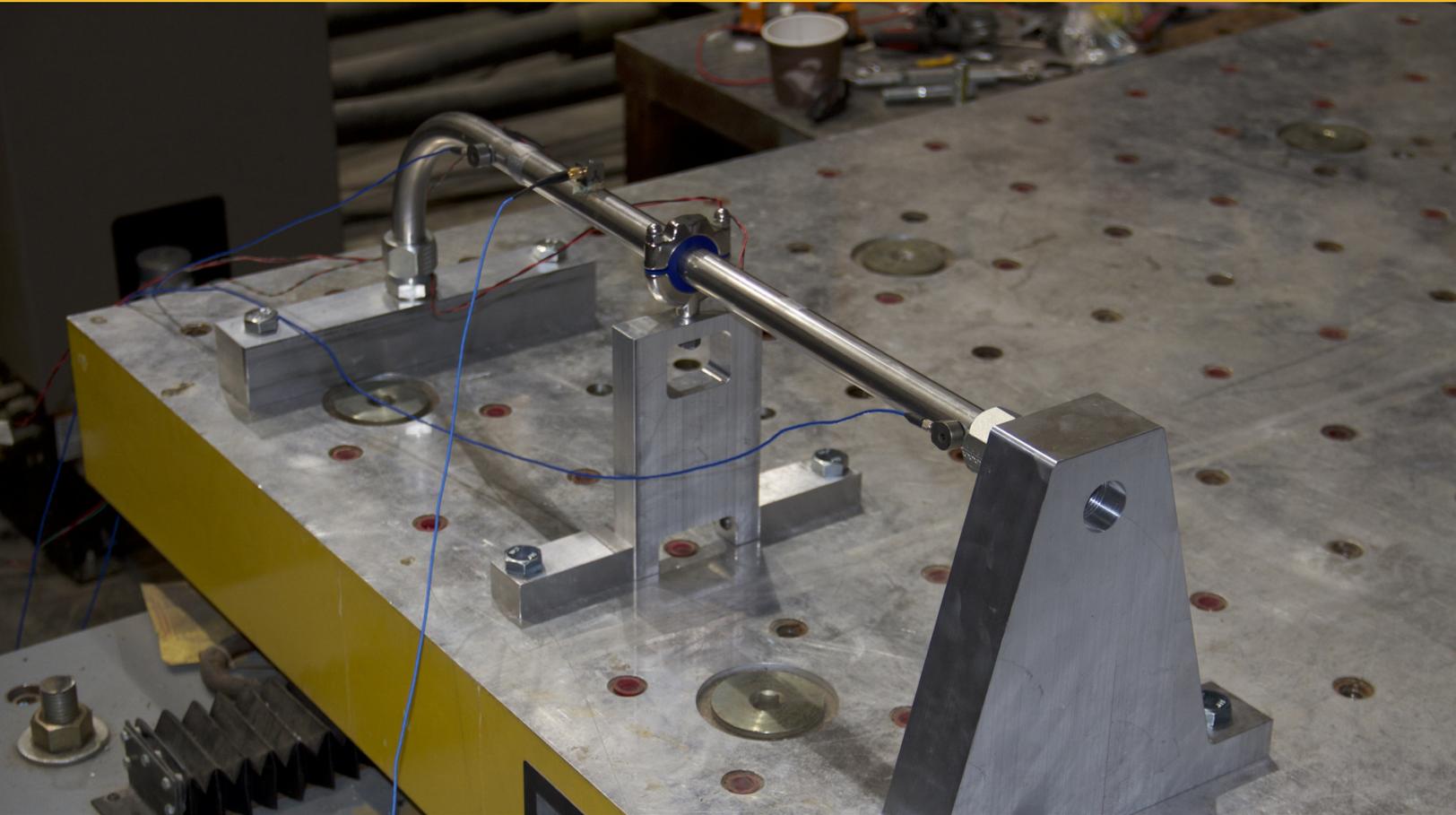


Understanding and Mitigating Piping Vibration



Client Sponser - Mohammed Alkaabi - Shell

Director - Stefan Berkower

Team - Joseph Borgerding, Isaiah Brooks, Austin Maes, Nestor Montejo,
Grant Stewart, Andrew Townsend

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Team Introduction



Andrew Townsend

Project Manager

Andrew was in charge of all team, director and client meetings, keeping the project on its timeline and assisted simulations, fabrication and testing.

Austin Maes

Logistics Manager

Austin acted as the main point of contact to the client. He handled meeting logistics, team scheduling, as well as assisted in testing and documentation.

Isaiah Brooks

Test Engineer

Isaiah coordinated all testing as well as helped start system design. He also helped simulate and analyze system data.

Grant Stewart

Manufacturing Engineer

Grant was the main fabricator for all of our systems, and their respective drawings. He helped develop designs and mitigation techniques.

Joseph Borgerding

Financial Manager

Joe made sure the team stayed on budget as well as contacting vendors and placing orders. He also helped the team stay on time by taking charge of simulations, and data analysis.

Nestor Montejo

Systems Engineer

Nestor helped determine sensor usage, calibration and application and was key in helping with testing and data analysis.

Project Overview

The main goals of this project were: to understand failure in piping systems due to vibration, to understand sources of vibration, to understand how sources of vibration can be simulated, and to understand how to mitigate against vibrations to ultimately lengthen the lifetime of system pipelines.

The first step in this project was to gain a full understanding of common vibration sources found in factory use. Vibration can be caused by mechanical forms of excitation, such as compressors, turbines and pumps. Vibration can also be caused by internal fluid flow. After conducting research it was determined that the vibration caused by fluid flow was much less than that of the mechanical sources. Because of this, it was decided to ignore fluid vibration. It was also necessary to understand what causes systems to fail. The Energy Institute (EI) guidelines for piping vibration offered a table in which systems response could be classified as: problematic, concerning, and acceptable. Our goal here is to create a system with a problematic response and mitigate that into an acceptable response.

The next step was to design piping systems that represent common designs found in industrial pipelines. The three most common designs in a system include: straight pipe (cantilevered),



Isaiah, Nestor, and Joe securing the expansion loop to the CIEST vibration table

90 degree bends, and expansion loops. Additionally, all bends needed to be three times the radius of tubing diameter, per industry standard. These systems were to be tested on a vibration table, and were therefore limited in size to fit specific parameters.

Next, the designs needed to be simulated on SolidWorks. SolidWorks is a 3D computer aided design (CAD) software that allows modeling and simulation of custom designed systems. This was necessary in order to gain understanding of how the systems will respond when testing begins. Also, CAD was used to iterate designs to adjust the response into what is considered problematic.

After system designs were finalized, the next step was to develop methods in which the vibration response could be mitigated. This was done using restraints, as was recommended by our client.

From there, testing began with inputs determined from the EI guidelines. Tests were conducted both with and without mitigation applied to show the impact the mitigation techniques had. Results were analyzed and a final report was generated with suggestions on how vibration in piping systems can be avoided while using restraint mitigation.

Designs

The three systems that were designed included: an expansion loop, a cantilever and a 90 degree bend system. These were chosen because they are the most common elements found in industry. The cantilever system represents straight pipe. The 90 degree bend system represents the corners of piping systems that change directions. The expansion loop system is frequently used in piping systems to alleviate stress caused by thermal expansion. Typically, these systems would be made from piping, whereas our systems were made from tubing. The only difference is the size and dimensions. Piping is much larger and due to the restraints of our testing parameters, our systems needed to be made from steel tubing. Given the assumptions made, the results are characteristic of a piping system.

All specifications were provided by our client to match industry standards. All systems were made out of 304 stainless steel with: outer diameters of one inch, wall thickness of 0.065 inches, and bends at three inches radii.

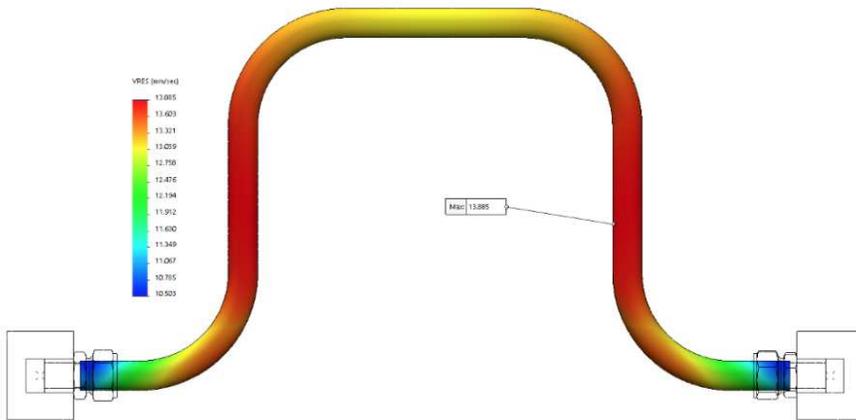


All 3 systems: Expansion loop (left), Cantilever (middle), and 90 degree bend (right) rendered in SolidWorks with restraints applied

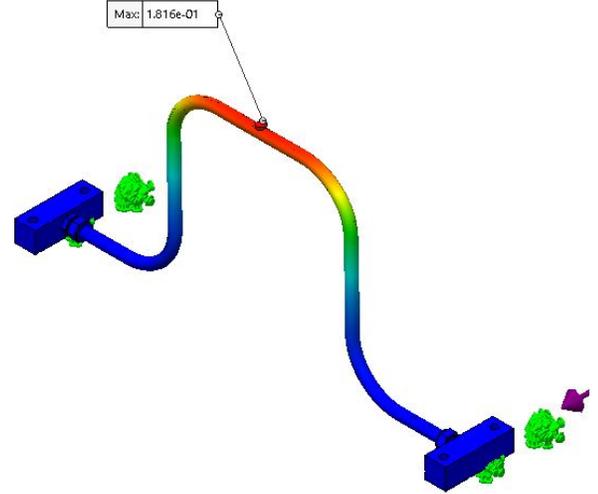
The rendering above shows the final iterations of all three systems, with the expansion loop on the left, the cantilever in the middle, and the 90 degree bend on the right. These systems were iterated multiple times to get vibration responses that were of a problematic range that could induce failure via cracks and fractures. This response range was defined through the EI guidelines. Once these systems had a problematic response, it was easier to recognize that mitigation was required.

The next step in the design process was to develop mitigation techniques for the systems that would decrease overall stress and velocity responses. Based on client suggestion, simple restraints were introduced as our form of mitigation and can be seen in the rendering above. The idea behind these restraints was to shorten the lengths of free piping by adding supports, which help to reduce vibration response. Additionally, fixed supports are practical to apply as real piping systems can usually be anchored down to a fixed point. Because of this, fixed supports are the most common application in industry.

Simulations



Velocity simulation with vibration direction into and out of the page



Simulation showing maximum velocity at center of expansion loop

Designs and simulations were done simultaneously throughout this project. Simulations were important in the design process because they allowed an insight into the response of a system to a given input without the need for physical testing. We were able to analyze how these responses changed once specific geometry had changed such as pipe length and different locations of fixed restraint.

These simulations were run in SolidWorks Simulation, the software that was used to draft the systems. There was a steep learning curve in this section of the project because we needed to learn how to successfully run a simulation with our given inputs. These simulations returned values for max velocity and max stress. We chose to focus on velocity and stress as our metrics to compare against mitigation. Also with simulations, we could easily find the natural frequency of a system. The natural frequency of a system is the frequency at which the system response blows up, meaning it induces very high stresses and velocities. Also referred to as the systems resonance, it was important to know so it could be shifted with mitigation. Shifting the resonance effectively reduces the amount of time a system is moving with high stress and velocity, which ultimately increases the systems lifetime.

Once system designs had been finalized. Simulations played a key role in developing mitigation techniques. We were able to quickly see the impact a restraint would have based on the location where it was attached to the system. Additionally, we could get numerical values to show whether or not the mitigation was working.

Our team tested out many different forms of restraints before finalizing the designs. We had developed methods in which the system response had gotten much worse, i.e. stress and velocity went up when the mitigation was applied. The simulations made it easy to recognize where the mitigation needed to be applied in order for it to be effective. The rendering directly above shows the high velocity in the middle of the expansion loop. This high value made it clear that this was where we needed a restraint. This was also useful in deciding where to place accelerometers and strain gages for data collection. Accelerometers went in areas of high velocity, and strain gages in areas of high stress.

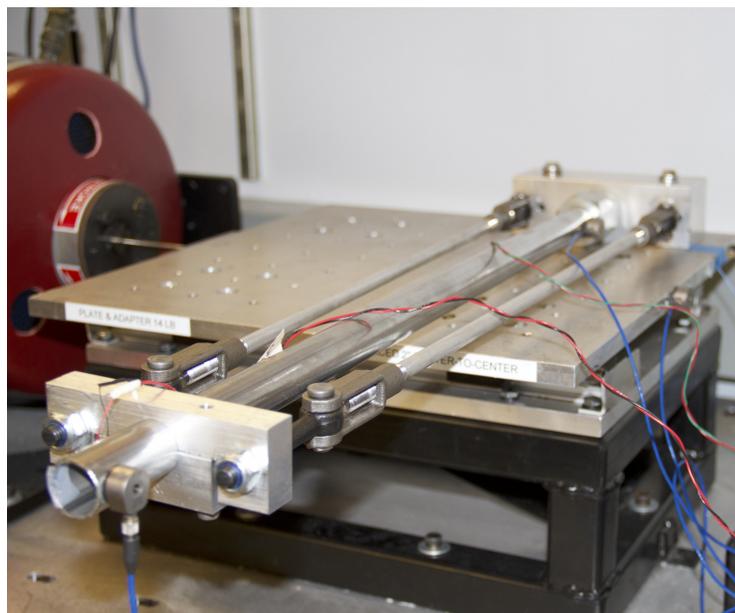
Testing

A focal point of our project revolved around physical testing. Physical testing worked to confirm our findings from Simulations and allowed us to experience piping/tubing vibration in person. For testing, two shake tables available on CU Boulder's campus were used: the vibration table in the Integrated Teaching & Learning Program (ITL) and the large vibration table in the Center for Infrastructure, Energy, and Space Testing (CIEST). The reasons for using two different tables included: cost, time, and the size of our systems. The ITL table was free to use but was too small to test the expansion loop and 90 degree bend systems, so the CIEST table was also needed. Testing was done with and without mitigation at single frequencies ranging from as low as 12.5 Hz up to 100 Hz. These frequencies corresponded with those of the EI guidelines and were the inputs we had been using for our simulation analysis.

Data was collected at several points of each system with accelerometers and strain gages. The data allowed us to determine success or failure of implemented mitigation which was then compared to our initial simulations.



Nestor adjusting a strain gage on the 90 degree bend system just before testing on CIEST table

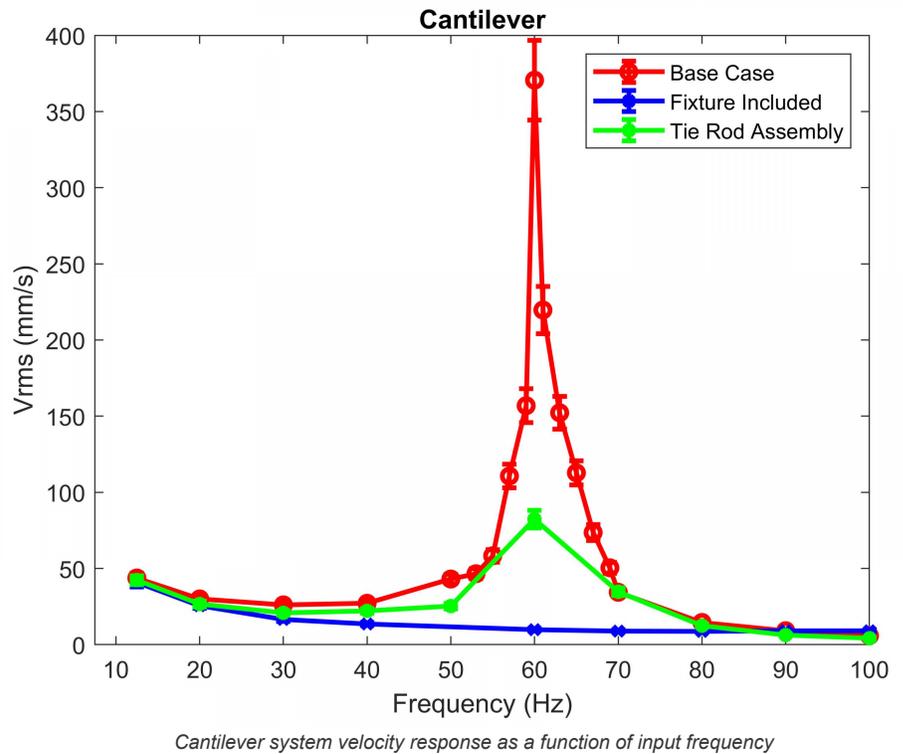


Cantilever system with restraints on the ITL table

Results

Once data was collected from the systems, with and without mitigation applied, we were able to analyze the data to prove the mitigation methods chosen had succeeded. Measure of success was how the reduction in the stress and velocity response.

The data from the accelerometers was imported into MATLAB, a coding software, where it was numerically integrated to get values for velocity. The root mean square (RMS) velocity was calculated for each frequency both with and without mitigation. Then, the data before mitigation was compared to after mitigation. The resulting data comparisons showed the mitigation techniques to be successful in relieving vibration. One example: the cantilever response, shown on the right, displays that there was a 97.3 percent reduction in the RMS velocity at the system's resonance (60 Hz) after including the restraints.



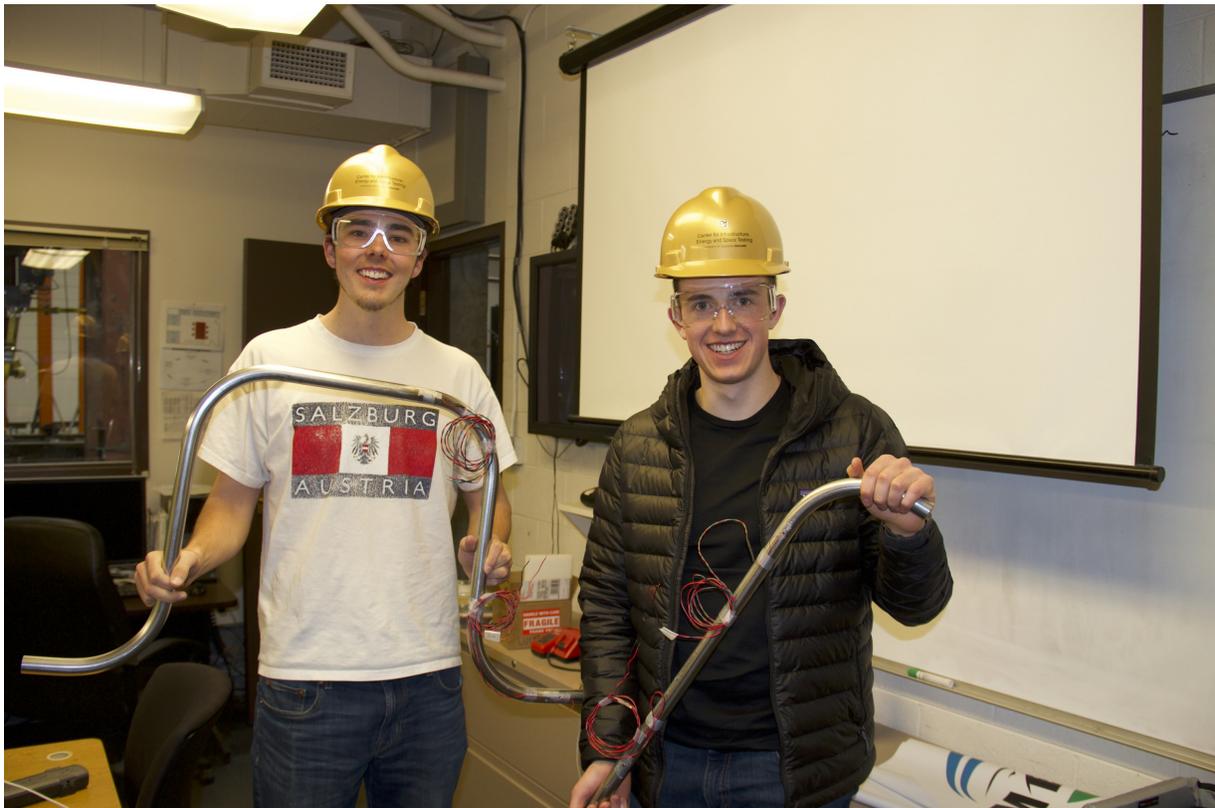
The strain gage data was analyzed by being passed through a calibration curve and then turned into a stress value.

The RMS velocity data comparisons as well as the stress data comparisons work together to show that our mitigation to the systems effectively reduced stress and velocity. This in turn will allow the systems to last longer before they fatigue.

These results give insight to how common piping features respond at different frequencies, as well as the best means to mitigate the response. We were able to effectively prove that the method at which we went about mitigation worked. This means that this restraint method can be applied to any system with the correct amount of analysis.

Challenges and Conclusion

Our team learned many skills from this project, ranging from SolidWorks Simulation to the use of a large scale vibration table. We were able to develop results that can be used in any industrial plants that use piping networks. We learned how to infer a systems' response due to a change in input or geometry. Lastly, we were able to give a substantiated recommendation to our client on how vibration can be mitigated in a piping system, as well as a method to predict piping failure, and a method to collect and monitor piping vibration. We encountered many challenges along the way, the most recent being the impacts of closures due to the COVID-19 pandemic. We had to spend ample amounts of time researching the unfamiliar topic of vibrations as well as learn how to run simulations in which the results were accurate. All of these tools that we were able to develop led our team and our project to success. Senior Design helped all of us grow as professionals and develop readiness to move into industry. We would like to thank our director, Stefan Berkower, and client, Mohammed Alkaabi for all the support and guidance they have provided us.



Joe and Andrew holding the expansion loop and 90 degree bend system in the CIEST lab on testing day