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Vibro-Acoustic Analysis of a Fan Blade

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VIBRO-ACOUSTIC ANALYSIS

OF A FAN BLADE

by

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ABSTRACT

VIBRO-ACOUSTIC ANALYSIS

OF FAN BLADE

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Faculty Mentor: Yawen Wang

A frequent problem with rotating machinery is vibration. Vibration in a rotating part can be caused by unequal mass distribution. A sound or acoustic wave is created by a pattern or disturbances traveling through a medium. Vibration and Acoustics can be dealt with individually, however, if they share a common source, both could be solved simultaneously. The purpose of this project is to correlate the fan noise to the rotor imbalance. The unbalanced mass can be removed by aligning the center of gravity (CG) with the axis of rotation, which eliminates any coupled moments. The vibration is measured using accelerometers and the noise is measured with microphones. Simcenter TestLab hardware and software were used to analyze the signals before and after the balancing of the fan. The vibration and noise level of the fan is expected to decrease after the rotor is properly balanced.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

The goal of this senior design project is to reduce the noise generated by the cooling system in automatic cars. May Mobility is an autonomous technology company that has partnered with Via Rideshare service and the University of Texas at Arlington to provide autonomous carpools. In summer of 2021, May Mobility received customer complaints that their electronics, located in the trunk of the vehicle, were producing too much noise. In Fall 2021, May Mobility reached out to UTA to help them reduce the noise of their electronics. The senior design team traced the noise to the sever computer that has two intake fans and a row of six exhaust fans. The noise can be eliminated at the source or in the air. The team contacted May Mobility about changing the fans or switching to a liquid cooling system, however, they have a warranty on the CPU. This project explores one way that could reduce the fan noise by opening the server computer.

1.2 Objective

The goal of this project is to relate the noise and vibration to mass being added to one side of the fan. If an unbalance in the fan proportionally changes the noise and vibration, then the fan could be balanced to reduce the noise the fan makes. In this experiment the balance of the fan is altered and then measurements are taken to determine how the noise and vibration have changed. The hypothesis is that when weight is added to one side of the fan's outer rim, the noise and vibration will both increase.

CHAPTER 2

BALANCING

There are two main types of balancing: static and dynamic. The main goal of all types of balancing is to distribute the mass evenly so that when the body spins, there is no unwanted wobbling. The perfect case would be if the body is spun, no forces are transferred to the bearings. In the real world, this is difficult and costly to achieve, so a tolerance is decided based on the application that the rotating part will be used for.

2.1 Static Balancing

Static balancing reduces the centrifugal forces in rotating machinery. This type of balancing happens in only one plane. A part is statically balanced when the axis of rotation is in the same place as the center of gravity. The center of gravity is the axis an object will rotate around naturally. The axis of rotation is the shaft that the part is rotating about. A balancing mass can be added to that plane to balance the part. The location of the balancing mass can be calculated by summing the centrifugal forces [1]. An example of multiple masses in one plane is shown in Figure 1.1. The balancing mass is an equal and opposite moment to the resultant force created by the four masses. The resultant mass can be calculated by summing the X and Y forces and then taking the root mean sum.

$$\sum F_x = m_1 * r_1 * \cos(\theta_1) + m_2 * r_2 * \cos(\theta_2) + \cdots$$
$$m_3 * r_3 * \cos(\theta_3) + m_4 * r_4 * \cos(\theta_4) = 0 \text{ e}$$

$$\sum F_y = m_1 * r_1 * \sin(\theta_1) + m_2 * r_2 * \sin(\theta_2) + \cdots$$
$$m_3 * r_3 * \sin(\theta_3) + m_4 * r_4 * \sin(\theta_4) = 0$$

$$F_{CR} = \sqrt{\left(\sum F_x\right)^2 + \left(\sum F_y\right)^2}$$

$$\tan(\theta) = \frac{(\sum F_x)^2}{(\sum F_y)^2}$$

$$F_{CR} = M * R \qquad \theta = \theta_R + 180$$

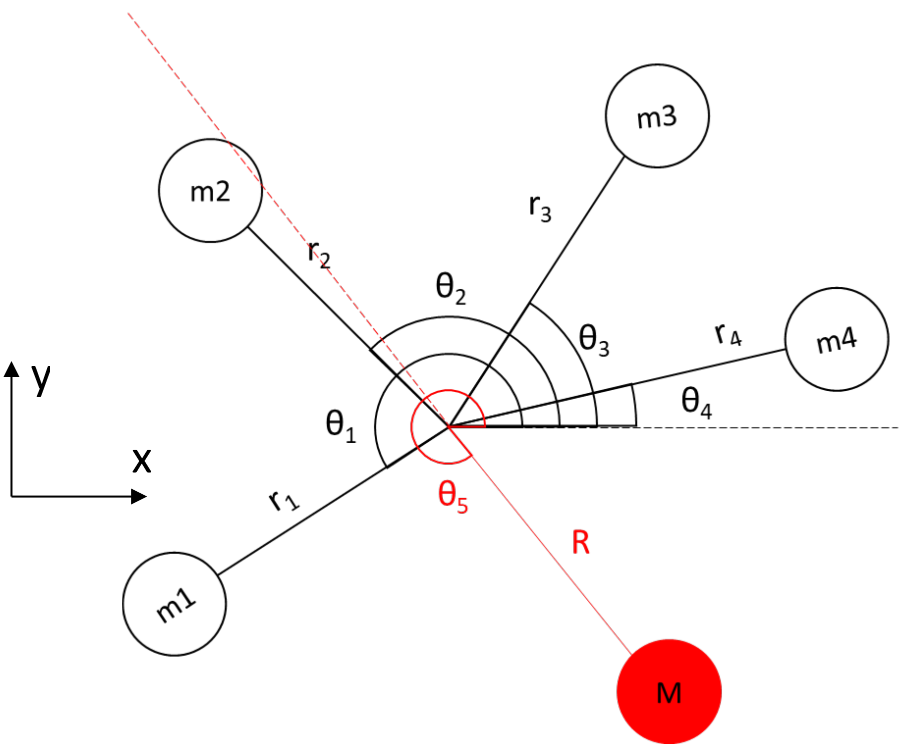

Figure 2.1: Balancing Multiple Masses in Same Plane

2.2 Dynamic Balancing

Dynamic balancing also reduces centrifugal forces like static balancing, but it also incorporates coupled forces. A couple is two equal and opposite forces that create a moment on an object. A part is dynamically balanced when the axis of rotation is aligned with the axis of the center of gravity and there are no couples. An example of balancing one mass with two masses is shown in Figure 1.2. The procedure is very similar to static balancing but with the addition of the sum of moments. The sum of moments about points A and B are done to balance the couple forces.

$$\sum F_y = F_{c1} - F_{c2} - F_{c3} = 0$$

$$\sum M_A = m_2 * r_2 * L_2 - m_3 * r_3 * L_1 = 0$$

$$\sum M_B = m_1 * r_1 * L_2 - m_3 * r_3 * L_3 = 0$$

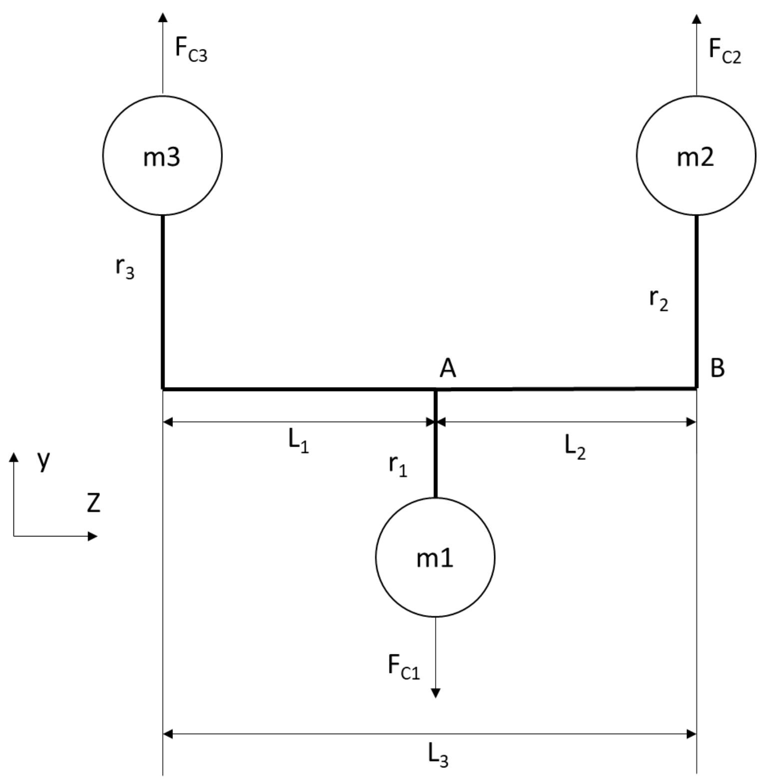

Figure 2.2: Balancing Single Mass with Two Masses

CHAPTER 3

METHODOLOGY

The end use of this project is to see if balancing is a viable option for reducing the noise and vibration in a fan. This project aims to establish a cause-and-effect relationship between an unequal mass distribution and the noise and vibration it makes. The cause-and-effect relationship can be seen with quantitative data. A set of primary data was collected for this purpose.

3.1 Approach

To test the noise and vibration of a fan, the team needed to design an experiment to measure the noise and vibration in response to a change in mass distribution. The mass distribution was the independent variable. The dependent variables were the noise and vibration. The control variables were the speed of the fan, ambient noise in the environment, and the fan's geometry. The experiment was conducted in an apartment, and it was assumed the ambient noise was negligible.

3.1.1 Control Variables

3.1.1.1 Fan Geometry

The fan was designed using SOLIDWORKS as shown in Figure 2.1. The fan consists of four blades, an outer ring, and a mounting surface. The fan blades overlap with each other but do not connect. This blade configuration is meant to replicate the same number of blades and type of blade to the ones that are present in the CPU of May Mobilities vehicles. The outer ring is sixteen equally spaced cavities that are designed to fit nuts. The mounting surface provides support to hold the fans and a hole for the motor shaft.

Figure 3.1: Fan Model Perspective View

3.1.1.2 Fan Speed

The speed of the fan was controlled with a stepper motor. The team used a NEMA 17 stepper motor for its price point and accuracy. Stepper motors require a motor controller and a pulse-width modulated (PWM) signal to run. The motor controller is a common circuit that converts the PWM signal into voltages that the stepper motor can accept. The team selected an EasyDriver motor controller because it could handle 12 volts. The PWM signal was generated from an Arduino mega board. The code used for generating the PWM signal is in the appendix.

3.2 Data Acquisition

3.2.1 Setup

To collect the quantitative data, a microphone measured the noise, and an accelerometer measured the vibrations. Figure 2.2 shows the experimental setup. The fan is mounted directly onto the motor shaft with an interference fit. The connection method is important because it can have small effects on the mass distribution. An interference fit does not require a keyway or a set screw that could introduce an imbalance. The accelerometer is mounted onto of the motor casing. Ideally the accelerometer would be mounted on the shaft, but that is difficult to achieve. In other setups, the accelerometer can be mounted onto bearings that support the drive shaft [2]. The microphone is placed a few inches in front of the fan to measure the noise generated. The placement of the microphone is not important to the measurement of noise, but it should be noted that the microphone must stay in the same location throughout experiments. In a free field, where there are no reflections of sound of objects, you only need to worry about the radial distance between the noise source and the microphone. In a diffuse field, where there are significant reverberations, the noise can be different at all points in cartesian space.

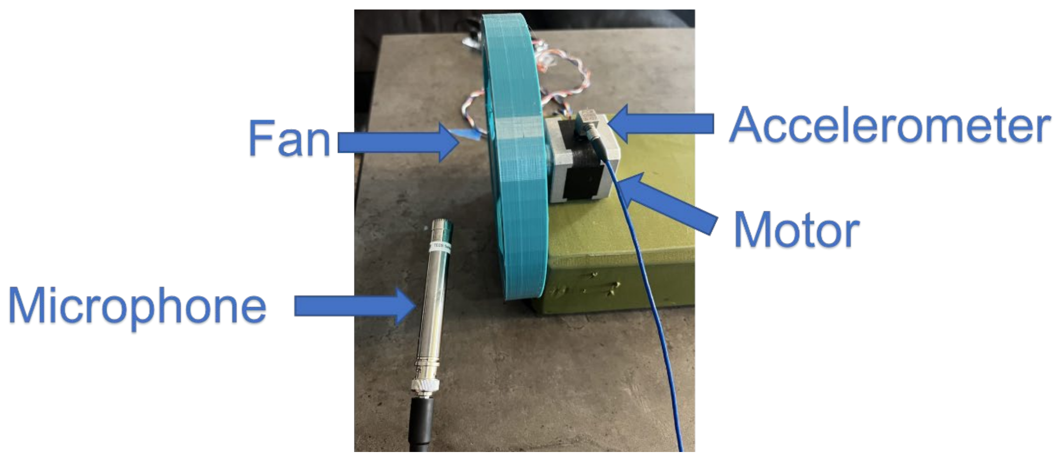

Figure 3.2: Test Setup

3.3 Procedure

The first step is to establish a baseline for comparison. The baseline was taken with a fan that had weight added to it. The fan ran at a constant speed of 200 rpm and the noise and vibration were recorded for 100 seconds. The fan was assumed to have an equal mass distribution. This assumption effects the final results, but the main objective is to find the relative effect. The mass distribution was changed by adding three nuts to the rim of the fan, which came out to 0.5 oz. The test was repeated at the same speed and the noise and vibration were measure for the same duration.

3.3.1 Signal Pre-Processing

The signals were processed with Simcenter SCADAS Mobile data acquisition system and Simcenter Testlab software [3]. I did not have a calibrator so the absolute measurements of these sensors could be slightly off due to the temperature and humidity. The relative measurements were all taken in the same day over the course of a few hours. Siemens software calculated the loudness and overall level of the frequency and vibration spectrums.

CHAPTER 4

RESULTS

The hypothesis of this experiment is whether there is a correlation between the mass distribution of a fan and the noise and vibration caused by it. The data collected was processed using Simcenter Testlab software. Waterfall plots were made of the vibration and frequency spectrum. Testlab was used to calculate and plot loudness, overall level, average, and peak values. The data agrees with the hypothesis.

4.1 Noise

These waterfall plots show Frequency vs Time, and the colors represent the amplitude of sound in pascals with dB(A) weighting. Figure 4.1 has peaks of 100 dB at approximately 600Hz, with a 50dB harmonic at 1242Hz. The second highest frequency is 70dB at 900Hz, with a 60dB harmonic at 1823Hz. There is also 50 dB at 1500 Hz. Figure 4.2 shows the loudness of all three trials on the same plot.

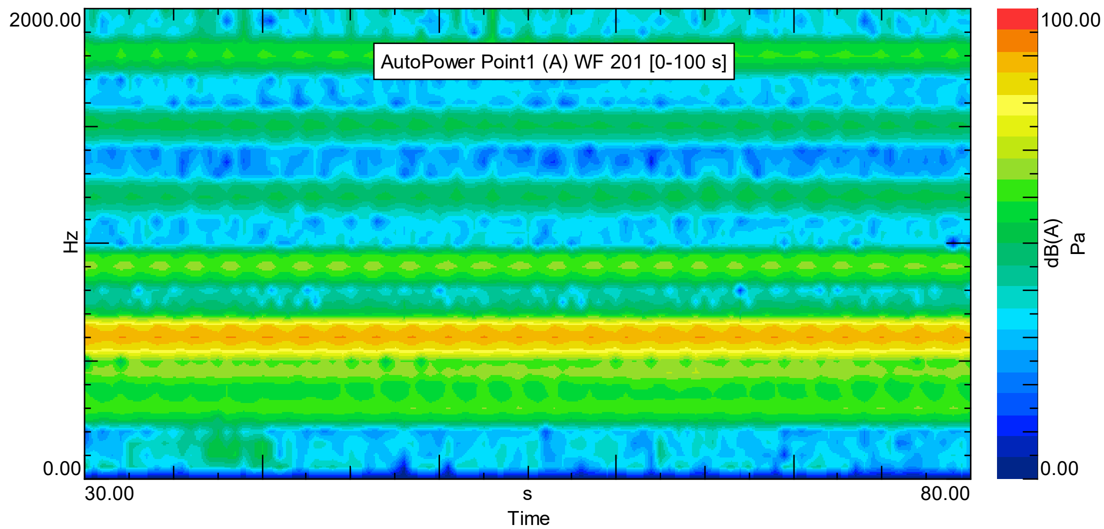

Figure 4.1: Frequency Spectrum with No Added Weight

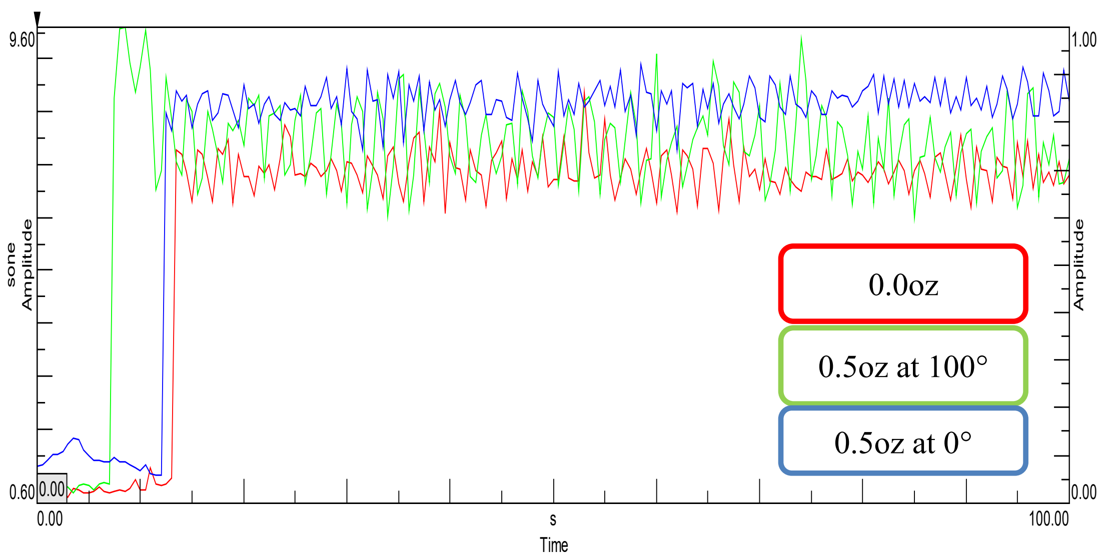

Figure 4.2: Loudness

4.2 Vibration

Figure 4.3 shows the vibration measured in acceleration (g) and time (s). The plot is scaled in decibels (dB). The red line in Figure 4.3 shows the vibration in the fan when there is no added mass. The red line is at approximately -29 dB. The green line shows the fan with 0.5oz added at 270 degrees. The green line is at -28 dB. Figure 4.4 depicts the overall level of the vibration. The fan with no added mass is shown in red. The fan with 0.5oz added is shown in green.

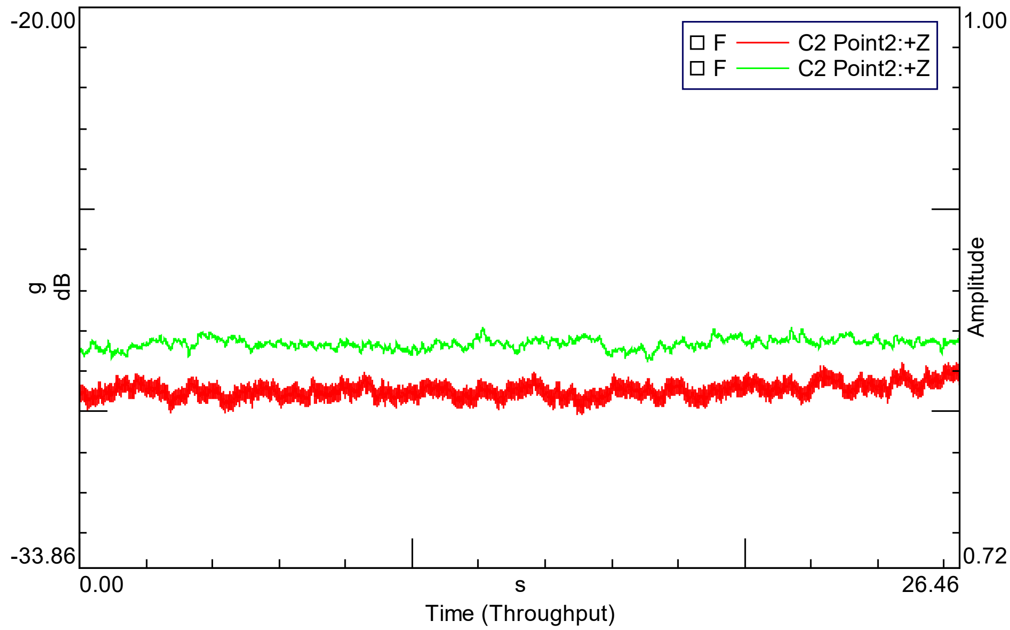

Figure 4.3: Vibration vs Time

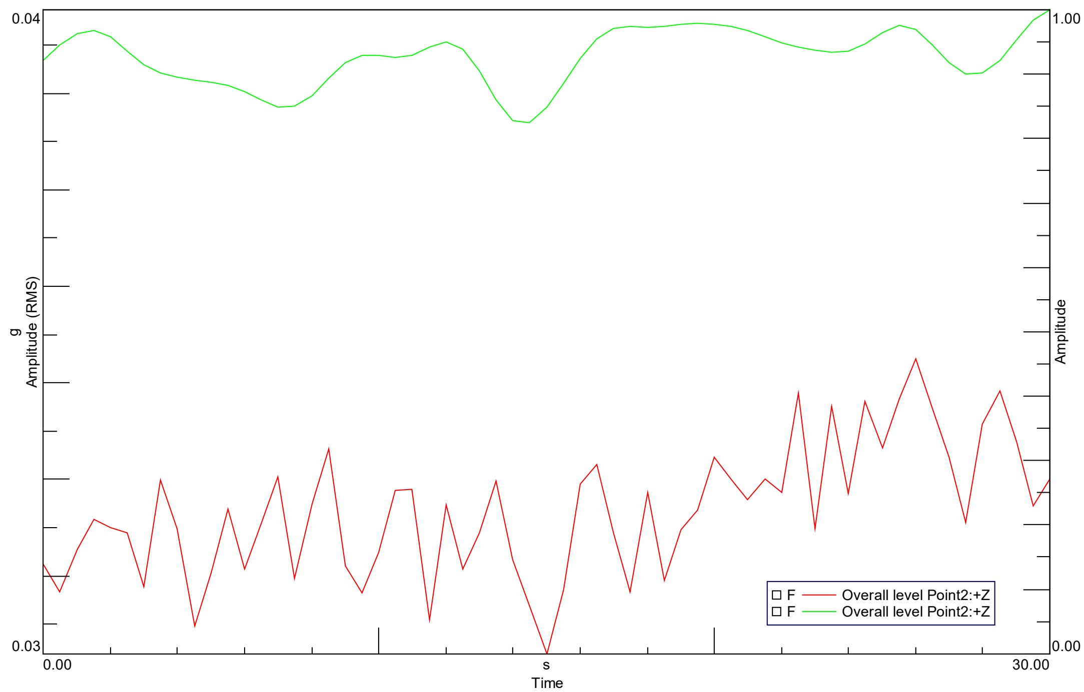

Figure 4.4: Overall Level of Vibration

CHAPTER 5

DISCUSSION

The main objective of this experiment is to determine the correlation between the fan's distribution of mass, noise, and vibration.

5.1 Mass Distribution and Vibration

The results do show a correlation between changes in mass distribution and vibration. Figure 4.3 shows that when mass is added to the fan, the acceleration increases from -29dB to -28dB. Figure 4.4 also supports the claim that vibration should increase when there is mass added to the fan. Figure 4.4 shows that the vibration signal of the fan with mass added has more power in it than the signal of the fan with no added mass. This does agree with the hypothesis that the vibration should increase when the fan is unbalanced. The results also agree with practice. The fan is approximately ¾ in, which is thin enough to be considered a single plane. With the assumption that the fan has mass evenly distributed initially, adding 0.5 oz at a radius of 3.5 in should create 1.75 oz*in of centrifugal force.

There were some limitations in this experiment. The vibrations were recorded using the uniaxial accelerometer, which measured the vibration in the Z direction. If there was any vibrations in the X and Y directions, they would not have been recorded. It was also assumed that the ambient noise from the environment, an apartment building, was negligible. The environmental noise could not be entirely controlled. A baseline measurement was taken to factor the noise into the data but passing vehicles, for example, can add background noise randomly. Some solutions to this problem are to conduct the measurements in a special testing room, like a whisper room, or to apply frequency filters. The accelerometer was mounted on the motor casing. The vibration spectrum shows static above 150 Hz. The stepper motor has a step every 1.8°. If the motor dominated the frequency spectrum, vibration at a higher frequency would show up on the waterfall plot.

5.2 Mass Distribution and Noise

The results confirm the hypothesis, but more testing to repeat the result is recommended. The waterfall plot, Figure 4.1, shows multiple fundamental frequencies. There is a 90 dB amplitude signal at 600 Hz. This is most likely the fan noise. There is another fundamental frequency at 900Hz, which is too high for it to be an event from the fan. The loudness comparison plot, Figure 4.4, does not agree with the results from the waterfall plot. The two trials where weight was added to the fan had a higher perceived loudness than the fan with no weight added. This could be because the initial assumption that the fan was balanced. The fan was manufactured using a 3D printer. 3D printers melt and rapidly cool polymers. During the cooling process, residual stresses are baked into the part. The cross-sections of the fan blades are very thin, and a few portions of the fan broke. The fan originally had symmetry, so those breaks make changes to the mass distribution. Adding weight could have improved the balance. The balance of the part could not be checked with the setup that was used. To check the balance, a different setup and a tachometer should be used.

5.3 Recommendations

Better results could be achieved by checking the initial balance of the part and by testing at higher rpm. The assumption that the part was balanced turned out to be a limiting factor in the results of this experiment. A shaft supported with bearings at both ends could determine the initial balance of the part. A tachometer would also need to be included for the software to calculate the angle that the imbalance exists at. The fan was spun at 200 rpm in this experiment. The industry standard is to spin the part up to 3000 rpm. A different type of motor, like a brushless DC motor, would work better for this purpose. Increasing the rpm will increase the vibration and noise the part makes by the power of 2, making the results much easier to compare.

CHAPTER 6

CONCLUSION

Balancing of rotary components has been used to increase part life and reduce the wear on the bearings. This experiment tested whether an unbalanced fan produced more noise and vibration. This could help the senior design team reduce the fan noise in May Mobility's vehicles at the source. Reducing noise in autonomous vehicles also has larger applications. Self-driving vehicles are in humanity's near future. These vehicles rely heavily on large computer power. As the rise of autonomous vehicles will alleviate people from the cumbersome task of driving, so should noise stop burdening people's ears.

APPENDIX A

ARDUINO CODE

2. *Arduino Code to generate PWM signal for stepper motor*

```
void setup() {
  int direction_pin = 2;
  int step_pin = 3;
  pinMode(direction_pin,OUTPUT);
  pinMode(step_pin, OUTPUT);
  digitalWrite(direction_pin, LOW);
  digitalWrite(step_pin, LOW);
  Serial.begin(9600); // send and receive at 9600 baud

}

void loop() {
  int direction_pin = 2;
  int step_pin = 3;
//  for (int i=2000; i>=500; i=i-100){
//    for (int j=0; j<=200; j++){
//digitalWrite(step_pin, HIGH);
//delayMicroseconds(i);
//digitalWrite(step_pin, LOW);
//delayMicroseconds(i);
//    }
//
//Serial.println(i);
//  }
  digitalWrite(step_pin, HIGH);
delayMicroseconds(200);
digitalWrite(step_pin, LOW);
delayMicroseconds(200);
//  delay(5000);
}
```

REFERENCES

[1] Varde, Gautam. “Balancing of Single Mass with Two Masses (DOM/TOM)_04.” DOM/TOM 3151911 GTU. 5 May 2022, Balancing of single mass with two masses (DOM/TOM)_04, Balancing of Single Mass with Two Masses (DOM/TOM)_04.

[2] Nisbett. *Dynamic Balancing of Rotating Machinery Experiment Technical Advisor ...* https://web.mst.edu/~stutts/ME242/LABMANUAL/DynamicBalancingExp.pdf.

[3] *Siemens DISW*, https://community.sw.siemens.com/s/article/balancing-static-coupled-and-dynamic.

BIOGRAPHICAL INFORMATION

He was inspired to become a mechanical engineer while on Erickson Middle School's robotics team. Under the mentorship of Calvin Moor, a retired Raytheon Engineer, Matthew competed in the Collin County Boosting Engineering Science and Technology (BEST) robotics competition. At Allen High School, he joined the Eagles Robotics team and continued competing in BEST, as well as competed in the For Inspiration of Science and Technology (FIRST) robotics competition. His experience with robotics competition informed his choice to enroll in University of Texas at Arlington's Bachelor of Science in Mechanical Engineering program. He was excited to expand his knowledge of science and be like the mentors of his robotics teams, who inspired him to pursue a STEM degree.

In his freshman year of college, he lived at KC Hall. He had AP credit for Physics, Calculus I, and Calculus II, but decided to start with calculus anyway. In his free time, he hung out with his new group of friends at the gym or studying for class. During his freshman year, he found a surplus blackboard in Woolf Hall. The 12 by 4 ft blackboard was carried down three flights of stairs in Woolf Hall, walked to the Fab Lab, split into thirds for each person, and is still with him in his apartment. Matthew was not involved in campus activities until his junior year when he joined the rover team. He enjoyed the collegiate robotics team. Despite going into college with robotics as his career interests, Matthew is now pursuing a career in acoustics because of his senior design and Honors capstone projects.