Miami University
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Modal Analysis of a Simple Metal Pipe
Water Pipe Simulation

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Executive Summary

This project was designed to test how input excitation frequencies affect water pipes in buildings, houses, or other structures. Pipes may be excited by fluid flow, pressure changes, or by outside sources near pipe locations. An experiment was completed to determine how these excitations affect a 22-inch long, 2-inch diameter piece of metal pipe. This pipe was used to simulate the effect of input frequencies on metal water pipe. The pipe was excited using an excitation hammer and data was collected during the experiment using a single degree-of-freedom accelerometer. The output of the load sensor on the excitation hammer and the output of the accelerometer were recorded with Microsoft Excel. From this data, Hammer output versus accelerometer output was plotted. The graphs were developed in order to determine the quality of the data collected. Once the graphs were completed, the data was inputted into Matlab for further analysis. After the data was input into Matlab, graphs of the transfer functions were plotted. The transfer function graphs were analyzed to determine where peaks occurred. Sharp peaks indicated that the pipe might resonate at that frequency for long periods. These peaks also indicated that the pipe was under damped. Using a simple mass-spring-damper principle, it was possible to propose ideas for improving the system in order to eliminate the possibility of exciting the pipe at a resonant frequency.
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**Introduction and Background**

Water pipes throughout many structures such as buildings, houses, and sewers, are bombarded by many frequencies waves. These waves can take place naturally or can be created by the motion of objects. Items such as motor vehicles, machine tools, and electronic devices are just a few of the things that create and perpetuate otherwise unnatural frequency waves. These waves known simply as vibration, affect almost everything around them. Vibration caused by rotating parts of a combustion engine, greatly affect the design of the components surrounding the engine. Like in a motor vehicle, vibration analysis has become a large part of design.

Water pipes undergo much of the same barrage of vibrations that pieces on a motor vehicle endure. Even though this vibration isn’t usually caused by the rotation of a combustion engine, water pipes can be affected by vibration caused by internal fluid flow, shock waves caused by the sudden change in flow, machine tools in close proximity to those pipes, or electrical devices operating in proximity to the pipes. These vibrations occur in ranges that can be heard by the human ear somewhere between 20 and 20,000 Hz, or they can occur at many other ranges that cannot be heard. When designing something as simple as water pipe configuration for a buildings water supply, vibration analysis needs to be considered. If vibration analysis is not completed, it is possible that early fatigue, resonance, or pipe fracture could occur due to the vibration of the pipe. Vibration analysis allows engineers to determine what frequencies a structure naturally vibrates at, and allows them to analyze the affects of other vibrations acting on the structure.

After initial research, an experiment and analysis was completed in order to determine the resonant frequencies of a simple piece of metal pipe. The following report includes details of the experiment, problems with the experiment, experimental analysis, and improvements based on the analysis completed.
**Literature Review**

In order to find other research projects pertaining to this system, very specific searches had to be conducted. The articles researched dealt with fluid flow and their effects on the vibration of the structure. In the case of a water pipe system, there are several factors that can cause the excitation frequencies which results in the pipes resonance. These changes can be the result of fluid flow, pressure changes, or by outside sources near pipe locations. The goal of much of the research conducted has been to find out what factors contribute to this vibration and how to reduce them. One of the articles researched provides information on cavitation and waterhammer, both of which contribute to pipe vibration. Waterhammer is essentially a pressure surge which is created by sudden changes to steady flow conditions. Cavitation is when the pressure falls below a certain pressure causing the pipes to vibrate.

Aside from reviewing literature on the subject matter, a great deal of research was conducted at the beginning of the semester during the classes visit to the Arvin-Meritor plant in Columbus, Indiana. On the trip, various techniques used to minimize vibrations in a system and to analyze vibrations in a system were shown. One analysis method that proved to be very applicable to this project was that involving the excitation of the system and its measured frequency response.

Some of the literature researched proved to be somewhat useful, however much of it was too specific and complex to be directly applied to this project.


**Research Approach**

In analyzing the metal pipe structures in Kreger Hall, information regarding the causes of noise as a result of pipe vibration and what can be done to stop it was researched. Websites were a valuable source of basic information regarding this topic. In analyzing the system, many different variables had to be eliminated. Since the pipe vibrates as a result of an excitation frequency, a reduction in the excitation frequency directly correlates to a reduction in the vibration of the system. For this reason, it was decided that testing needed to be performed that determined the frequency response of the system to an excitation force. It was decided that the method to be used should be very similar to those done at the Arvin-Meritor plant. The equipment available in Kreger would allow for a slightly more simplistic version of this test to be performed. The experiment to be used would involve exciting the structure with an impact hammer. A special type of hammer would need to be used in order to measure the force on impact. In order to measure the frequency response of the system, an accelerometer would need to be used. The analysis of the data provided by this experiment would then allow these desired frequencies to be determined.

In any pipe system there are many different types of pipes. Although the pipes are almost always made out of the same material throughout, their width, length, shape (curves), pressure and temperature can vary. The pressure and temperature varies as a result of the fluid flowing through the pipe. It would not be possible under the limitations of the experimental equipment available to account for these factors in the modal analysis. For the purposes of this experiment, it was deemed more feasible to eliminate these variables from the system and analyze a single straight pipe. Although a great deal of vibration is occurs in bent pieces of pipe when the fluid hits the side of the pipe it would not have been feasible to test multiple shapes of pipes. Another variable that was considered was the extent to which the system would be isolated. In the working system, hangers are used to attach the pipes to the supports. However, if accurate impact testing was to be performed, it would be necessary to isolate the pipe from the system. If the pipe was not isolated from the system, the resulting data would not be possible to analyze. In order to isolate the pipe from any surrounding systems, it was determined that it would need to be placed on some sort of cushion or suspended from a bungee apparatus. The bungee apparatus was ruled out due to lack of availability.
Experiment

To complete the experiment, a 2 inch diameter 22 inch long metal pipe was used to simulate the makeup and geometry of a water pipe. The pipe was divided into seven equivalent sections to be analyzed. The center of each of the seven sections was marked with a number by a marker. As seen in the figure below, the marks were made along the axis of the pipe in line with each other. The marks on the part are indicated by the small yellow dots.

The picture below shows the orientation of the accelerometer. The position of the accelerometer is a critical part of the experiment. The accelerometer was mounted in the first section of the part directly on the first mark. Wax was used to hold the accelerometer in place. Because the accelerometer is a single-degree-of-freedom accelerometer, it can only measure movement in one direction. The way this accelerometer is placed on the part shows that the direction of wave propagation in this part is in the z-axis, or vertically.

The placement and orientation of the accelerometer means that the object must be excited in a certain manner. This experiment included the excitation by an impact hammer. Since the accelerometer was placed on the part vertically, it is critical that the hammer strike the surface of the part from a vertical direction parallel with the mounting of the accelerometer.

To complete the experiment, once the measurement locations were determined and the accelerometer was mounted, the data acquisition system was set up. The system used to record the data included an IBM PC with Microsoft Excel, two sensor signal conditioners, a cable to attach the accelerometer to the sensor signal conditioner, coax cables to attach the signal conditioners a circuit board, a circuit board, and an impact hammer. Shown here is the configuration of all the measurement and data acquisition components. The impact hammer is connected to the “sensor” socket of one of the signal conditioners with the attached coax
From the same signal conditioner, another coax cable is attached to the “scope” socket of the signal conditioners. This coax is then connected to the “0” slot of the circuit board. The accelerometer cable is attached to the other signal conditioner in the “sensor” socket. The “scope” socket of that signal conditioner is then connected to the “1” slot of the circuit board using another coax cable. The circuit board is connected to a sensor card installed in the IBM PC.

It is also important that the object being tested be isolated from other masses. This is important because the addition of masses will change how the energy or the frequency inputted into the pipe by the impact hammer is dissipated throughout the object. The best way to isolate the pipe would be to keep it from touching anything but the experiment tools. However, since this is not possible, the object should be isolated from any masses by an isolation pad or hung using elastic cords. It is important that whatever isolation device is used is made of a material with a small mass and has a low ability to propagate vibration. In this experiment a soft foam pad was placed between the pipe and the table to isolate the pipe from its surroundings. The isolation material is the pink foam shown in the figures above.

After all the components are correctly connected and the batteries in the signal conditioners are checked, the experiment can take place. The experiment will use Microsoft Excel to record the voltage output of the accelerometer and the voltage output of the impact hammer. Using the program in Excel, the recording frequency, sampling rate, file location, and many other features can be changed to record only the information needed. These things can be determined after a trial run. After adjusting all of the features of Excel, the impact hammer is used to strike the metal pipe on the marks previously identified. Before each strike of the hammer, the recording program can be started. After the first mark is struck, the program should be allowed to complete. This will help ensure the excitement from the first impact will be completely damped. When the data is being recorded it may be helpful to graph the data while being collected. This will make it easier to determine if the sample rate you have chosen is correct and that the data is acceptable.

Once the data has been collected for each mark along the axis of the pipe, the data can be analyzed. Before disconnecting the data acquisition system, it is important to verify that the data is acceptable. This can be completed by a quick graph of the data that was gathered in Excel. Things to look for include excessive input amplitudes from the accelerometer at multiples of 60 Hz. These amplitudes indicate noise caused by electronic devices near the experiment. If all of the peaks occur at these locations the data that has been collected is probably inaccurate and the experiment should be rerun.
Experiment Concerns

Some of the problems that can arise when recording the data include incorrect or loose connections, excessive noise near the location of the experiment, and incorrect isolation material supporting the pipe. If all of the cables connecting all of the devices are not connected correctly, data errors may occur. The data recorded may end up being the electrical noise the instruments or wires have gathered from electrical devices near the location of the experiment. It is also possible that the data collected will not show up on the transfer function graphs when analyzing the experiment.

If the experiment is completed in a location where excessive noise is being emitted by other devices, this noise will show up in the experiment. The noise will show up as peaks on the transfer function graph at multiples of 60 Hz. The noise is actually frequency waves or vibrations emitted by electrical devices. The experiment should take place in an isolated location away from electric motors, computers, excessive electrical wiring, machine tools, or other items that may produce noise in the form of frequency waves. If the experiment picks up noise, it will be seen once the data is analyzed and the transfer function plots are completed.

Incorrect isolation material between the pipe being tested and the ground can also cause errors in the data collection. If the pipe is not properly isolated from other rigid bodies or masses, the excitation input by the impact hammer will propagate and dissipate differently than they would if the pipe was isolated. The data recorded will not represent how the pipe reacts to impact forces on the pipe alone, but as a system that includes other rigid bodies that are not isolated from the pipe.
**Data Analysis and Observation**

After completing the experiment, the data gathered in Excel was analyzed using Matlab. The accelerometer data recorded was plotted versus frequency for each point. This was done because each point on the pipe should show similar peak frequency values. This is based on the principal of reciprocity. Reciprocity is based upon the mutual dependence of two points. Experimentally the principal is used because the response of each point on the pipe depends on each other. This principle makes it possible to leave the accelerometer in one location while using the impact hammer to hit the other points marked on the metal pipe.

When the accelerometer data is plotted versus frequency, the common peaks can be more easily analyzed when the data from all points are plotted on one graph. Using only the acceleration makes it easy to see how the of the forced impact hammer wave propagates throughout the pipe. This is also the first graph that should be plotted in Excel to ensure that the data being collected is acceptable.

Once the accelerometer data is plotted in Excel, the data can be inputted into Matlab for further analysis. Since two trials were completed to ensure one of the two sets of data was acceptable, two graphs of the accelerometer data were completed. Shown below in the two figures is the result of all of the point data recorded. The different colored lines indicate the response at the accelerometer location due to impact by the impact hammer at different points along the pipe. Those points are indicated in the key of the graph.

An easy way to determine if the data is acceptable is to identify peaks that occur for multiple impact points. This is very visible below in both graphs below. For the first
experimental trial, peaks at 36 Hz, 173 Hz, 245 Hz, and 293 Hz were identified by the graph labeled “Trial #1 Accelerometer Amplitude,” as being points that occur at multiple impact locations. This proves that the data is reasonable and that these are probable resonant frequency locations. Since these are resonant frequencies that the metal pipe can be excited at, these are the frequencies that should be eliminated in order to improve the vibration qualities of the metal pipe.

The second graph labeled “Trial #2 Accelerometer Amplitude,” shows the same results as the first trial. Many of the same peaks occurred at the same frequencies as in the first trial. Some other peaks were also noted at 340 Hz, 400 Hz, and 420 Hz.

Once the graphs of the accelerometer data were completed, graphs of the transfer functions were plotted. The transfer functions combine the data collected from the accelerometer and the data collected from the impact hammer. These functions make it possible to see how the impact created and affected the data recorded at the accelerometer. However, the graphs of the transfer function proved to contain a lot of noise. It was hard to determine the difference between the noise collected and the actual data that was gathered. Because of this problem, a Matlab function was used to create plots of the estimated transfer function. Matlab creates a plot which helps reduce the noise visible in a regular transfer function graph. The graph below is the estimated transfer function graph of the first trial labeled “Transfer Function Estimation of Trail #1”. This graph shows the amplitude of the transfer function estimator versus frequency for each impact point. Though it is not as easy to see, some of the similarities between the
points are still visible. Because of the inaccuracies in the transfer functions, the accelerometer data was used for the conclusion of the experiment.
**Design Studies**

Based on the data observation and analysis, there are many design improvements that could be made to help eliminate the effects of harmonic excitation on a metal water pipe. Some of these improvements are actually in use today. Some of the more reasonable improvements include mounting water pipes using vibration isolators, using elastomeric joints, and changing the pipe material from metal to plastic.

If all water pipes were hung using vibration isolators, virtually all resonant frequencies could be properly damped. Vibration isolators on pipes are a lot like the isolators used on the exhaust of a car. These devices are often made up of a soft rubbery material with a reasonably high stiffness value and a high damping value. The high stiffness value holds the pipe in place and the high damping value dampens almost all of the resonance vibration caused by external sources. These devices could be added to current pipe hangers by means of surround a pipe with one of these materials before the pipe is clamped into place or by using isolators as structural members between the pipe and the pipe hanger. Using isolators will help eliminate the transfer of frequency waves from surrounding structures and will also help dampen excitations imposed on the pipes by waterhammer or fluid flow.

Another way to help eliminate the chance that a water pipe will be excited at resonant frequency is by using elastomeric joints. These types of joints are often used in buildings that are built in areas that are susceptible to earthquakes. The joints allow individual pipes to move independently and gives pipe systems flexibility. These joints help dampen any excitation from one portion of a pipeline to another. They are usually made of a plastic of rubber material that is flexible. The addition of these joints will reduce audible noises from pipes and can eliminate any fractures in the pipes.

It would also be possible to use a different type of material to help eliminate resonance in pipes. Depending on the properties of the materials chosen, pipes can be used that have different stiffness and damping values. If the pipe material was changed from metal to plastic, plastic may help eliminate resonance completely. Because of the properties of plastic, propagation of excitation waves can be damped more quickly.
Conclusion and Future Work

The goal of this project was to analyze a metal pipe system and design methods to reduce the amount of noise that results from the vibration of the pipe. To accomplish this, a straight piece of metal pipe similar to those found in the system was experimented with and then analyzed. The experiment consisted of the excitation of the system by striking designated locations with an impact hammer. The vertical acceleration of the piece was measured with an accelerometer and the data was transferred to an Excel worksheet. The first step of the analysis involved converting the data into a Matlab readable format. The data was then transferred into the Matlab program. In order to view the various modes, Fourier transform was performed on the acceleration results and force results. The modes of the system that were found are considered resonant frequencies. By attempting to reduce the magnitude of these frequencies, when the system is excited, it will not vibrate as much.

One of the ideas considered for reducing these frequencies involved the implementation hangers that are vibration isolators. Using isolators would help eliminate the transfer of frequency waves from surrounding structures and would also help dampen excitations imposed on the pipes. The other two main ideas involved using elastomeric joints and changing the pipe material from metal to plastic.

Future work to be done on this system would involve more tests on different shapes of pipes. This way the various resonant frequencies that exist throughout the system could be determined. Much of the future testing would center around the potential improvements to the system. Various types of vibration isolators could be developed and the magnitude of the resonant frequencies measured with the vibration isolators as part of the system.

Other future work could be the creation of a computer simulated model. This way more complex systems would be able to be analyzed much easier.
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Appendices