Aer E 322 Aerospace Structures Laboratory – Lab Report 2023

Lab 10 Structure Model Building

Section 5, Group 5

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12/10/2023

Introduction

Our final project for this course involved the application of knowledge obtained throughout the semester to construct and test a model structure of our own. In three weeks of work, we were able to rapidly go through the cycle of design, construction, testing and analysis, and in the same short timeframe also gain a good quality of learning experience, applying the "rapid design, prototyping and learning" concept. This comprehensive test involved the use of most of the PASCO toolkit to obtain relevant data from some type of loading environment as chosen by the group.

The focus of our analysis is to apply and understand the basic theories of vibration and structural dynamics. From the PASCO Toolkit, we used the building blocks, the wave driver to cause vibration to our structure, and the displacement needle to measure displacement. The structure our team designed was the base frame of a missile with stabilizing fins. The test we wanted to analyze was the impact of high Mach number vibrations on a fin structure during full and empty weight cruise procedures. The frame would be constructed out of PASCO beams and subjected to a wave driver.

Objective

We intend to test the displacement in the cylindrical structure of a missile in-flight by adding vibration in the trailing edge of its fin, simulating vibration due to turbulence. We also wanted to understand how extra load could affect those results.

Hypothesis

Our working hypothesis is that the vibration effects, measured as displacement, on the fin will decrease when payload weight is increased uniformly throughout the structure. This idea is of course backed by theory, so moreover we intend to analyze by what kind of factor or percentage the central structure's vibration will decrease with a corresponding increase in load.

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Variables

For our experiment, the true variable we would be measuring will be displacement. We can also use the weight we apply to analyze the total load on the structure and possibly stress. The total mass applied to the system was 2.4 kg.

Variable	Symbol	SI units
Displacement	Δ	Millimeters
Force	F	Kg*m*s^-2
Weight	W	Kg*m*s^-2
Stress	σ	Kg*m^-1*s^-2

Table 1. List of variables

Work Assignments

For the work done in lab, we worked together to decide on the design of our structure and the objective of our analysis. Everyone also worked together to build the structure and set up the systems for data recording, in each of the three days we were in the lab for this project.

For the report, Lucas did the Methodology, Procedure, and Apparatus, the Objective, and part of the Introduction. Isaac did the Introduction and Hypothesis. Ethan did the Variables and Data. Joseph did the conclusion. Every group member contributed to the Analysis, but Isaac and Ethan contributed the most.

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Methodology, Procedure, and Apparatus

In order to apply the concept of "rapid design, prototyping and learning," we have used the PASCO Toolkit to build and analyze our model of a missile. Our design was basically two octagons connected to each other by eight longer beams (one in each vertex), modeling a body tube. The two fins were a rectangle and a triangle geometry combined, attached to the side of the body tube in a way that they would be symmetric. We decided to do octagons to get a model that best simulates a circular cross-section.

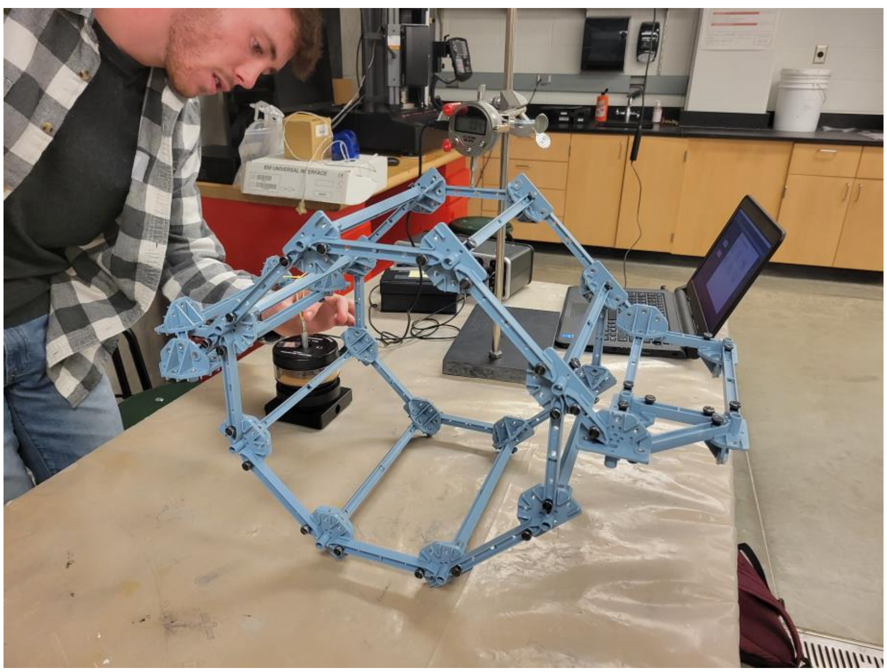

Figure 1. Front view of our missile model

Figure 2. Side view of a missile. Our design is modeling the area of a missile in the red rectangle

To simulate turbulence, we connected a wave driver to induce vibration in the trailing edge of the missile fin (Figure 3). A displacement needle was positioned in the top beam of the "body tube" as you can see in Figure 4. We intended to analyze the effect on the main structure of the missile as the fin vibrated. Using the PASCO Capstone software, we could control the vibration and record the needle displacement vs. time as the system vibrated. Six sets of data were collected. For all of them, the wave driver was configured with an amplitude of 15 dB, which likely corresponds to the force being applied by the wave driver. For run 1 we used a frequency of 5 Hz; for run 2, frequency was 10 Hz; and for run 3, frequency was 15 Hz. We then added extra weight to the structure, which was distributed as seen in Figure 5. The two big weights on the top beams had 1 kg each, and the two smaller weights on the side beams had 200 g each. We then proceeded to repeat run 1, 2, and 3 as 4, 5, and 6, but now with the extra load.

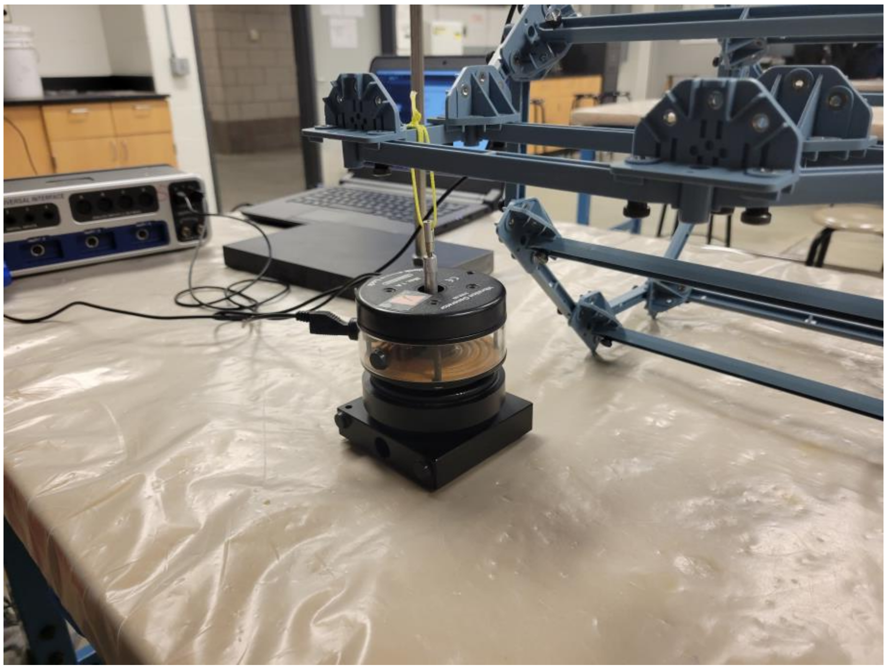

Figure 3. Wave driver attached to the trailing edge of the fin

Figure 4. The displacement needle positioned over a top beam of the missile model

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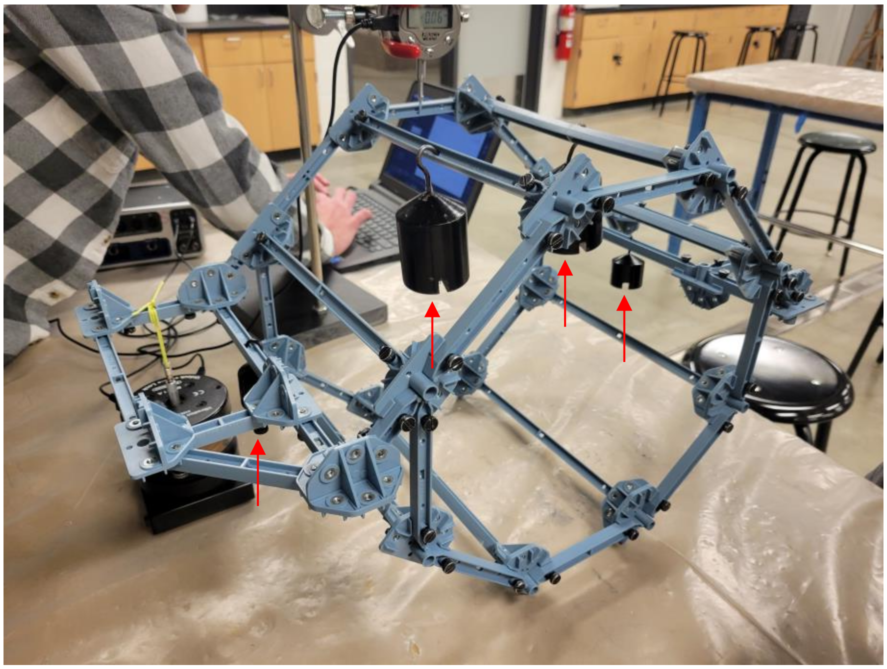

Figure 5. Missile model with extra weights (indicated by red arrows for better visualization)

Data

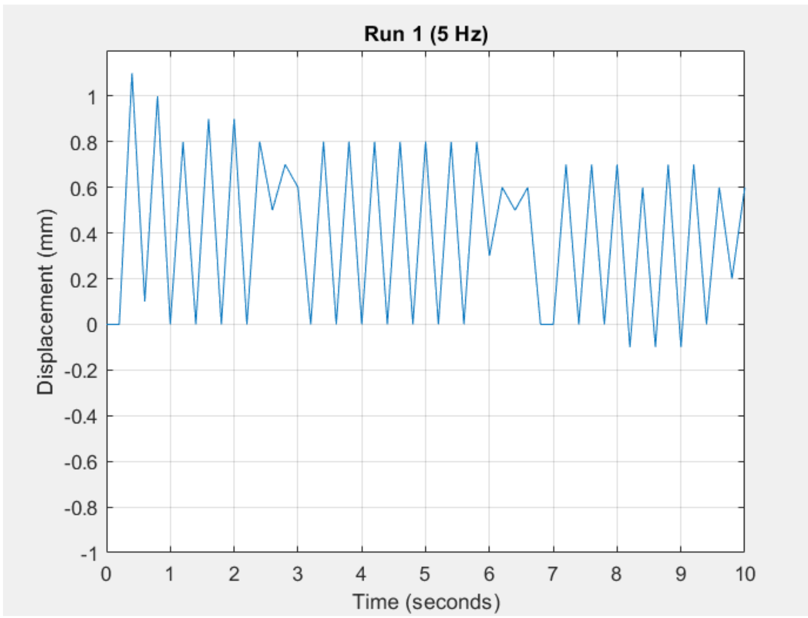

Figure 6. Run 1 at 5 Hz

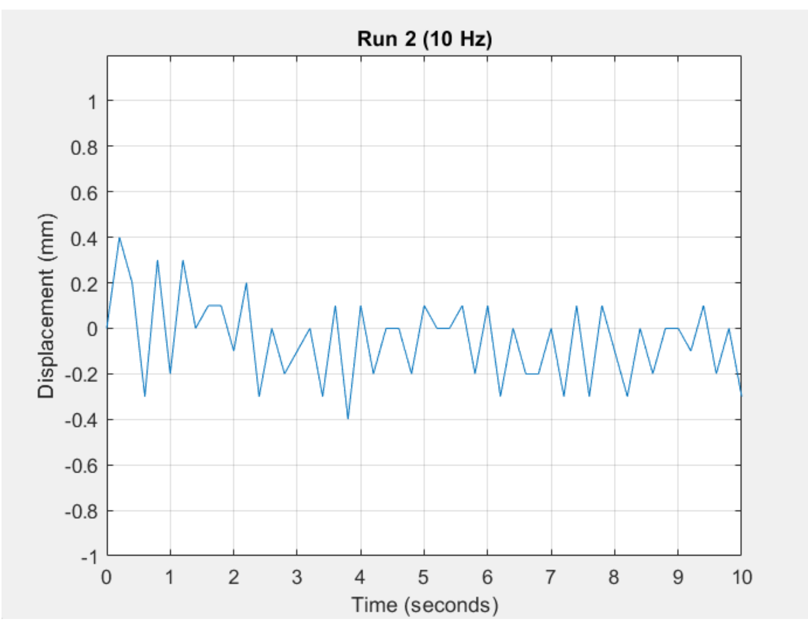

Figure 7. Run 2 at 10 Hz

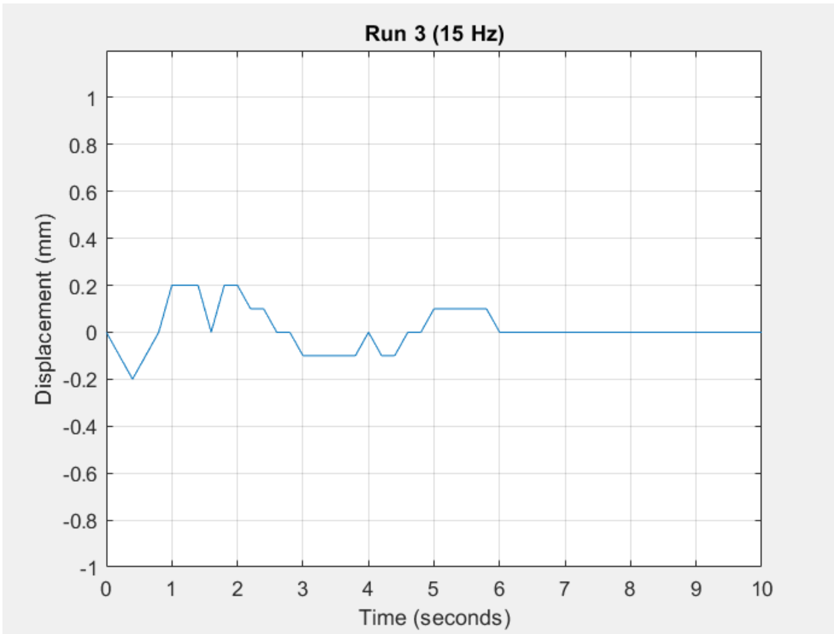

Figure 8. Run 3 at 15 Hz

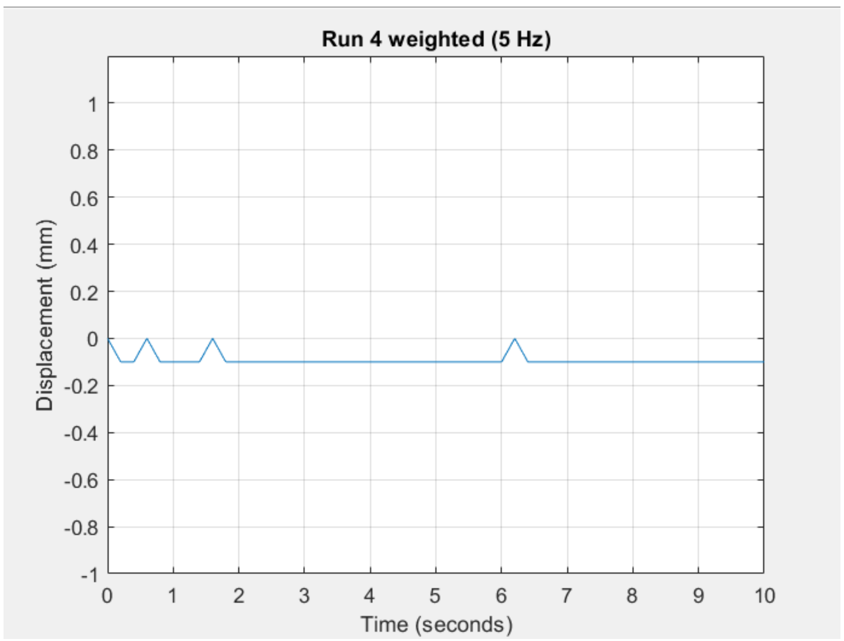

Figure 9. Run 4 at 5 Hz (weighted)

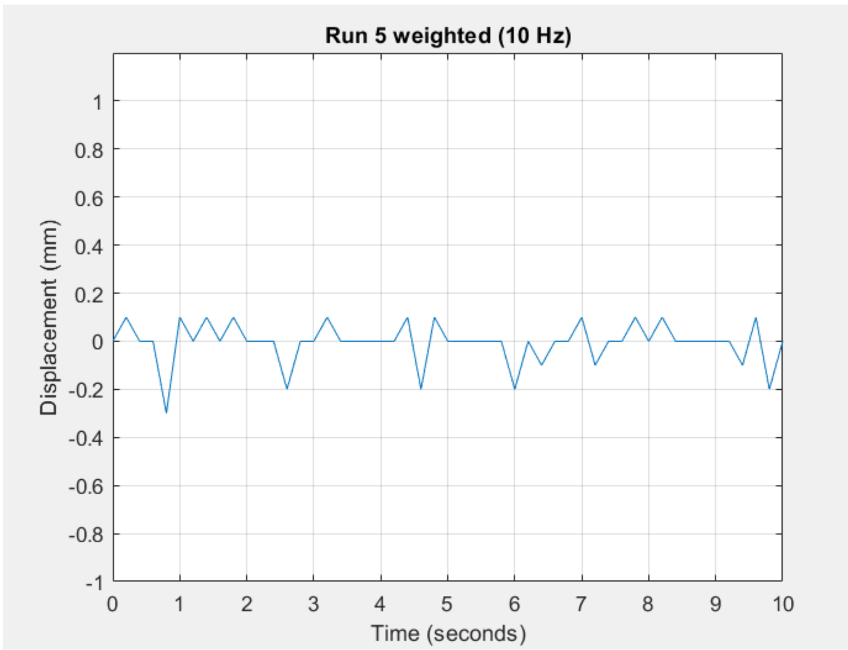

Figure 10. Run 5 at 10 Hz (weighted)

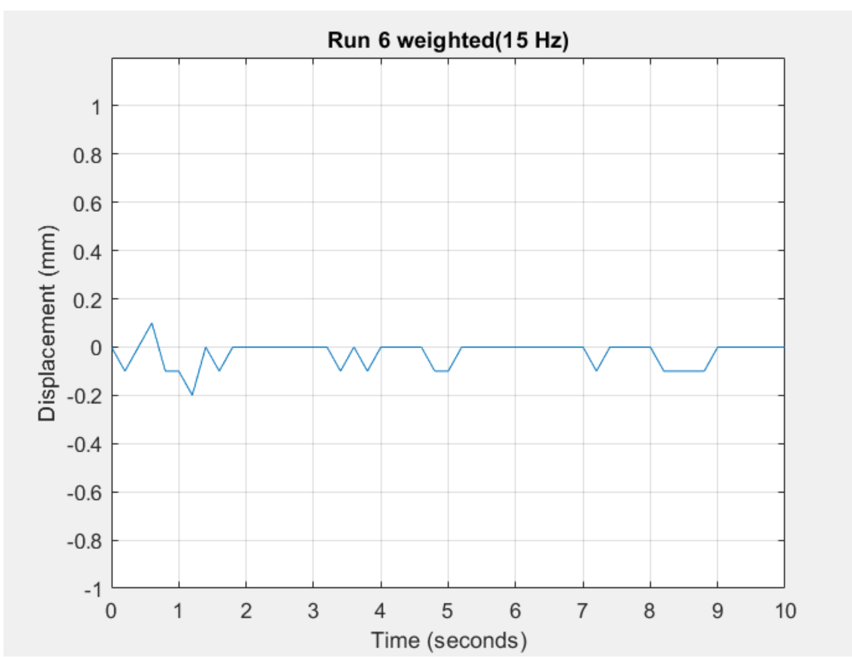

Figure 11. Run 6 at 15 Hz (weighted)

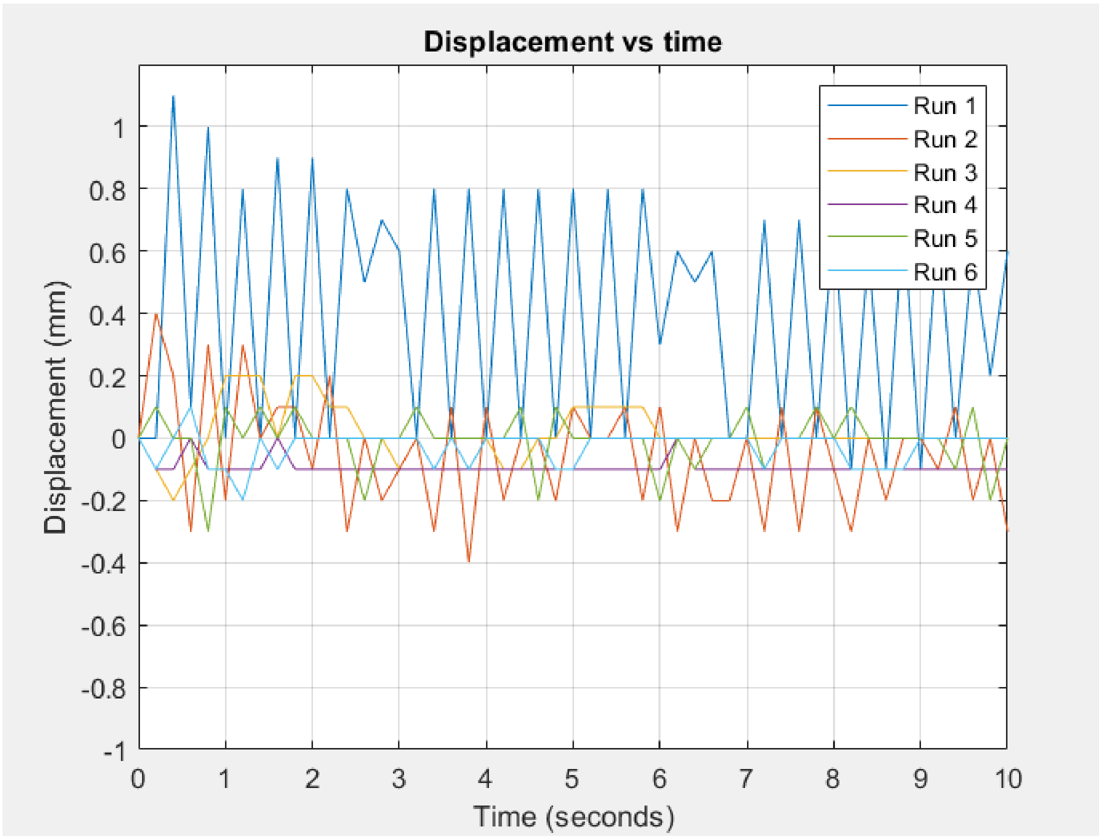

Figure 12. Runs 1-6 plotted together

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Analysis

I. Starting with the first three runs unweighted, the first observable effect is the trend of decreasing displacement as frequency increases. This can be explained theoretically, as there is an inverse relationship correlation between frequency and amplitude. If one were to continually increase the frequency of an oscillation such as this, keeping all other parameters the same, the force being translated through the wave driver would also remain the same. Frequency is a measure of time between peaks in amplitude and the amplitudes in this test are given by maximum displacements. Because of this, decreasing the time between peaks would necessitate that less distance could be travelled via the wave force per peak. In other words, the force causing the fin to vibrate would have less total time to displace before being reversed to maintain oscillation. To maintain the same amplitude of displacement, one could theoretically increase the amplitude of the force being applied, thereby increasing the acceleration and increasing the amount of distance travelled between peaks. displacement amplitude (A) can be related to frequency (f) using the formula A = k/f, where k is a constant. At extreme speeds, missiles would likely experience increased force due to wave drag and other flow effects, therefore this inverse relationship has little useful application there.

II. Also during the unweighted runs, it was observed that the system amplitude remains roughly constant, particularly notable for the low frequency runs. Since we also have the wave driver acting as a constant external force, without some internal damping force the system would be undamped, and the displacement magnitude would displace indefinitely. Instead, from a free body diagram including frictional resistance due to air viscosity, we can see that the system is a type of forced damped vibration with damping forces like air, gravity and the reaction forces generated by the normal force between the structure and the table. This system has the general form:

$$my'' + \gamma y' + ky = F_0 \cos(\omega t)$$

Where m is mass, gamma is damping coefficient and k is the stiffness. Displacement is given by y(t) and omega is frequency. Of course, the system we are operating with is more complex than this model alone allows for, as the vibration is applied on the fin and the displacement is measured at the center of the system. This setup showed how much the center of the structure is affected by external vibration forces.

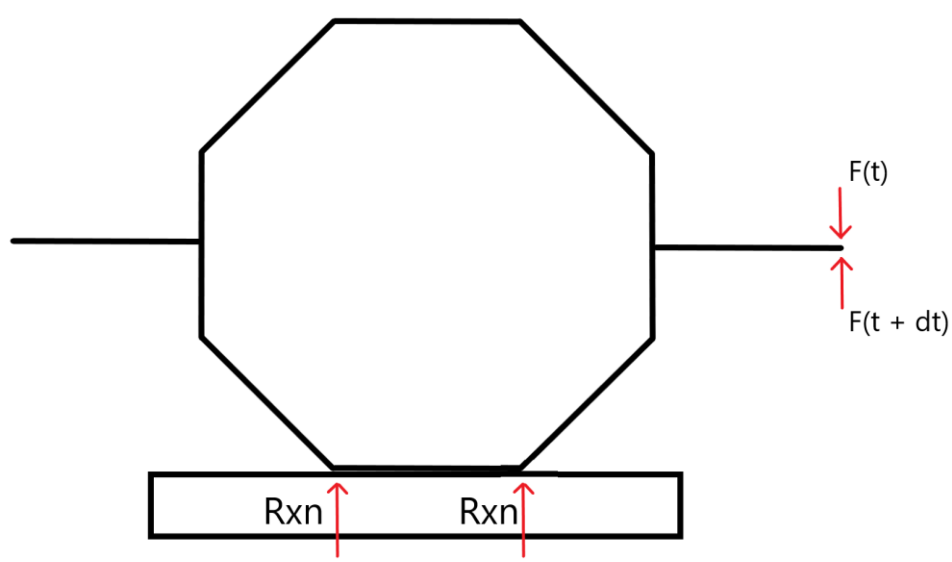
III. Assuming a simplified system like this can allow us to draw some conclusions about our data. The general solution is given as

$$y_p(t) = \frac{F_0}{\sqrt{m^2\left(\omega_0^2-\omega^2\right)^2+\gamma^2\omega^2}}\cos\left(\omega t-\theta\right)$$

We can see from this solution that the variable parameters, mass, frequency and damping all contribute inversely to the displacement output, which in this case will have a steady state that is a sinusoid of constant magnitude. This lends credence to our hypothesis as with increased mass and frequency we saw a marked decrease in displacement magnitude. An explanation of why total displacement was not only reduced but balanced closer to the zero axis comes from a free body analysis of the structure, in a 2D system, we can place in the oscillatory force and for the unweighted portion we can also include upward reaction forces from the points where the structure was in contact with the ground. For the weighted portion, we will also have a negative, or clamping reaction force from the 2.4 kg mass acting down on the system.

From the simple FBD figures below, analyzing only the major reaction forces, we can see that at a time t when the wave driver is creating a downward force, the table reaction forces push against the force but do not provide a control moment as there are no pins of any kind. This causes the oscillation to be much higher when the wave driver switches to an upwards force at time t + dt. At that time, there are no damping or reaction forces against the external wave driver, so the upward vibration is bounded almost exclusively the amplitude and frequency of the external force. The reason the displacement is not too great is likely because the wave driver cannot provide a sustained upwards force due to the use of a string as the vibrating medium, this also means that when pulling on the system the string creates a tensile force that cannot be counteracted by the table.

For the weighted portion, at time t the table reaction forces provide the same reaction, but the increased mass also provides an increase control moment against the downward vibration. At time t + dt, the weights provide a much greater negative reaction force against the wave driver. This is primarily what causes the vibration for the weighted section to be reduced. This sort of damping analysis can be used to determine better control systems for wing and fin structures in aircraft. For our test, this fin was modelled as having no interior structure, but instead as a composite mold. In this sort of system, vibration comes from wing tip vortex effects induced by various types of drag and pressure differentials. This sort of fin acts similarly to our system in that it ideally undergoes constant vibration, which is a cycle of air bending the fin, and the stiffness causing the fin to bend back, causing twist etc.



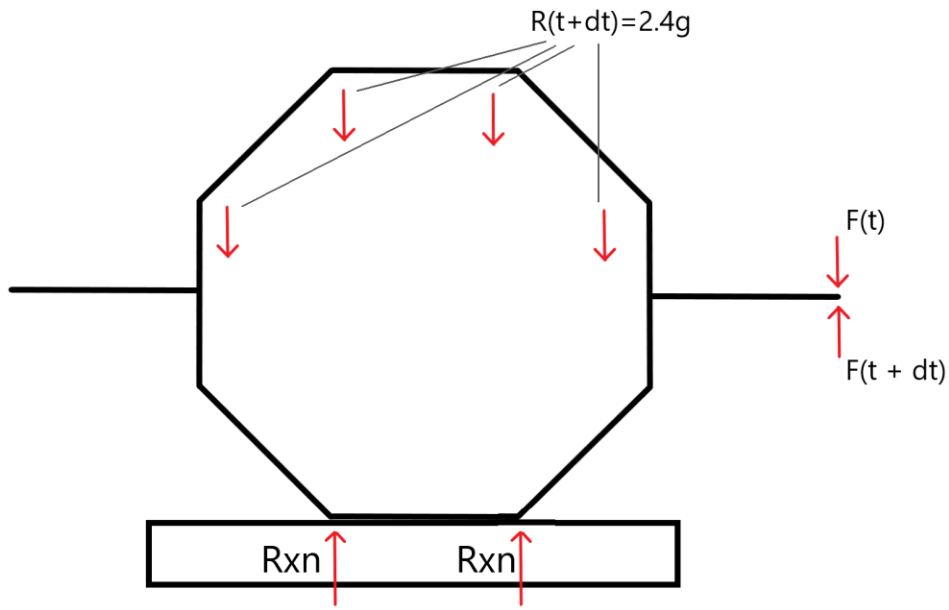


Figure 13(a-b). Analysis of reaction force versus time

IV. There were many places in the lab that caused a bottleneck on our data and consequentially could have negatively affected it. One that was only thought of after the experiment was over was the sampling speed of the displacement sensor. In our experiment it took a measurement every 0.1 seconds, we thought that this would be a short enough sampling speed to get very good data from our experiment. However, we noticed that in some of the data it seems as if there is no change in displacement, in fact it is visible in more than one of our graphs. As this is the case, we have to attribute that there more than likely is some error in the data for that reason. There is also the string that was attached to the wave driver, which we as a group found was difficult to tie and at times was not tight enough. We also noticed that since it is not elastic and it is constantly moving up and down exactly in line with the wave driver, and that there very well could be times when the wave driver was moving but the structure was not feeling the full vibrational effects of the driver.

V. It is noted how extra weight could help the model structure possess greater resistance to vibration. In a realistic scenario, the payload and structure weight can reduce the vibration propagation over the missile structure when subjected to diverse atmospheric inputs, as seen in this model experiment and in theory. There are some parameters that, if addressed, could give this experiment a more precise result. Our "body tube" was modeled as two octagons connected to each other by eight longer beams. The fin was a rectangle and a triangle structures merged. A circular cylinder representing the body and a plate model of a fin could have presented results closer to reality. Additionally, we could have the weight better distributed around the structure. However, considering our objective of applying the "rapid design, prototyping and learning" concept, our design was able to deliver a good representation of the bottom section of a missile for the purposes of our analysis.

Conclusion

It was seen that when weight was added to the structure the theory was proven correct and the total displacement of the beam was decreased. Additionally, it was noticed that the trends of displacement were the inverse of each other. For instance, in the unweighted testing as the frequency decreases the displacement increases. Whereas in the weighted testing it is seen that the opposite happens and that as the frequency of the wave driver was decreased the displacement of the beam was seen to also decrease. The reason for this was modeled as a spring-mass-damper system where the mass added causes the displacement to generally decrease. From this we can take the idea one step further and conclude that all the variables inversely contribute to displacement, and this is why the pattern of the displacement inverses when mass is added to the structure. From this we can further conclude that our model follows known theories and creates a good real world approximation of what is expected to happen. Additionally, if the instrumentation could obtain data with more precision the model would become even more accurate.

Appendix

MATLAB code:

```
clear
clc
close all

% Read data
data = readmatrix("run6_15f_15a_weight - Copy.csv");

% Identifying columns of data
Time1 = data(:,1);
Displacement1 = data(:,2);
Displacement2 = data(:,4);
Displacement3 = data(:,8);
Displacement4 = data(:,10);
Displacement5 = data(:,12);
Displacement6 = data(:,14);

% Plotting data
figure(1)
plot(Time1,Displacement3)
title('Run 1 (5 Hz)')
xlabel('Time (seconds)')
ylabel('Displacement (mm)')
ylim([-1 1.2])
grid on

figure (2)
plot(Time1,Displacement1)
title('Run 2 (10 Hz)')
xlabel('Time (seconds)')
ylabel('Displacement (mm)')
ylim([-1 1.2])
grid on

figure (3)
plot(Time1,Displacement2)
title('Run 3 (15 Hz)')
xlabel('Time (seconds)')
ylabel('Displacement (mm)')
ylim([-1 1.2])
grid on

figure (4)
plot(Time1,Displacement4)
```

```
title('Run 4 weighted (5 Hz)')
xlabel('Time (seconds)')
ylabel('Displacement (mm)')
ylim([-1 1.2])
grid on

figure (5)
plot(Time1,Displacement5)
title('Run 5 weighted (10 Hz)')
xlabel('Time (seconds)')
ylabel('Displacement (mm)')
ylim([-1 1.2])
grid on

figure (6)
plot(Time1,Displacement6)
title('Run 6 weighted(15 Hz)')
xlabel('Time (seconds)')
ylabel('Displacement (mm)')
ylim([-1 1.2])
grid on

figure (7)
plot(Time1,Displacement3)
hold on
plot(Time1,Displacement1)
plot(Time1,Displacement2)
plot(Time1,Displacement4)
plot(Time1,Displacement5)
plot(Time1,Displacement6)
hold off
title('Displacement vs time')
xlabel('Time (seconds)')
ylabel('Displacement (mm)')
ylim([-1 1.2])
legend(‘Run 1’, ‘Run 2’, ‘Run 3’, ‘Run 4’, ‘Run 5’, ‘Run 6’)
grid on
```