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(ECE/ME/MSE4500J)

Analysis of Vibration-Induced Measurement Inaccuracies in Riveting Processes

Design Review # 3

Sponsored by
Shanghai Systence Electronics Co.,Ltd

Section Professor
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Group 24

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* In the rest of the report, blue text signifies modifications based on DR1 report feedback, which primarily involved correcting typos and word choices.

1 Abstract

This project is sponsored by *Shanghai Systence*. During their manufacturing process, inaccuracies caused by rivet vibrations have prevented their products from meeting client requirements. Therefore, this project aims to assist the company by developing a system comprising a sensor and a software interface. The sensor will capture vibration data during the riveting process and the software will visualize the vibration patterns as well as identifying anomalies. Ultimately, the project will provide recommendations to mitigate these vibrations. While commercial products exist that achieve similar goals, they are often expensive, do not meet the company's specific requirements, or are too large to be easily placed around the small rivets of interest to the company. Through discussions with the company, we have identified ten customer requirements and established engineering specifications, including mass, volume, price, sensor characteristics like resolution, repeatability, response time, frequency response range, error range, and success rate. By building evaluation matrices to compare candidate products, we selected the displacement laser sensor from *Keyence*. This sensor not only met all engineering specifications for accuracy but also fit within our budget. We chose the Arduino board as the micro-controller, PyQt in Python for the user interface framework, and Ansys for performing simulations to minimize vibration. In concept selction processes, price weighed more heavily due to budget constraints. Design values were compared with the target specifications: measurements on the final hardware product confirmed it met the requirements for mass and volume. Sensor parameters were carefully considered during selection. The system's processing time was evaluated by measuring the update time for real-time vibration visualizations, achieving a 15ms processing time, which met the specifications. The Arduino's baud rate and sampling frequency were adjusted to ensure smooth data transmission. Validation for the last specification, sensor's success rate, will be performed in week 11 using the commercial trial unit from **Keyence** a reference. The team will adhere to the timeline for the last part of the project. We hope that the final product will enable the company to better control the riveting process, saving time and energy, and boosting confidence in attracting potential customers.

Key Words: vibration analysis; rivet accuracy; data visualization

Contents

2 Introduction

2.1 Project Background

Shanghai Systence Co. is a prominent entity in the assembly line industry, specializing in the production of three primary product categories: electro-mechanical assembly presses, riveting machines, and the comprehensive design and construction of assembly line systems for various factories. Group 24 will focus on the optimization of riveting technology, specifically targeting the identification and mitigation of vibration-related issues inherent in the riveting process. The aim is to provide *Shanghai Systence Co.* with actionable insights and recommendations to enhance the efficiency and reliability of their riveting operations. group 24's investigation is specifically concentrated on radial riveting technology, a widely utilized technique in the assembly of mechanical components. Despite its prevalent use, *Shanghai Systence Co.* faces challenges in quantitatively analyzing the riveting process. The existing methodology predominantly relies on experiential knowledge and qualitative assessments of the rivet's behavior. While this traditional approach has its merits, it often falls short in addressing the nuanced complexities of the riveting process, leading to sub-optimal solutions that result in financial losses, wasted time, and diminished confidence in the company's problem-solving capabilities.

2.2 Problem

A thorough literature search on the impact of vibrations during the riveting process on rivet accuracy yielded no substantial results from academic search engines. Consequently, the nature of this problem is primarily based on descriptions provided by *Shanghai Systence Co.* and an example of a previously encountered issue. *Shanghai Systence*, along with their partner *FMW Friedrich*, an industry pioneer in data-driven riveting, report that vibrations are a significant cause of inaccuracies in the riveting process, sometimes failing to meet customer specifications. The riveting process at *Shanghai Systence* involves the machine initially determining the rivet's height before proceeding with the riveting operation until the required height is achieved. However, rivets' vibrating during this process compromise the accuracy of height measurements, resulting in inconsistent output parameters. A notable instance illustrating this issue involved a complex U-shaped riveting part, where additional bending occurred due to momentum. This complication led to significant time and financial investments as parts were sent to Germany for testing, in-house experiments were conducted, and repeated consultations with the multinational client were necessary. This iterative and inefficient problem-solving approach highlights the urgent need for a quantifiable solution to address the vibration-induced inaccuracies in the riveting process. Therefore, group 24 aims to address this critical issue by developing a system to quantify and visualize vibrations during the riveting process. The primary objectives include:

- Data Collection: Finding robust sensors to gather real-time data on vibrations occurring during the riveting process.
- Data Visualization: Creating visualization tools to identify anomalies and patterns in the vibration data, providing insights into the correlation between vibrations and rivet accuracy.
- Problem Mitigation: Offering actionable recommendations to eliminate or minimize the impact of vibrations on the riveting process.

By quantifying the impact of vibrations and visualizing the data, group 24 intends to facilitate a deeper understanding of the riveting process anomalies. This approach aims to significantly expedite and economize the problem-solving process for future riveting challenges, thereby enhancing the operational efficiency and product quality for *Shanghai Systence Co.* and its partners.

3 Quality Function Development (QFD)

As stated in previous section, the goal for this project is to develop a system that can detect, visualize, analyze the vibrations of rivets during the riveting process and suggest potential solutions for managing these vibrations. We collaborated with the company to identify the top 10 customer requirements. We then determined the engineering specifications for the entire product, which we categorized into three major parts: data collection, data analysis, and overall appearance.

3.1 Customer Requirements

Our sponsored company, *Shanghai Systence* is the primary customer for this project, as they will be the main users of the product. The customer requirements, summarized in Table 1, were established based on their input and prioritized according to their weighted importance.

Table 1: Customer requirements with weighted importance

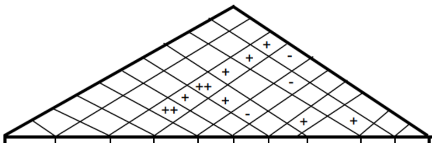
Requirements	Weight (1-10)
Accurate vibration capture	10
Easy-to-use	9
Stable (long-distance transport)	9
Accurate vibration analysis	8
Fast	8
Portable	8
Easy-to-install	4
Cheap	3
Less parts needed	2
Appealing design	2

Through discussions with the company, we found that they prioritized accuracy and ease of use over cost and aesthetics of the final product. The highest priority was **accurate vibration capture**, as the company was aware of the existence and impacts of vibrations but needed a way to visualize and categorize them. Therefore, our primary goal was to first obtain the correct vibrations so as to provide further accurate analysis. **”Ease-of-use”** followed, as the product interface needs to be intuitive for engineers. **Stability** refers to the product's durability during long-distance transportation; the final product should maintain good functionality after being transported, as it will be used in various factories and client locations. **Accurate vibration analysis** and **speed (fast)** in both data capture and software processing were also crucial. Additionally, **Portability** and **"Less parts needed"** both means the product should be a compact design that ensures the ease of transport and assembly. **Easy installation** of both software and sensors, though less critical, was still a consideration. The least important factors were **cheap** and **design appeal**, but the company expressed their wish for a good-looking product so that they can also present it in front of their clients.

3.2 Engineering Specifications

Based on customer requirements, we established corresponding engineering specifications, summarized in the QFD chart in Figure 1.

We categorized the engineering specifications into three main areas: data collection components, data analysis (user interface, software), and overall product attributes. Each category aligns with specific customer requirements.



	Weight (1-10)	mass	volume	price	system's processing time	sensor's resolution	sensor's Repeatability	sensor's response time	sensor's frequency response range	sensor's error range	sensor's success rate	Benchmarks: m+p Analyzer	Benchmarks: VibrationData Toolbox enDAQ	Benchmarks: Dplot
Accurate vibration capture	10			1		9	9		9	9	9	5	5	/
Easy-to-use	9				9		1	3			1	5	2	3
Stable (long-distance transport)	9	3	3	3								5	4	5
Accurate vibration analysis	8				3	3	3		9	3	3	5	5	4
Fast	8			1	9			9				5	4	4
Portable	8	9	9									1	2	/
Easy-to-install	4	3	3	3								5	2	1
Cheap	3	3	3	9		3	1	9	3	3	1	1	3	5
Less parts needed	2	3	3	1								4	2	/
Appealing design	2	1	1									3	3	4
Measurement Unit		g	cm^3	RMB	ms	um	um	ms	Hz	%	%			
Target Value		1000	8000	4000	2000	1	±1	10	0-1000	±1	70			
Total		128	128	86	177	123	126	126	171	123	126			
Normalized		0.10	0.10	0.07	0.13	0.09	0.10	0.10	0.13	0.09	0.10			

Figure 1: Quality Function Development chart for the project. Engineering specifications highlighted in yellow are the most important ones, followed by those highlighted in green.

For the overall product, we focused on **mass**, **volume**, and **price**, which correspond to requirements for stability, portability, ease of installation, and minimal components. In terms of the software, we prioritized **processing time**, ensuring the system can quickly visualize vibration patterns, identify types of vibrations, and provide solutions. For data collection, the key parameters were sensor characteristics, such as **resolution**, **repeatability**, **response time**, **frequency response range**, **error range**, and **success rate**. These specifications were obtained by evaluating parameters for commercial sensors and are relevant for the identified customer requirements, such as capturing accurate and reliable vibration data.

- Resolution: The smallest detectable change in the measured variable by the sensor.
- Repeatability: The sensor's ability to provide the same output for repeated measurements under unchanged conditions, crucial for accurate vibration capture.
- Response Time: The time the sensor takes to respond to a change in the

measured variable, impacting the speed of data capture.

- Frequency Response Range: The range of frequencies over which the sensor can accurately measure the variable, ensuring all relevant vibrations are detected.

- Error Range: The range within which the true value lies considering all potential sources of error, essential for accuracy.

- Success Rate: A parameter specific to our vibration detection, comparing the performance of our chosen sensor with a high-accuracy laser vibration sensor used as a benchmark (JI has the laser sensor that professor Huang said we could borrow).

After normalizing the scores, we found that the system's processing time and the sensor's frequency response range received the highest scores, followed by the mass and volume of the overall product, as well as the sensor's repeatability, response time, and success rate. These are highlighted in yellow and green in Figure 1. This prioritization aligns well with the customer requirements and we will focus on these specifications during our project development. For each customer requirement, we identified at least one engineering specification with a strong correlation (9 points), except for "Stability", "Easy Installation", "Less parts needed", and "Appealing Design", which had lower weighted importance or were inherently addressed by the overall product design.

Target values for these specifications were agreed upon with the company and bench-marked against commercial products. Specifications like mass, volume, processing time, and sensor success rate were directly provided by the company based on their machinery and needs. The project budget guided the target price, set at 4000 RMB. Sensor specifications were derived from averages of commercial sensors available on Amazon. We will try to meet the target values when deciding the types of sensors we will use in the project.

4 Concept Generation and Selection

4.1 Concept Generation

The entire design was classified into four categories: data acquisition, data transfer, analysis tools, and user interface. The objective was to select one concept from each category that best suited our project. These four categories are closely interconnected: data acquisition involves selecting devices to capture raw vibration data during the riveting process; data transfer involves choosing a micro-controller to convert analog signals to digital ones for computer processing; analysis tools are used to evaluate and offer solutions on minimizing vibration; and the user interface displays the vibration patterns and analysis results. After brainstorming and researching, we identified three concepts for each category, as listed in Figure 2. For data acquisition, we considered various sensors including accelerometers, laser sensors, and capacity sensors. For data transfer, we evaluated the Arduino board, NI DAQ, and Raspberry Pi. For analysis tools, we compared Ansys, SolidWorks, and theoretical calculations. Finally, for the user interface, we assessed three Python frameworks: PyQt, Kivy, and Tkinter.

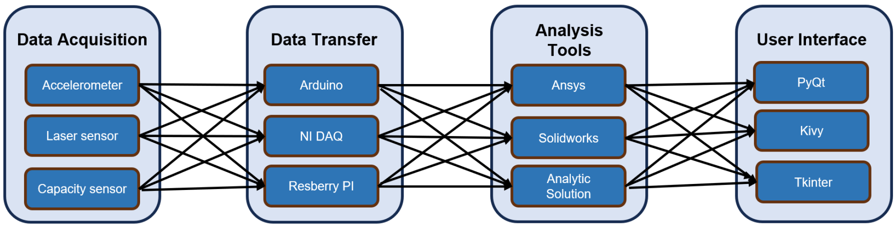


Figure 2: Morphological analysis chart. Each arrow represents a potential path that, when linked together, generates a concept that can be used to realize the whole design for our project.

4.2 Concept Selection Process

4.2.1 Sensor Selection

Sensor selection is crucial for this design, as it closely related to the most important customer requirement: accurate vibration capture. For each of the three sensor types, we identified one commercial product available from Jing Dong: the **SG-MEMS-XYZ-V1 accelerometer**, the **Keyence IL-S030 laser sensor**, and the **enDAQ S3-D16 capacity sensor**. We compared the parameters of these three products based on the following criteria, ranked from most to least important: price, resolution, sampling rate, mass, repeatability, error range, volume, and frequency response range. These criteria were directly extracted from the engineering specifications in the QFD chart that were related to sensors; detailed explanations for their meanings can also be found in Section 3 of this report.

Figure 3 includes the quantitative comparisons of these three sensors. Among these criteria, price and resolution were given the highest weight due to their importance in balancing performance and budget. Typically, a higher resolution sensor comes at a higher price, so our goal was to find the highest resolution sensor within our budget. The rest criteria were assigned similar weights, as in our opinion, they are equally important for evaluating sensor performance. In the end, the Keyence IL-S030 was selected because it offers high resolution at a reasonable price and does not require direct contact with the measured part. This is particularly advantageous for our project, since the measured part is small. The SG-MEMS-XYZ-V1 accelerometer, despite its low price and small size, requires direct placement on the measured part, making it unsuitable for our needs. The enDAQ S3-D16, while lightweight and highly accurate, exceeded our budget. Thus, the Keyence IL-S030 emerged as the optimal choice for our project.

Design Criterion	Weight factor	Unit	Accelerometer SG-MEMS-XYZ-V1			Laser Displacement sensor KEYENCE IL-S030			Capacity sensor enDAQ S3-D16		
			Value	Score	Rating	Value	Score	Rating	Value	Score	Rating
Price	0.2	RMB	950	10	2	2500	7	1.4	7000	1	0.2
Mass	0.11	g	50	9	0.99	60	8	0.88	16	10	1.1
Volume	0.1	mm^3	18900	10	1	36719	8	0.8	34061	8	0.8
Resolution	0.14	um	1.5	7	0.98	1	10	1.4	0.1	10	1.4
Repeatability	0.11	um	1	10	1.1	1	10	1.1	1	10	1.1
Sampling Rate/ Period	0.13	ms	0.04	10	1.3	0.33	9	1.17	0.31	9	1.17
Frequency Response Range	0.1	kHz/mm	6	6	0.6	30	9	0.9	32	9	0.9
Error Range	0.11	%	2	4	0.44	0.1	9	0.99	0.1	9	0.99
Total	1				8.41			8.64			7.66

Figure 3: Concept evaluation matrix for sensor. The concept highlighted in green (*Keyence* laser displacement sensor) has the highest total score and will be selected for this project. It is followed by concepts highlighted in yellow and red.

4.2.2 Micro-controller Selection

Based on our group's experience, **NI DAQ**, **Arduino**, and **Raspberry Pi** were proposed as potential micro-controllers as they all have been used by some of us in previous courses. They were evaluated based on price, mass, volume, clock speed, number of I/O interface, and ease-of-use. In addition to price, mass, and volume, which were included in the engineering specifications, new evaluation criteria were added, as the rest specifications were not targeted for micro-controllers and relying on those three alone may not help us find the best concept. For these new criteria, clock speed determines the number of cycles a micro-controller can execute per second. A higher clock speed is desired, because it enables faster processing and better real-time data capture. The I/O interface represents the number of input and output ports the micro-controller has for interacting with other devices. Since our project requires at least one analog port to receive data from the sensor, higher weights were assigned to this criterion. Ease-of-use was rated on a scale of 1 to 5, based on factors such as development time and learning curve. Given that the user interface was the result to be shown to the sponsor, our group prioritized minimizing time spent troubleshooting code regarding data collection.

Figure 4 shows the detailed comparisons where Arduino stood out due to its lowest price, smallest size and weight, and ease of coding, as all ECE students in the group had prior experience with it. Although Raspberry Pi has the highest clock speed, itself can function like a tiny computer, whereas our project only requires converting analog signals to digital ones. Thus, using Raspberry Pi would be overkill. NI DAQ was rejected as an option due to its high price and large volume.

Design Criterion	Weight factor	Unit	NI DAQ			Arduino			Resberry Pi		
			Value	Score	Rating	Value	Score	Rating	Value	Score	Rating
Price	0.28	RMB	3500	2	0.56	150	10	2.78	600	6	1.67
Mass	0.06	g	500	7	0.39	25	9	0.50	45	8	0.44
Volume	0.11	cm^3	2000	5	0.56	35	8	0.89	80	7	0.78
Clock speed	0.11	MHz	200	8	0.89	16	8	0.89	1500	9	1.00
I/O Interface	0.22	1-5	4	8	1.78	4	8	1.78	5	8	1.78
Ease-of-use	0.22	1-5	3	6	1.33	5	9	2.00	4	7	1.56
Total	1.00				5.50			8.83			7.22

Figure 4: Concept evaluation matrix for micro-controller. The concept highlighted in green (Arduino) has the highest total score and will be selected for this project. It is followed by concepts highlighted in yellow and red.

4.2.3 Analysis Tool Selection

To understand the vibration patterns and propose solutions, we considered three methods: **Ansys**, **SolidWorks**, and **Theoretical Analysis**. Beyond the criteria mentioned in engineering specifications, we evaluated these tools also based on model geometry accuracy, material properties, ease of implementation, post-processing and visualization, frequency analysis, and automation.

- Model Geometry Accuracy: Minimizes discrepancies between the actual and modeled geometry.
- Material Properties: Saves time and ensures consistency with validated material data.

- Ease of Implementation: Measures how user-friendly the tool is for quick setup without extensive training.
- Post-Processing and Visualization: Helps interpret results, making it easier to identify key performance indicators and failure points.
- Frequency Analysis: Understands the natural frequencies and modes to avoid resonance and ensure structural integrity.
- Automation: Ensures consistent application of methods across multiple simulations, reducing human error.

For our project, model geometry accuracy and automation were given the highest weight, as our goal was to build an accurate model efficiently. As shown in Figure 5, Ansys was selected for its strong performance in these areas. SolidWorks performed poorly in ease of implementation and frequency analysis. Theoretical analysis was inadequate in visualization and post-processing and required extensive theoretical knowledge, which was challenging for the two ME/MSE students in our group to master within one month.

Design Criterion	Weight factor	Unit	Theory (Analytical Solution)			SolidWorks			Ansys		
			Value	Score	Rating	Value	Score	Rating	Value	Score	Rating
Model Geometry Accuracy	0.2	mm	5	2	0.4	0.5	8	1.6	0.05	9	1.8
Material Properties	0.1	%	14	5	0.5	8	8	0.8	3	9	0.9
Ease of Implementation	0.1	#	5	8	0.8	4	6	0.6	3	4	0.4
Post-Processing & Visualization	0.15	#	2	4	0.6	4	7	1.05	5	9	1.35
Frequency Analysis	0.15	%	7	4	0.6	2	8	1.2	0.4	9	1.35
Automation	0.2	#	2	4	0.8	4	9	1.8	4	9	1.8
Cost	0.1	RMB	0	10	1	10500	6	0.6	105000	3	0.3
Total	1				4.7			7.65			7.9

Figure 5: Concept evaluation matrix for analysis tools. The concept highlighted in green (*Ansys*) has the highest total score and will be selected for this project. It is followed by concepts highlighted in yellow and red.

4.2.4 User Interface Framework Selection

The user interface is a another critical component of this project, as it is the primary point of interaction for users. Given our background as three ECE students and the simplicity of Python, we chose to use Python and proposed three popular frameworks: **Tkinter**, **PyQt**, and **Kivy**. Since the current engineering specifications include only "system's processing time" as a criterion for evaluating frameworks, to ensure a comprehensive evaluation, we proposed additional criteria:

- Leaning curve: The hours required for a Python programmer who has never used the framework before to learn it.
- Development speed: The time used to develop a standard user interface.
- Community support: The activeness of the community and the amounts of resources one can access.
- Response time (processing time): The start and response time for a standard program.
- Cross-platform support: The number of operating systems this frame supports, like Windows, Linux, macOS, Android, IOS.

The highest weight was assigned to response time, as capturing real-time vibration data depends not only on the sensor's sampling rate and the microcontroller's transfer speed, but also on the framework's data processing speed. Conversely, cross-platform support was assigned the lowest weight since all these frameworks support Windows, Linux, and macOS, which are sufficient for this project's scope. The remaining criteria focused on ease of learning and development speed, considering our limited time and beginner status to these frames. Figure 6 shows the evaluation results, where PyQt received the highest score due to its fast response time, relative ease of learning, and strong community support. Although Tkinter and Kivy have a smaller learning curve, their processing times do not meet the project requirements.

Design Criterion	Weight factor	Unit	tkinter			PyQt			Kivy		
			Value	Score	Rating	Value	Score	Rating	Value	Score	Rating
Learning Curve	0.14	h	20	10	1.43	50	7	1.00	40	8	1.14
Development Speed	0.21	h	30	9	1.93	70	7	1.50	60	8	1.71
Community Support	0.18	1-5	4	8	1.43	5	10	1.79	3	6	1.07
Response time	0.36	ms	100	6	2.14	50	10	3.57	70	7	2.50
Cross-platform Support	0.11	#	3	6	0.64	4	8	0.86	5	10	1.07
Total	1.00				7.57			8.71			7.50

Figure 6: Concept evaluation matrix for user interface framework. The concept highlighted in green (PyQt) has the highest total score and will be selected for this project. It is followed by concepts highlighted in yellow and red.

4.3 Concept Description

Based on the concept selection process, we have determined the components for our final product, as illustrated in Figure 7. The design consists of a hardware set including a laser sensor, an amplifier, an Arduino board, and a 24V power supply. This hardware will be connected to a computer running the user interface, showing the vibration patterns. Additionally, we built CAD models and performed FEA simulations using Ansys. By simulating the entire radial riveting process, we identified parameters that minimize vibration (or the rivet's displacement) during riveting. The analysis and solutions obtained from these simulations will also be displayed in a dedicated section on the user interface.

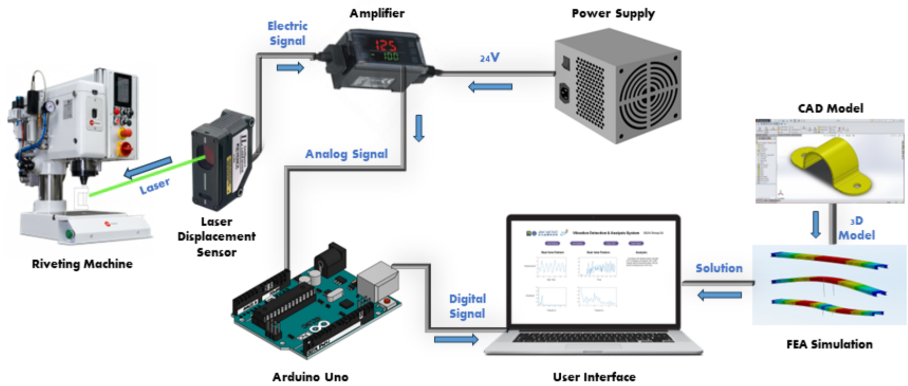


Figure 7: Concept diagram. The system was designed to receive and display vibration patterns from hardware, then provide solutions for minimizing them. To receive data, the proposed four-component hardware design includes a laser displacement sensor with an amplifier, an Arduino board, and a computer-displayed user interface. Raw electric signals are converted to digital signals through the process. Solutions will be provided through modeling and simulation of the radial riveting process. [1–8]

The U-shaped part will be fixed on the riveting machine, with the sensor measuring the displacement of the point of interest during the riveting process. For data transfer among the hardware components, the *Keyence* laser sensor captures raw displacement data as an electric signal, which is sent to its accompanying *Keyence* amplifier. The amplifier converts the electric signal to an analog signal, specifically voltage in our case. The Arduino board then maps the 0-5V voltage to a 20-45mm displacement, converting it to digital signals, and sending it to the computer. Finally, the user interface will display a real-time plot showing the displacement changes of the measured object.

5 Design Description

5.1 Current Progress

This section describes the progress group 24 achieved in building each part related to the final concept. It details the engineering principles employed to meet project goals, the methods used to determine specific parameters, and the engineering logic and equations used to justify each decision. The primary questions addressed are how our system can be created, how it will function, and why it will be effective.

5.1.1 U-shaped part

The design and manufacturing of the U-shaped part aim to address issues previously encountered in the company's collaboration with a multinational customer. This approach also allows Group 24 to efficiently manage resources, minimizing the number of rivets used for testing. Due to the joint between the rivet and the U-shaped part, it was not possible to reuse riveted items after one full riveting cycle. Additionally, manufacturing U-shaped part is time-consuming - It takes 2 hours to manufacture one U-shaped part using CNC equipment. Therefore, instead of using rivets, the decision was made to use bolts made of bare steel as they can simulate riveting process and not deform in a way that it is not possible to repeat the experiment with the same items after.

Quantitatively, bare steel, with an average yield stress of 2000 bars, is suitable for this purpose as the average input pressure during tests is 5 bars. This significant difference enables multiple experiments using one bolt instead of a rivet. The design, shown in Figure 8, was chosen due to its low cost, the similarity to rivets, and the time savings in production. The sponsor company provided a package of bolts free of charge, as they had many available. All parts have been manufactured at the sponsor company's facility.

During the design stage, two versions of the U-shaped part were considered, with varying widths for the middle section that connects the bottom and top cantilever beams. The detailed sketch is shown in Figure 9(a). The decision to vary the width and analyze its impact on vibrations was guided by the formulas for natural frequency f_1 and deflection δ of a cantilever beam, as given in Equation (1) and (2):

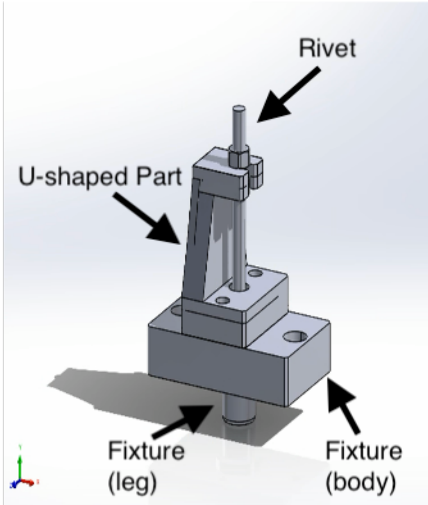


Figure 8: SolidWorks Model - U-Shaped Structure. It illustrates the design of the tested sample and includes its subparts: the Fixture Leg, which connects the machine to the tested item; the Fixture Body, which holds the U-shaped part; the U-shaped part itself; and the Rivet.

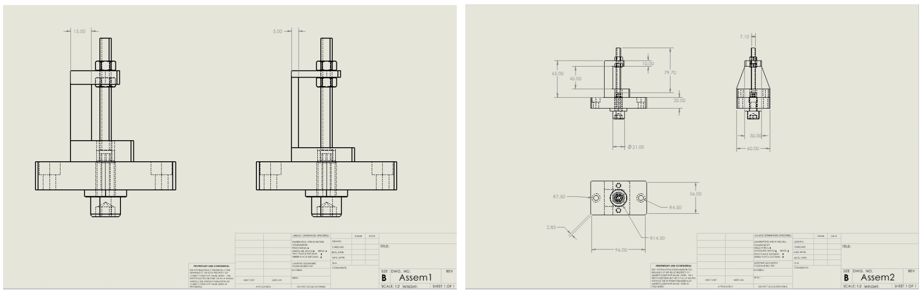
$$f_1 = \frac{1.875^2}{2\pi} \sqrt{\frac{EI}{\rho A L^4}} \tag{1}$$

$$\delta = \frac{FL^3}{3EI} \tag{2}$$

where in these equations, E represents the Young's modulus of the material, I is the second moment of area (moment of inertia), ρ is the density of the material, A is the cross-sectional area, L is the length of the beam, and F is a point load.

Given that changing the material was not feasible due to its cost-effectiveness and relevance to the actual scenario the company faced, modifying the cross-sectional area of the U-shaped part would be more costly than altering the width of the middle section, as any change in the cross-section would require a corresponding adjustment to the other beam to maintain symmetry, which would incur additional expenses. Therefore, adjusting the width of the middle section was deemed more practical and economical. This modification impacts the length L, as illustrated in Figure 9(a), and subsequently affects the vibration characteristics. According to vibration theory, an increase in L leads to a lower natural frequency and a higher amplitude of vibration. The open top cantilever beam design allows for easy insertion and removal of bolts during experiments. Shorter bolts are used to simulate bending under a constant force applied to the right part of the top cantilever beam. This scenario mirrors the deformation of a rivet contacting the top surface of the cantilever beam, leading to the bending scheme detailed in the Appendix section of this document.

The fixture body and leg were designed in accordance with the machine parameters for fixtures, which are standardized based on the machine model, size, and applied input parameters. The material for the fixture was selected based on manufacturing and supply costs. Stainless steel, with an average yield strength of 4000 bars, was chosen to minimize stress-induced expansion and potential machine damage. A sketch of the entire testing apparatus, shown in Figure 9(b), is provided with dimensions in millimeters.



(a) Two designs of different widths

(b) Whole Manufacture Scheme

Figure 9: U-shaped part design details: (a) Dimensions for 2 types of the U-shaped part with varying different width but identical other dimensions. (b) SolidWorks drawing that shows all required dimensions for manufacturing; pre-made bolts for joint are neglected in the picture.

5.1.2 Data Collection & UI

To achieve the project goals of measuring vibrations during riveting processes, the fundamental engineering principle employed is Light Detection and Ranging (LiDAR) technology for distance measurements. The sensor used in this project, the *Keyence* IL-S030 laser displacement sensor, utilizes the triangulation method for distance measurement. This process involves emitting a laser beam from the sensor, which reflects off the target object. The reflected light is then detected by a CMOS sensor, and the position of the light spot on the CMOS changes with the distance to the target. This variation enables precise distance measurement through triangulation, calculated using the following formula:

$$d = \frac{L}{\tan(\theta)} \tag{3}$$

where d is the distance to the target, L is the baseline distance between the laser emitter and the detector, and θ is the angle of incidence.

To analyze the vibration data, Fast Fourier Transform (FFT) is used to convert the time-domain signal into the frequency domain. This method allows for the identification of vibration frequencies and amplitudes, which is critical for understanding the characteristics of the vibrations. In this project, the FFT is applied to the measured distance data to determine the frequency components of the vibrations. It's computed using the formula:

$$X(f) = \sum_{n=0}^{N-1} x(n) \cdot e^{-j2\pi fn/N} \tag{4}$$

where $X(f)$ is the frequency domain representation, $x(n)$ is the time-domain signal, N is the number of samples, and f is the frequency.

The project utilizes the *Keyence* IL-S030 LiDAR sensor for distance measurement and the Arduino Uno R3 microcontroller for data acquisition and transmission. Although the *Keyence* IL-S030 sensor supports a sampling rate of up to 3 kHz, we have configured it to 30 Hz in our project for two main reasons. First, during experiments, the observed vibration frequency was below 15 Hz. According to the Nyquist sampling theorem that states "an analog signal can be digitized without aliasing error if and only if the sampling rate is greater than or equal to twice the highest frequency component in a given signal. [9]", a 30 Hz sampling rate is sufficient to accurately capture these vibrations. Second, real-time display of distance and FFT results is a priority. The computer requires approximately 20 ms to compute and update the graphical results, and a higher sampling rate could lead to data accumulation in the serial port, causing processing delays. Additionally, the FFT analysis uses a window size of 32 samples. This size balances adequate frequency resolution with efficient real-time computation, ensuring responsive updates to the graphical display of the vibration data.

The system overview is shown in Figure 10. The laser is mounted on a bracket and aimed at the U-shaped part, which is fixed on the operating desk of the riveting machine. All hardware, including the sensor amplifier unit (Keyence IL-1000), the Arduino board, and the power supply, is encapsulated in a 3D-printed container to ensure neat wire organization. The hardware connects to the computer via the USB port linking the Arduino to the computer, on which the distance and corresponding FFT results are displayed.

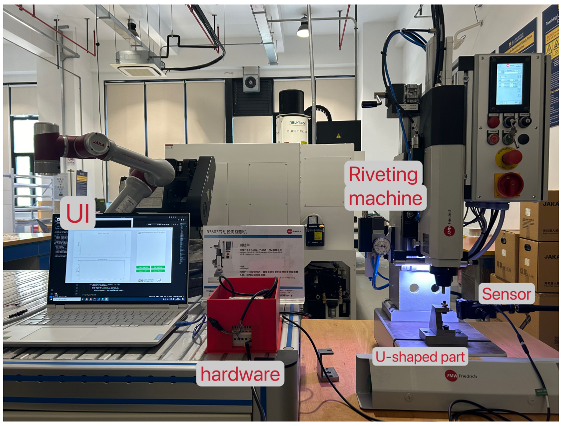


Figure 10: System Overview: In addition to the riveting machine and the U-shaped part used for vibration measurement, our final product primarily comprises three components: a laser sensor mounted on a tripod, an encapsulated hardware set, and a computer for user interface display.

Detailed design and function of the user interface can be found in Figure 11. Developed using PyQt, the interface enables real-time display of distance measurements, FFT results, and provides interactive functions for data visualization and analysis. The interface features four major sections: **Real-Time Displacement Graph** that displays displacement measurements over time. The graph updates dynamically during the sampling process, offering a visual representation of the vibrations being measured. **FFT Result Graph** shows the frequency domain representation of the vibration data, which also updates in real-time during sampling. **Text Box** will display the dominant frequencies of the vibrations during sampling and provides vibration analysis results when the riveting process is terminated. Lastly, there are four buttons that enable user interactions.

The **Start Sampling** button initiates the data collection process. Upon pressing, the system begins real-time sampling of distance data, as well as converting and displaying the FFT results on the user interface. The peak frequencies detected are shown in the textbox on the right side of the interface. The **End Sampling** button stops the data collection process. When pressed, the UI displays the collected distance data and the corresponding FFT results for the entire sampling period. The textbox then provides an analysis of the obtained vibration data. Users can export the collected data and reports using the **Export .CSV** and **Export Report** buttons. The Export .CSV button allows users to export the collected distance data in CSV format, including all the raw distance measurements taken during the sampling period. The Export Report button generates a report containing the distance and FFT result graphs, along with the analysis results. This report can be used for further documentation or presentation purposes.

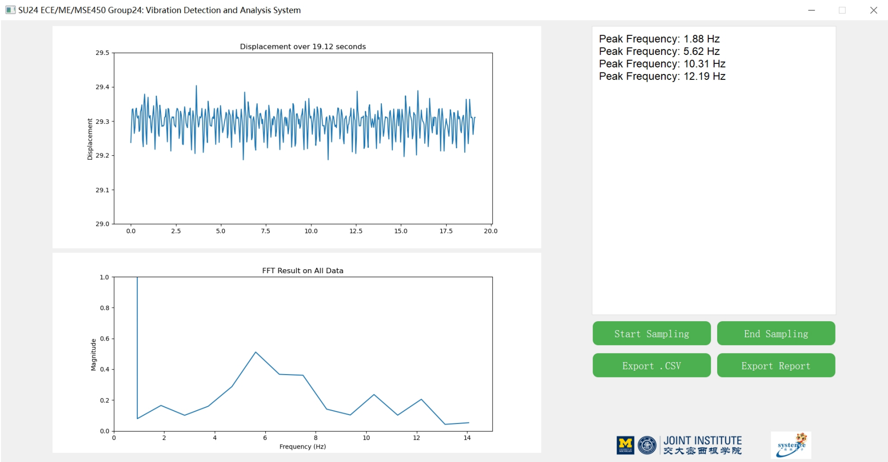


Figure 11: User Interface: The left column contains two real-time plots showing displacement changes during the riveting process and the corresponding FFT results. The right column features a text box displaying peak FFT frequencies during riveting and analysis results post-riveting. Below the text box are four buttons for starting and ending data collection, exporting raw vibration data in .csv format, and generating an analysis report.

5.1.3 Modeling & Simulation

The purpose of modeling and simulation is to reproduce the radial riveting process on the U-shaped part using finite element analysis to identify parameters that can minimize vibration. The part was designed in SolidWorks based on the issue description the company had with their client, and simplicity in manufacturing and testing for this project. Thus, it can simulate the issue that happened in a real scenario and at the same time not be that consuming in terms of resources.

Subsequently, we imported the model into Ansys, which helps in determining the vibration modes of an object under specified conditions. To complete the analysis, we tested four main modules in Ansys, including **Static Structure**, **Modal**, **Harmonic Response** and **Transient Structural**. The logical relationship between them is shown in the Figure 12. Each module is interconnected by lines of different colors. Blue lines indicate the four modules share common initial conditions, including engineering data, geometry, and model parameters that were established during the project's creation phase. Pink lines indicate the calculation results from the previous module are used to initialize the configuration of the subsequent module.

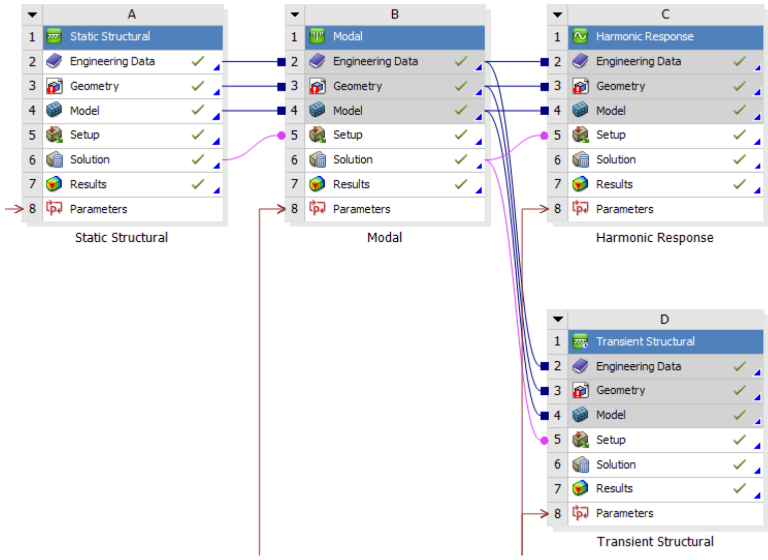
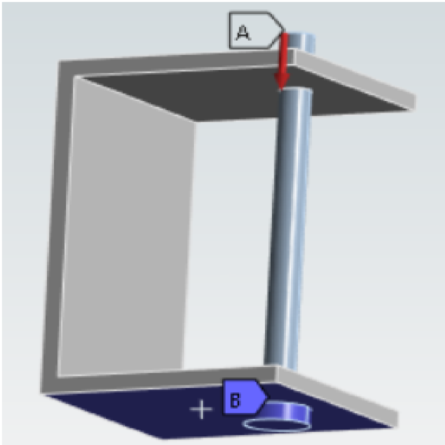


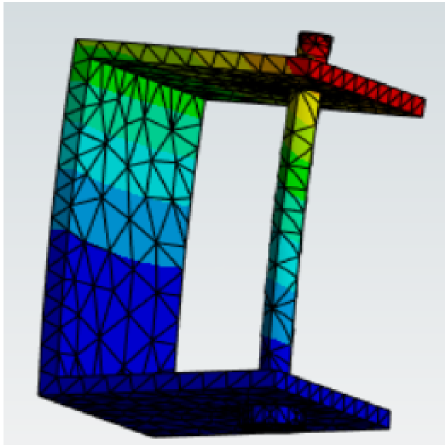
Figure 12: Ansys Workbench Qverview. Four modules are linked linearly: blue lines indicate shared initial conditions across all modules, while pink lines represent the transfer of calculation results from one module to initialize the next.

To begin, we imported the U-shaped model, including material properties and structure, into the **Static Structural** module. This module is used to analyze the response of structures under static loading conditions. To simulate the vibration process, we designated the bottom plane of the part as a fixed support and applied a vertical downward force along the center axis of the rivet at the top, as illustrated in Figure 13(a). After performing the operation, we obtained the distribution diagram of total deformation, as shown in Figure 13(b). This diagram illustrates the extent of deformation in each section of the U-shape when subjected to the fixed force. Additionally, the maximum and minimum principal stress and shear stress were also determined in this operation. With this Static Structural Analysis, we can further conduct comparative analysis by changing boundary conditions like the magnitude of the input force.

Based on the data and the initial condition configurations we obtained from Static Structural Analysis, we used the **Modal** module to determine the natural frequencies and mode shapes of the U-shaped part. The principle is to decompose the object into finite elements, calculate each element independently, and then superimpose the results to approximate the prediction of the vibration



(a) Initial Conditions



(b) Total Deformation

Figure 13: Modeled U-shaped part in Ansys: (a) Initial condition: force A = 800N acts vertically on the top of the rivet, with plane B as the fixed support. (b) Distribution of total deformation: red indicates the maximum principal stress, and dark blue indicates the minimum principal stress.

behavior. Mode and corresponding frequency is listed in Table 2. Additionally, Modal analysis provides the requested number of modes which later can be used for the superposition and harmonic analysis.

Table 2: Modal Data Table

Mode	Frequency [Hz]
1	774.36
2	969.87
3	3762.4
4	4411.0
5	5201.6
6	5985.2
7	6702.3
8	6776.1
9	7236.7
10	9571.8
11	12908
12	13472

After obtaining frequency values, it becomes possible to determine the steady-state response of structures under sinusoidal (harmonic) loads, which helps to understand the behavior of structures under dynamic loads. This analysis provides frequency response plots that illustrate the relationship between frequency and phase angle, as well as the relationship between frequency and amplitude, shown in Figure 14. This procedure allows us to determine frequencies that result in the largest/smallest amplitude values.

Lastly, the **Transient Structural** module was also tested to ascertain the time-dependent response of the part when subjected to dynamic loading conditions. Based on the acquired steady-state response results and the initial conditions from the previous module, new vibration data closely resembling the real riveting process can be obtained through calculations. After being transformed through FFT, data simulated from this module can be compared with data obtained through our data collection system for validation. In the end, by varying factors such as force magnitude, material properties, and structural design, we can provide suggestions on minimizing vibrations.

It is important to point out that with the current progress, we understand how to conduct a simplified simulation of our tested item in Ansys, however, there are several challenges that are present in this part of the project which are discussed in the more detailed way in the Analysis of Potential Problem section.

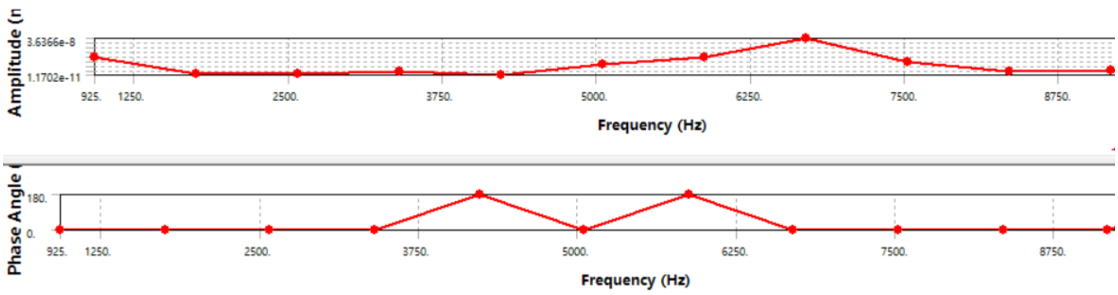


Figure 14: Frequency Response

5.2 Engineering Design Analysis

Based on our concept selections and the final product design, we have successfully met most of the engineering specifications outlined in the QFD chart. Table 3 provides a summary comparison between the target values and the actual values obtained for our final product.

Table 3: Engineering Design Analysis Table

Specifications	Target Value	Actual Value	Met requirement
mass	1000g	890g	Yes
volume	$8000cm^3$	$3073.6cm^3$	Yes
price	4000RMB	239RMB	Yes
processing time	2000ms	15ms	Yes
sensor's resolution	1μm	1μm	Yes
sensor's repeatability	1μm	1μm	Yes
sensor's response time	10ms	0.33ms	Yes
sensor's frequency response range	1kHz	30kHz	Yes
sensor's error range	1%	0.1%	Yes
success rate	70%	-	TBD

Mass and volume considerations primarily about the hardware set of the final product. Mass was validated using a scale and by measuring the dimensions of the container holding all the hardware components, total volume was determined. The price corresponds to the budget spent on building the final product and purchasing hardware components, excluding transportation costs. A detailed explanation for the minimal budget used is provided in Section 9 of this report. Processing time refers to the duration required for our system to refresh and update the real-time vibration plot. This was measured by calculating the time difference before and after each update in the software, with an average time of 15 ms. As probably could tell from the table, many engineering specifications are related to the sensor, as we believe selecting an accurate sensor for vibration detection is crucial for our project's success. These considerations were addressed during the sensor concept selection stage. Lastly, the system's success rate, which measures our ability to capture the vibration pattern, has not been validated yet. However, with the validation plan detailed in the following section, we are confident in meeting this specification as well.

6 Project Plans

6.1 Plan for Manufacture

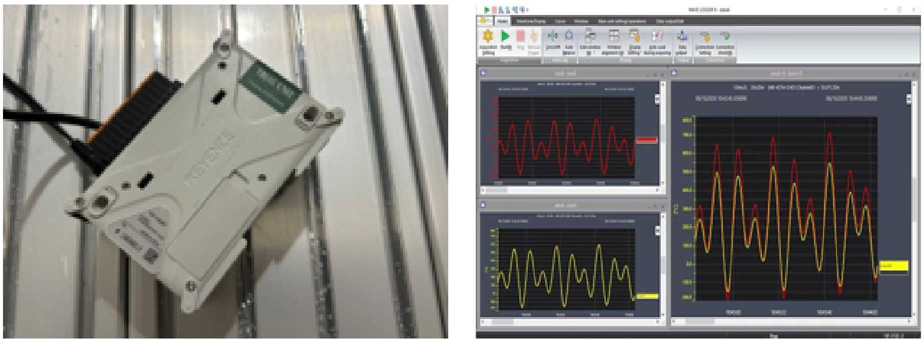
Upon the time of writing this report, the U-shaped part has been manufactured. The process involves three main steps, each utilizing a different processing machine. First, **Electric-discharge Machining (EDM)** was used to create the main geometry of the U-shaped part. EDM is preferred for its ability to precisely machine complex geometries and intricate contours that are difficult to achieve with traditional methods. Additionally, EDM does not require direct mechanical contact, eliminating stresses and deformation on delicate or thin sections. It also works well with hard and brittle materials, providing high surface finish quality and maintaining tight tolerances essential for advanced engineering applications. After obtaining the main geometry, a **milling machine** was used to create the necessary holes in the part. Milling allows for accurate control over dimensions and tolerances, ensuring the finished product meets stringent specifications. Its ability to perform various operations such as cutting, slotting, and contouring on a single setup increases efficiency and reduces production time. Finally, a **grinder machine** was used to achieve a high surface finish quality. In terms of the sub-components of the U-shaped part, the fixture leg was pre-made by the company using butadiene rubber. During the entire manufacturing procedure, the fixture's dimensions were of the highest importance; if its accuracy was not met, the U-shaped part could not be properly held during experiments.

In terms of Ansys simulation, our "manufacture" goals include simulating the radial riveting process and acquiring a deeper understanding of the Harmonic Response analysis, as it directly provides frequency-based results of the U-shaped part's behavior under conditions similar to riveting. However, additional research should be conducted to identify complementary methods beyond Harmonic Response, as it is primarily applicable to constant force applications. In our project, forces may act randomly due to the deformation of the tested item. Additionally, seeking consultation or advice from an expert with experience in vibration analysis using Ansys is another crucial goal for this part.

For user interface development, new features will be added to enhance convenience and user-friendliness. The system will be upgraded to allow multiple sampling sessions without needing to restart the program before each riveting process. Additionally, buttons will be locked during program execution to prevent accidental presses. A scrollable bar will be added to the text box to ensure that lengthy analysis reports do not disrupt the overall interface layout.

6.2 Plan for Validation

To ensure the accuracy and validity of our project, and to demonstrate that the engineering specifications have been met, we have developed a comprehensive validation plan to test the manufactured U-shaped part, the data collection system, and the Ansys simulation results.



(a) Trial Unit NR-500 (b) Trial Unit Software Interface [10]

Figure 15: Keyence Trial Unit. (a) Outward appearance of the product, featuring analog and USB ports for connection with the laser sensor and computer. (b) User interface for Keyence's trial unit, which allows users to start sampling, end sampling, adjust axis ranges, and export data.

For the physical test item, an inside diameter gauge is used to measure the dimensions of the grooves on the machine and fixed components, ensuring the precise production of our U-shaped work piece. The detailed measurement results include: diameter of the fixture hole (29.88-30 mm), inner diameter (27.0-27.25 mm), width of the channel (11.89-12.1 mm), depth of the hole (52.85 mm), and depth of the channel (19.71 mm). Based on these measurements, U-shaped work pieces suitable for our machines can be accurately manufactured.

For data collection validation, we will use a commercial analysis device, the Keyence Trail Unit NR-500, and its corresponding software (provided by the Shanghai Systence Company free of charge), as a reference for the success rate of our developed system. They are shown in Figure 15. Experiments on each sub-part of the U-shaped part will be performed multiple times using both our system and the Keyence Trail Unit under the same conditions. Once data are obtained from both measurements, they will be plotted on the same figure, and the vertical distance between the two lines will be measured to evaluate how closely our detected vibration pattern matches the one obtained from the commercial product. The percentage of closeness will be calculated and used as our success rate. This approach ensures that we have a quantifiable measure of how well our system performs compared to an established commercial standard.

For Ansys simulation, based on the U-shaped model created in SolidWorks, our plan is to proceed with simulating its vibration mode to mimic the radial riveting process. The accuracy of the simulated pattern will be compared with the vibration pattern detected by our system during actual riveting processes. We will use the relative error between simulation and experiments for evaluation:

$$\frac{|Amplitude_{simulated} - Amplitude_{experimental}|}{Amplitude_{experimental}} \leq 0.15 \tag{5}$$

$$\frac{|Frequency_{simulated} - Frequency_{experimental}|}{Frequency_{experimental}} \leq 0.10 \tag{6}$$

This means the simulated amplitude is acceptable if it is within 15% of the experimental amplitude, and the simulated frequency is acceptable if it is within 10% of the experimental frequency.

6.3 Project Timeline

Group 24 will adhere to the schedule set by the Design Reviews. Figure 16 outlines the key technical development and delivery milestones leading up to the Design Expo. With the major components of the product already developed, our current focus is on refining the user interface, conducting validation experiments, realizing Ansys simulation and providing recommendations for vibration elimination based on the simulation results. The temporary timeline for tasks and each group member's responsibility are summarized below

- July 24: Design Review 3 report.
  Polishing the content and format of the report to ensure high-quality text that can be directly used in the final thesis. All group members participate.
- July 26: Complete all technical tasks and validations.
  Yiming and Mansur will continue working on Ansys simulation and offer suggestions on minimizing vibration; Jingtian, Heng and Yujia will beautify the user interface and test our system's success rate.
- July 30: Project Delivery to the sponsored company
  All group members participate.
- August 6: Prototype setup and final thesis writing.
- **August 7: Design Expo and Oral Defense**

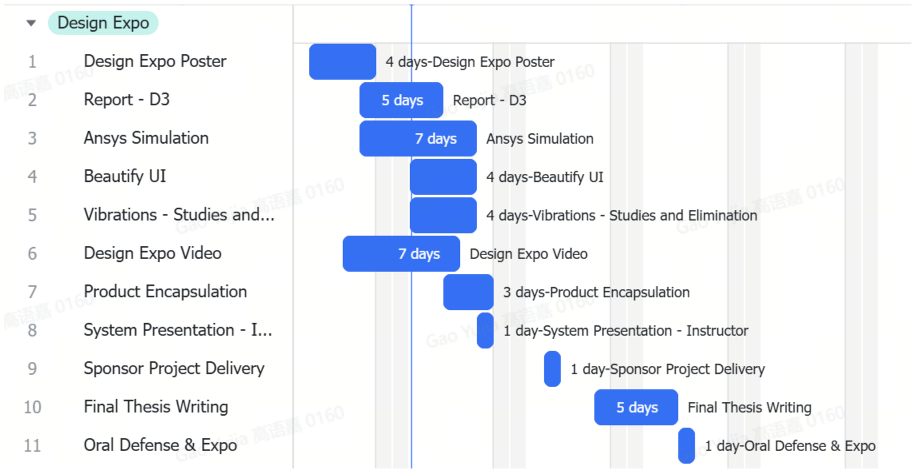


Figure 16: Gantt Chart regarding tasks management for Group 24 Project

7 Budget

The major costs for this project are related to hardware purchases and transportation. Table 4 details the allocation and expenditure of our budget. Notably, the Keyence laser sensor and Keyence sensor amplifier are marked with a red $*$, meaning they didn't spend the actual budget, as during discussions with our sponsoring company, we were informed that Keyence, one of their suppliers, would lend us these products. Nevertheless, we still decide to included them in the budget table to demonstrate that even with all costs accounted for, our total budget remained within acceptable limits, as we avoided purchasing high-value items to achieve our project goals.

Table 4: Group 24 Budget list

Item	Quantity	Cost(RMB)
*KEYENCE Laser Displacement Sensor IL-S030	1	2500
*KEYENCE Amplifier Unit IL-1000	1	1500
Arduino Uno REV3	1	169
Stainless steel	1 kg	56
Camera tripod	1	35
Sensor clip	2	15
Alligator Clip Wire	10	10
Dopont thread	20	6
Screw Adaptor	1	3
3D printing	1	50
Transportation	4	700
total	-	5044
total (excluding *)	-	1044

8 Analysis of Potential Problem

Even though we will try our best, there is a possibility that Ansys simulation of the riveting process will not be achieved accurately before the project deadline due to several factors. The complexity of the riveting process, which involves intricate interactions between materials, stresses, and dynamic forces, requires detailed modeling and significant computational resources. Additionally, the process of setting up boundary conditions, and validating the simulation results against experimental data can be challenging and prone to errors. Potential gaps in specific simulation knowledge further compound these issues, making it difficult to ensure the accuracy and completeness of the simulation within the constrained timeline. Right now there are 4 different analyses connected together by our group in Ansys all being used for different purposes but with one goal of simulating the riveting procedure. However, there is a chance of missing some additional analysis method, incorrectly setting up current methods, or both.

9 Conclusion

The report introduces vibration-related challenges encountered by Shanghai Systence Company during the riveting process. Currently, the existing methods heavily rely on empirical knowledge and qualitative assessment, rather than quantitative analysis. Our objective is to develop a system that would enable the quantification and visualization of vibrations during riveting, while also suggesting appropriate remedies. The primary goals encompassed data collection, data visualization, and problem mitigation. To achieve this, we built concept selection matrices and decided to use Keyence laser displacement sensor for data collection, Arduino board as microcontroller, PyQt as user interface framework, and Ansys for simulation. The dimensions and materials used for the U-shaped part, which is of interest in this project, have also been carefully chosen.

We have successfully designed, manufactured, and validated the U-shaped part crucial to our project. The user interface is operational, capturing real-time vibrations and converting data from the time domain to the frequency domain via FFT. Additionally, we modeled the U-shaped part using SolidWorks and have engaged in Ansys simulation. Most engineering specifications have been met, with only the system's success rate awaiting validation in week 11.

Future work will involve further refinement of the user interface, enhancement of its features, and continued simulation efforts. We will compare the accuracy of our system with Keyence's commercial product and evaluate the simulation results against experimental data. Our goal is to ensure that the vibration patterns are closely aligned. The project remains within budget, and progress is on track to meet our objectives.

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10 Appendix

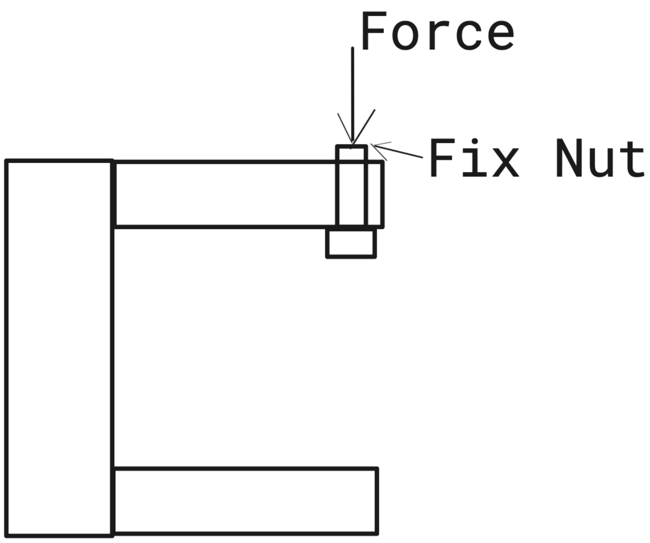

Figure 17: U-Shaped Part - Bending Simulation. Short bolt and fix nut are used in this case to simulate the scenario when the rivet comes to contact with the U-shaped part and this force starts bending the item.

Github repo for Arduino and PyQt codes: VE450 Group24 repo