pressure to the fluid. The pressure is the same throughout the fluid, which is consequently used to push and pull a piston.
Hydraulic systems are lightweight and compact. Low compressibility of the medium and low sensitivity to temperature are also advantages. Hydraulic actuators are best for heavy loads and high speeds allowing for large forces and accuracy. The use of fluids allows for inherent damping which results in no added vibration. The lightweight components in a hydraulic system allow for quick acceleration and low heat generation.

Some disadvantages exist as well. These systems are typically complex and require maintenance to numerous filters, fitting, valves and tubes. Maintenance must be performed by someone with expertise in the hydraulic field and frequent testing of the hydraulic oil must be done. Noise as well as leaking of oil are concerns, especially since the oil can be a fire hazard. Costs can add up quickly as a separate power source is needed as well as component replacements and energy to generate power.

Electric

Electrodynamic and electromagnetic are two different options for electric actuators. These electric actuators use an electrical power supply as a drive. The electrodynamic uses an electric motor, while the electromagnetic uses magnets and varying voltage to drive the actuator.

Both offer low noise advantages as well as low power supplies which mean lower energy costs. Electric actuators are excellent with light loads and low speeds. Electrodynamic actuators are lightweight and do not use pipes or pumps. Without the use of flammable or compressed fluids, the electric systems are environmentally safe. Neither unique nor extensive maintenance is needed in electric systems. Electromagnetic systems have a quick response time and can generate high forces.

The electromagnetic actuator is heavy and this can cause slow acceleration. Elements, such as screws or gears, within the electrodynamic actuator may transmit vibrations to the moving parts. As the parts of the system wear, the system may lose accuracy.

Research

Importance of Vibrations in Design

Vibration is a very important issue to study and analyze when it comes to design because it has many effects on the overall system and how the system performs. Safety, human factors and ergonomics, and style are three primary issues that account for vibrations considerations in their designs.

Safety

One of the primary reasons for analyzing a system’s vibrations properties is safety. Since structural integrity and coupling are affected by changes in vibrations properties, if a system is not designed to withstand the vibrations it is going to encounter, the structure could fail and human lives could be in danger. A perfect example of when vibration was not properly considered and analyzed in design is the
Tacoma Narrows Bridge Disaster. According to (**reference website**) on the Tacoma Narrows Bridge disaster, “on November 7, 1940, at approximately 11:00 AM, the first Tacoma Narrows suspension bridge collapsed due to wind-induced vibrations. Situated on the Tacoma Narrows in Puget Sound, near the city of Tacoma, Washington, the bridge had only been open for traffic a few months.” The bridge had been designed for structural grace with slender towers and shallow stiffening trusses. The bridge was so light that it behaved much like an airplane wing, generating lift with significant enough winds. On the day that the bridge failed, the wind speed was such that the bridge began to oscillate at its resonance frequency, thus causing the bridge components to fail.

Until the Tacoma Narrows Bridge disaster, designing with resonance frequencies in mind was virtually non-existent, and thus the study of design against resonance frequencies is a fairly new field. Now, experiments in the field include placing tiny accelerometers all over a structure to monitor how it is behaving and to be able to detect changes in the system behavior. This way, if there is a significant change in the behavior of the structure, the proper measures can be taken to ensure the safety of those using the structure.

Other safety considerations have to do with the modal properties of structures. Certain physical quantities are characteristic of every structure; these properties are known as Modal properties. Modal properties (resonance frequencies, mode shapes, etc.) of the structure are very closely related to how vibrations affect the system and are functions of their physical quantities; consequently, when damage in the system results in a change in the physical properties of the structure, the outcome is a corresponding change in modal properties of the structure. If these changes are too great, the integrity, and therefore the safety, of the structure will be compromised. For this reason, it is very important to consider the modal properties of all the materials to be used in a structure.

**Human Factors/Ergonomics**

Another important factor when it comes to vibrations in design is the consideration of human factors and ergonomics. According to the Merriam Webster Online Dictionary ergonomics is “an applied science concerned with designing and arranging things people use so that the people and things interact most efficiently and safely -- called also human engineering.” Therefore, vibrations is important to consider when it comes to ergonomic designs because if the vibration of a structure that a human is using is causing the person to become uncomfortable in someway, this may cause them to become less focused on using the structure properly and could lead to safety hazards. A perfect example of the importance of this issue is when it comes to driving a car. Vibrations in the structure of the car can cause fatigue and decrease the safety of the driver. According to a study done by Australian Transport Safety Bureau (ASTB), “Some studies identified vibration as a stimulant and others as inducing drowsiness…random and stimulating vibration exposure can act to increase alertness and that low frequency monotonous vibration has the
opposite effect by increasing drowsiness.” If there are many high frequency vibrations, this could keep the
driver awake as “vibration and noise exert a stimulating effect on the central nervous system, however
result in muscle fatigue in the back and arm muscles due to the strain of controlling the car. Body
chemistry changes due to the vibrations experienced when driving. According to the ASTB study, “the
increase in lactic acid is due to muscle activity in the spine directed at maintaining posture under exposure
to vibration.” This muscle fatigue could be due to changes in the body’s metabolism. Despite the reason
for increased fatigue due to vibrations, this could be avoided if the car had been designed with vibrations
and how they affect ergonomics in mind. On the other hand, if there are too many low frequency
vibrations, more similar to a rocking motion, this can increase the driver fatigue and drowsiness and also
decrease the safety of the driver. Again this could have been avoided had vibrations been considered in
design. In general it was found that drivers became more fatigued from a large amount of low frequency
vibrations rather than a large amount of high frequency vibrations, however, regardless of the type of
vibrations induced on the driver by the car, high and low frequency vibrations are both dangerous and
therefore need to be considered in the design of cars and any other structure where the user can be
negatively effected by the vibrations the structure causes just due to normal use.

Style

Another aspect when it comes to the importance of vibrations in design is the style of the structure. It
is possible to tune the engine such that it vibrates at a certain frequency to give a desired sound. This is
usually done for cosmetic reasons, such as the Ford Mustang, which has what one would call a signature
sound. Harley Davison has actually patented its sound and now each new Harley Davison engine must be
tuned to that desired, patented frequency or it is not of acceptable quality for the Harley Davison Company.

Trip to University of Cincinnati Vibrations Lab

One of the first steps in the team’s research was to visit the University of Cincinnati’s vibrations
laboratory in order to get an idea about what a vibrations simulator looks like and how such a system
works. The team was unable to go at a time where they could see the simulator in operation; however, the
team was able to get an idea about what types of components go into such a the design of such a structure.

A picture of the simulator used at the University is shown in Figure 1.
This simulator is very large scale. An entire car can be driven onto the simulator for analysis and a separate controls room is used to monitor the forces going into the car, as well as the vibrations effects which result on the system. Hydraulics are used as the force of power for the simulator and each wheel is placed on one of the four hydraulically operated shakers. A specially designed floor built on top of springs is used to isolate the experiment from vibrating the rest of the building during the experimental testing.

The simulator is part of the SDRL (Structural Dynamics Research Laboratory) at University of Cincinnati, which has a large list of corporate sponsors. The Boeing Company, Ford Motor Company, General Motors Corporation, Hewlett Packard, Leuven Measurements and Systems (LMS), The MathWorks, The Modal Shop, MTS. Noise and Vibrations Division, PCB Piezotronics, Pemtech, Structural Dynamics Research Corporation (SDRC) and Vold Solutions all cooperate with UC’s SDRL laboratory in some form.

Discussion of Primary Design Components

Building a vibrations simulator like the one used at the University of Cincinnati would require a much more space, funding, and time than the team has available for their project; consequently, the goal is to be able to scale down UC’s design and create a table top simulator that can be used to conduct an experiment with the same principles in mind. Although the simulators will have obvious differences, the four major components needed in the design remains the same: the physical structure, sensors, actuators, and data acquisition and analysis software. The following section discusses some of the team’s research and reflection on each of these components:

Physical Structure

The first consideration the team debated was what physical structure to test using their simulator. An entire car, an entire scaled model of a car, or individual car components were all options for what object should be tested. Testing an entire car was eliminated immediately on account of a lack of space and funding available. The next consideration was the level of intuitiveness involved in the design. Since the
simulator was designed with the goal of being used for a beginner’s vibrations experiment, the team wanted to make the design very intuitive in order for students to be able to readily see the real world applications involved. The team believed that using an entire scaled down model of a car supported this goal. Also, if individual car components were to be the subject of testing, the experiment would want to eventually relate the effects on the individual components back to see the entire ride of the car later in the experiment. A system of relating the two would have to be developed, and consequently, by testing an entire scaled down model, this step can be eliminated from the process.

Sensors

Two types of sensors will need to be used in this experimental setup. These are force sensors and accelerometers. Force sensors will be used to measure the input force applied to the system by the actuator. The team will need to select their actuator before they can select a force sensor that can be used in combination to accurately measure the impact. Miami University already has three accelerometers available to be used in the experiment. The team hopes to use these readily available accelerometers in order to cut back on some of the costs involved with the project.

Actuators

The three primary types of actuators the team debated using in the design of the simulator were hydraulic, electric and impact systems. The design team primarily investigated these three types since they are the most commonly used techniques, and information on them is readily available and accurate.

Hydraulic

As previously mentioned, hydraulic actuators operate using Pascal’s Law, which states, “when a pressure is applied to a liquid in a sealed container, the pressure is distributed across the liquid, and the pressure is the same everywhere throughout the liquid.” In hydraulic systems, a power source must supply pressure to the fluid. The pressure is the same throughout the fluid, which is consequently used to push and pull a piston. The vibrations simulator used at the University of Cincinnati, as well as the Model 3.53.10 Multi-Axial Simulation Table, both have impact forces powered by hydraulic systems.

Hydraulic systems are lightweight and compact. Low compressibility of the medium and low sensitivity to temperature are two additional advantages. Hydraulic actuators are best for heavy loads and high speeds allowing for large forces and accuracy. The use of fluids allows for inherent damping which results in no added vibration. The lightweight components in a hydraulic system allow for quick acceleration and low heat generation.

Some disadvantages exist as well. These systems are typically complex and require maintenance to numerous filters, fitting, valves and tubes. Maintenance must be performed by someone with expertise in the hydraulic field and frequent testing of the hydraulic oil must be done. Noise as well as leaking of oil
are concerns, especially since the oil can be a fire hazard. Costs can add up quickly as a separate power source is needed as well as component replacements and energy to generate power.

**Electric**

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The electromagnetic actuator is heavy and this can cause slow acceleration. Elements, such as screws or gears, within the electrodynamic actuator may transmit vibrations to the moving parts. As the parts of the system wear, the system may lose accuracy.

**Impact**

Impact testing is the third option the team has considered as the actuator for the applied vibration force. In impulse testing, the input force to the system is a single impulsive force applied by a specially designed impact device, such as an impact hammer. Force sensors are present inside the impact hammer which measure the impulse force the hammer is applying. Due to the reciprocity theorem, which basically states that the properties of \( (X/F) \) are the same as those from \( (F/X) \), it is not necessary to have both input and output response measurements for each data point that the system hopes to monitor. Each point only needs to be either hit by the impact hammer or have an accelerometer, but both are not necessary.

There are several benefits to impact testing. It can be said that “the usefulness of the impulse technique lies in the fact that the energy in an impulse is distributed continuously in the frequency domain rather than occurring at discrete spectral lines as in the case of period signals. Thus, an impulse force will excite all resonance frequencies within its useful frequency range.” (Halvorsen) This basically means that impact testing can capture all of the same results as the other two methods for system excitation, and achieve a relatively accurate representation of the system’s vibrations properties in doing so. Impact testing is also simple and fast, as well as inexpensive and portable.

One of the largest downsides to impact testing is that it is not a very intuitive method of testing, one of the primary goals for the team’s experimental design setup. It is doubtful that vibrations beginners would believe that the force applied by an impact hammer can represent a road vibration as accurately as an electrical dynamic shaker. Also, impact testing is very subject to human experimental error. In order to obtain the most accurate results, it is desirable to average multiple hits on the system. In doing so, testers need to make sure that they are striking the exact same place each time they repeat the experiment. They...
also must strike the object being tested directly along a single axis of impact in order to obtain accurate results and be sure to only strike the system twice, for if vibrations cause a second impact to take place, the results on the system will not be accurate. Lastly, impact testing is ineffective for exciting larger structures and can result in non-linear behavior due to large impulse amplitudes. (** reference)

Selection

The goal of enhancing the educational experience of vibrations students at Miami University was one of the primary considerations in selecting the actuator to be used in the vibrations simulator design. Since the target audience is students with little previous experience, the team wants to make the design very intuitive in its application to real-world situations. Consequently, the electrodynamic actuator devices have a major advantage in that an electric motor is the most intuitively similar to the forces that would be applied to an automobile in a real road situation, whereas the hydraulic and impact actuators are unlikely forces to be encountered.

The constraints of time, cost, and physical laboratory space all come into play in making the hydraulic actuators an unfavorable option. As mentioned previously, hydraulic systems require experienced operators, considerable funds and space, and can have dangerous consequences if the system malfunctions or is misused. Hydraulics are also generally used in high-force and high-load situations which, although necessary for testing an entire automobile in a setup like University of Cincinnati’s experiment, would likely be unnecessary for testing a scaled-down model of a car. Maintenance issues involved in hydraulic system upkeep is also a disadvantage over the more self-sufficient electric devices. Impact testing is subject to human error, and consequently, with inexperienced beginner students, inaccurate results would be more likely to occur. In addition, electrodynamic actuators have been found to be more versatile in application, and as stated in the team’s problem definition, one of the goals of the experimental setup is versatility in its design.

Taking all of these considerations into account, the team has decided that electrodynamic shakers are likely the best option for this experimental setup. The team has begun to investigate costs for several different models of small electrodynamic shakers. See appendices for several of the specific actuators which the team has researched. The team is currently leaning towards use of the MB Dynamics Modal 50A Electrodynamic shaker. One of the benefits of this particular device is its lightweight, compact design, which make it portable and easy to setup. Another advantage is that the device is designed to excite small structures, making it applicable to the team’s scaled-car testing setup. One of the largest benefits is that the team has already acquired a quote from the company and knows that the device is reasonably priced and readily available, as the company is located in Cleveland, OH. This is a major advantage over some of the other designs which were available overseas and thus would take a longer time to order and would be harder to communicate with if problems were encountered with its implementation into the team’s
simulator design. The quote also includes a power amplifier and accessory kit, which eliminates the need for further research to acquire compatible components.

**Data Acquisition and Analysis**

*Matlab*

Matlab is a software program designed to aid in the mathematical analysis of system models and experimental analysis. Some of the capabilities of Matlab include technical computing, control design, test and measurement, and image processing. In this experiment, the goal will be to develop the capability to integrate Matlab into the experiment in order to collect and analyze the experimental data. Matlab will also likely be used to obtain transfer functions (graphs of the system output/input with respect to time) and other relevant vibrations graphs for the laboratory experiment.

*LabVIEW*

An alternative to MatLab is LabVIEW. LabVIEW is another software program that can provide a graphical way for the group to acquire and measure the signal, analyze the measurements, and present the data in an easy-to-use fashion. It is advertised to be easier to use than other traditional development tools.

**Selection**

Although research is still being done about the pros and cons of each of these software alternatives, as well as specifics about how they are to be integrated into the team’s overall design, the group is leaning towards use of Matlab primary due to more extensive experience with this software. Three of the students have had at least some previous experience with Matlab, and two of the students have used Matlab in a vibrations-based experiment for data acquisition as well as analysis. In addition, research thus far has not concluded that LabVIEW’s data acquisition and analysis capabilities are superior to Matlab’s in a way that would counteract the benefits of using Matlab.

**Other Considerations**

It is likely that other design considerations will develop as the team progresses further in their design of the vibrations simulator corresponding experiment and lab manual. One such consideration that was brought up in the visitation to the UC vibration testing facility was that of proper system isolation. Taking into account the team’s constraints on space and funding, having a specially isolated floor such as UC’s is not a practical design. Bungee chords and foam were two ideas brought up by the team to be used in this experiment. It has also been found that systems can be isolated by supporting them with cork, springs, or other special bearings. Each of these possibilities will be investigated further as the design process progresses.
Conclusions and Future Work

Conclusions

The design and development of a road vibration simulator for the vibration laboratory has many components to it. The initial component to be decided upon is the physical structure to be used as the specimen being tested. The three preliminary ideas for this were an entire car, an entire car scale model, or an individual car component. The design team chose to design the simulator for use with either an entire car scale model or with individual car components. The next component to be decided upon is the type of sensor to be used. The two main preliminary ideas for this were force sensors or accelerometers. After performing some initial research, it was decided that a force sensor would be used to measure the input while an accelerometer would be used to measure output. The third component to be decided upon is the actuator. There were three preliminary ideas for this: an electrodynamic shaker, a hydraulic shaker, or an impact tester. The design team decided, after performing much research, that an electrodynamic shaker would be the most suitable option for this simulator. The final component that needed to be chosen was the type of data acquisition/analysis package to use. The preliminary ideas were Matlab, LabView, Wireless, or Desktop. Matlab was chosen as the type of data acquisition/analysis package to be utilized due to the fact that the majority of the design team members have had prior experience with Matlab.

Future Work

The design team working on the road vibration simulator for the vibration laboratory has decided upon a rough timeline to ensure finishing implementation of the design in a timely manner. The first semester deliverables are as listed below.

Design Development and Component Selection

The design team will continue to work on the design of the simulator using knowledge gained from continuous research. Once the design becomes more finalized, the components suitable for use will be narrowed down and eventually specific components will be selected.

Purchase Components

Once the design team has selected specific components, suppliers will be researched. Once the most cost effective and convenient supplier is selected, purchasing of these components will ensue.

Test Components

After the components are received, the design team will test each one to make sure it performs as desired and is reliable and durable. This deliverable will continue into the second semester of the school year due to the amount of components involved in assembling the road vibration simulator.

Develop Data Collection/Analysis Software

Developing the data collection and analysis software will be a very intricate part of the road vibration simulator and will require quite a bit of research as well as time for debugging. This part of the design
project is essential because it allows for interpretation of the acquired results and will aid any student using the simulator in understanding its purpose. Due to the tediousness of this deliverable, it will continue into second semester of the school year.

Writing of Final Report

The final report will be comprised of items gathered and written about this semester as well as next. Due to this fact, the final report writing has already begun. This deliverable is not formally due until the end of the second semester of the school year so it will continue through the second semester.

In order to deliver these first semester items on time, the design team will cooperatively work together to finish intermediate tasks thoroughly so the larger deliverables will be feasible and not too overwhelming. The design team will continue to have weekly meetings as well as more informal meetings to stay on track with the projected timeline on the attached Gantt Chart in the Appendix.

References


About the Team

There was 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 learning style. The group was able to take advantage of the shared learning styles by taking a hands-on approach to the project, for instance scheduling a trip to see a full scale road vibration simulator at the University of Cincinnati. Two of the group members, Sarah and Mandy, have taken a Vibrations class at Miami University, and Mandy spent last summer at Miami assisting in vibrations research. Sarah and Jessica also 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. Although small tasks were occasionally divided up between group members, the main tasks were accomplished as a group.
Appendices