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Effects of Identical Parts on a Common Build Plate on the Modal Analysis of SLM Created Metal

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ABSTRACT

The frequency response of parts created with Additive Manufacturing (AM) is a function of not only process parameters, powder quality, but also the geometry of the part. Modal analysis has the potential to evaluate parts by measuring the frequency response which are a function of the material response as well as the geometry. A Frequency Response Function (FRF) serves as a fingerprint of the part which can be validated against the FRF of a destructively tested part. A practical scenario encountered in Selective Laser Melting (SLM) involves multiple parts on a common build plate. Coupling between parts influences the FRF of the parts including shifting the resonant frequencies of individual parts in ways that would correspond to changes in the material response or geometry. This paper investigates the influence of the build plate properties on the coupling phenomena. This work was funded by the Department of Energy's Kansas City National Security Campus which is operated and managed by Honeywell Federal Manufacturing Technologies, LLC under contract number DE-NA0002839.

1. INTRODUCTION

Recent improvements in AM have allowed various materials to be used to create specimens as well as creating complex geometries. With AM increasing in usage, small-scale manufacturing is becoming less prominent, resulting in the need for validation techniques. There are NDE methods in place, such as Computed Tomography, which are used to detect porosity or other geometry defects; however, they are expensive [1]. A cost effective means that is used to detect defects is modal analysis and it has been applied to various structures in the automotive, civil infrastructure, and aerospace industries. [2]

Modal analysis can be used to validate parts on the basis of their resonant frequencies. If a part is less dense than another, the resonant frequency will shift upward due to the inverse relationship between the resonant frequency and the density of the part. A concern arises however, when multiple parts are tested modally on a common build plate that is used during the SLM process and the result is a coupling effect that presents itself similar to a tuned mass damper. To show this effect a simulation was conducted in which one rectangular cantilever was in the middle of the build plate and another where two were symmetric about the vertical axis and were separated by one inch. Figure 1 shows the resulting FRFs of the single and two cantilever systems. To showcase the sensitivity of the frequency response, the same two geometries were used but instead the stiffness of the parts was decreased by one percent.

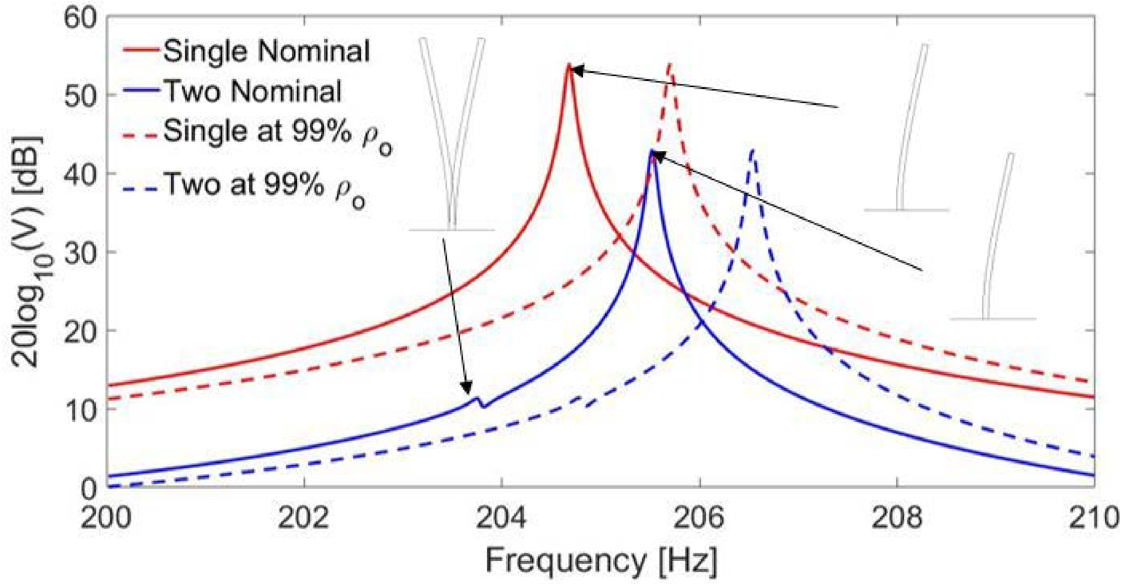

Figure 1: Single versus two cantilever frequency response.

From the graph, the mode shapes of the two cantilever system includes a mode shape where the two parts are out of phase from each other in addition to an in phase shape. A problem that can be seen in validating parts is that if a part is defective in terms of stiffness, the resulting FRF of a single cantilever is approximately the same in terms of frequency as the nominal two cantilever system. Consequently, validating multiple parts becomes troublesome since it is almost impossible to distinguish between a two nominal cantilevers and a single defective cantilever.

A basic way to address this issue is to print each part separately and run the modal test; however, time becomes a major problem since it will obviously increase the testing time. Another common way to approach this problem is to ensure that the parts that are printed on the same build plate have natural frequencies that are far away from each other. The problem with this approach is that it eliminates the possibility of "fingerprinting" or comparing parts against nominal parts as a means of removing bad parts from a batch.

This study serves the purpose of identifying the underlying reasoning behind the coupling effect and investigates ways to improve upon current modal analysis techniques as a means to test AM parts. Simulation tests were designed and analyzed to determine the relationship between the coupling-response as a function of the underlying frequency of the build plate first mode as well as the deformation change of the build plate as a function of its material properties.

2. SIMULATION SET-UP AND RESULTS

To explore the coupling effect, the first mode of the build plate was found using ANSYS and can be seen in Figure 2. The geometry of the build plate used was 250 mm × 250 mm × 12.7 mm and modeled as 1010 steel. The first mode shows clear node and anti-node lines which will be utilized in tests that will be explained later in this report with the theory that the coupling response between cantilevers is dependent on their location on the build plate itself.

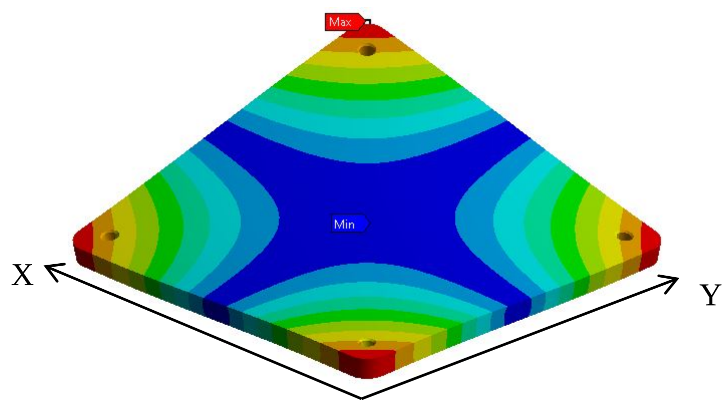

Figure 2: Build plate first mode from ANSYS simulation.

The first natural frequency of the build plate itself was 671.66 Hz. The cantilever geometry was designed to have the first natural frequency of the cantilever resonate at the same frequency as the build plate. The geometry of the cantilevers was 0.375” x 0.15” x 2.61”. The properties of the cantilevers were set to be that of as-printed 304L stainless steel, with a young’s modulus of 1.8×10^{11} Pa, a density of 7.85 g/cm^3, and a Poisson’s ratio of 0.24. The two cantilevers were centered about the Y axis and were positioned at 1/3 and 2/3 along the X axis.

The height of the cantilevers was varied from 95% to 102.5% of the nominal length. The first three eigenfrequencies were recorded which represented the two coupled mode shapes as well as the build plate first mode. Figure 4 shows the eigenfrequencies of the first three mode shapes as a function of the length ratio of the current height to the nominal height.

The first eigenfrequency was the build plate and the next two were the in phase and out of phase modes of the two cantilevers. This behavior remained true until the heights of the cantilevers reached 98.5% of the nominal length; the eigenfrequencies started transitioning and the coupled responses between the cantilevers reached its maximum. When the cantilevers were at the nominal length, the order of modes was now the coupled response between the two cantilevers followed by the build plate mode. Figure 3 shows a surface plot of the eigenfrequency response from the cantilevers as well as the eigenfrequencies imposed on top of the surface plot. As expected, the frequency response of the system had the same shape as the eigenfrequency plot.

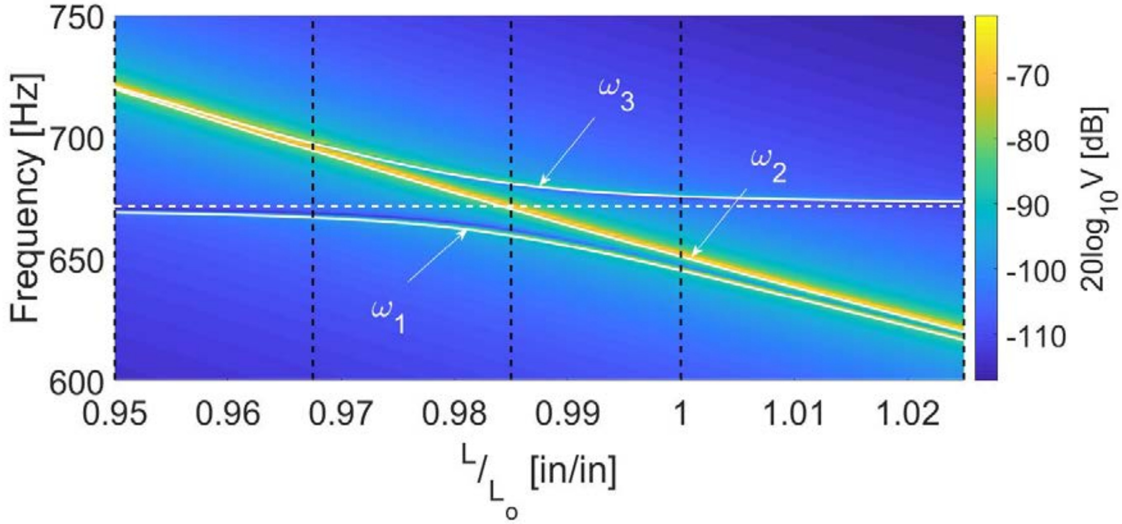

Figure 3: Surface plot showing the velocity frequency response with eigenfrequency black lines imposed above surface plot.

To see how the response of the structure changes as the cantilevers approached the build plate's resonant frequency, five FRFs were recorded at critical ratios: 0.95, 0.9675, 0.985, 1 and 1.025 L_o, seen as the vertical black lines in the surface plot. Figure 4 through Figure 8 show the respective FRFs of each of the five length ratios.

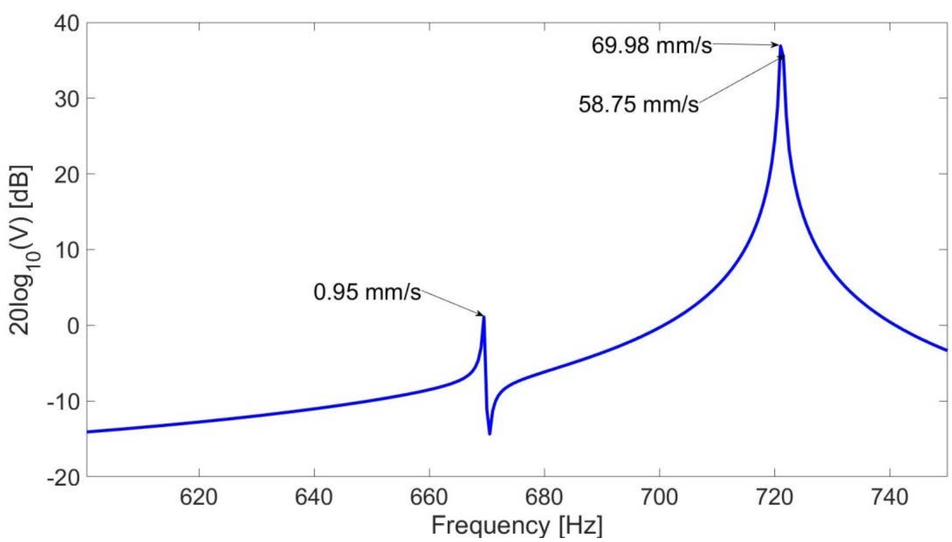

Figure 4: L/Lo = 0.95 Frequency Response

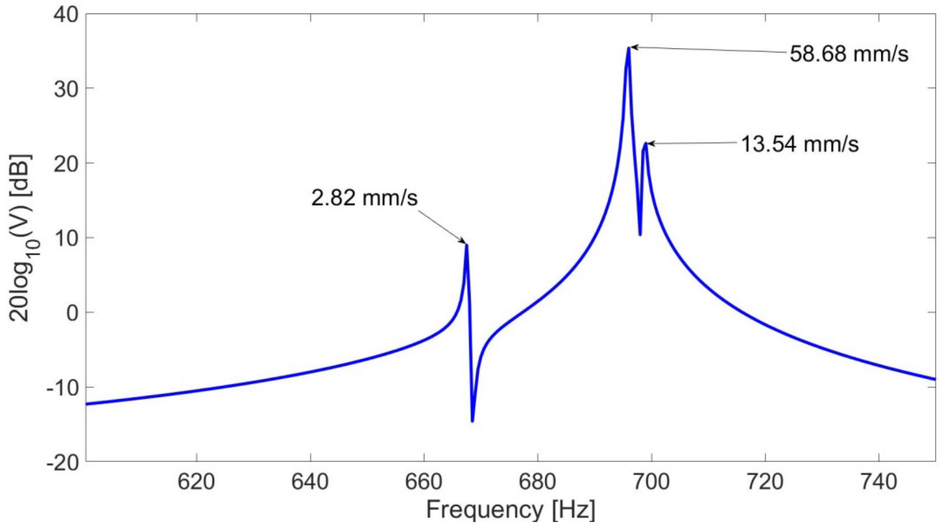

Figure 5: L/Lo = 0.9675 Frequency Response

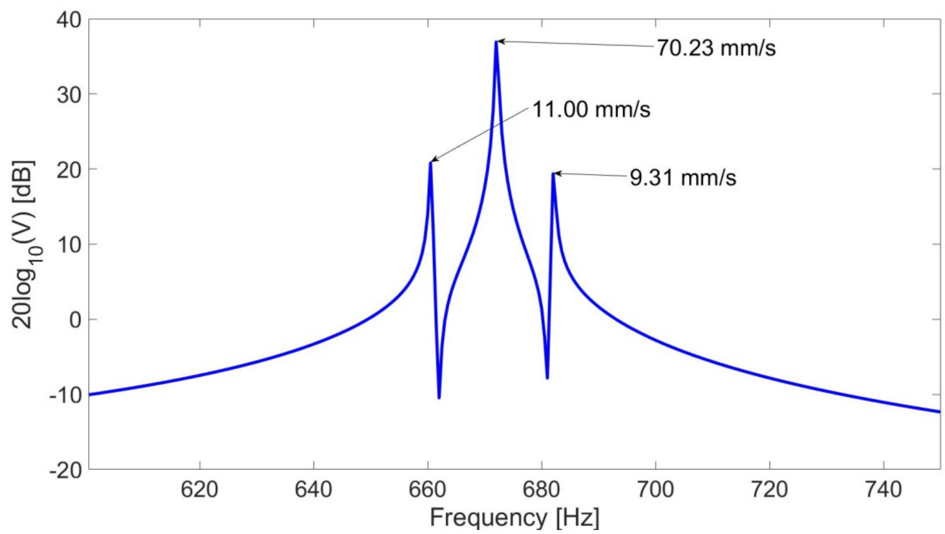

Figure 6: L/Lo = 0.985 Frequency Response

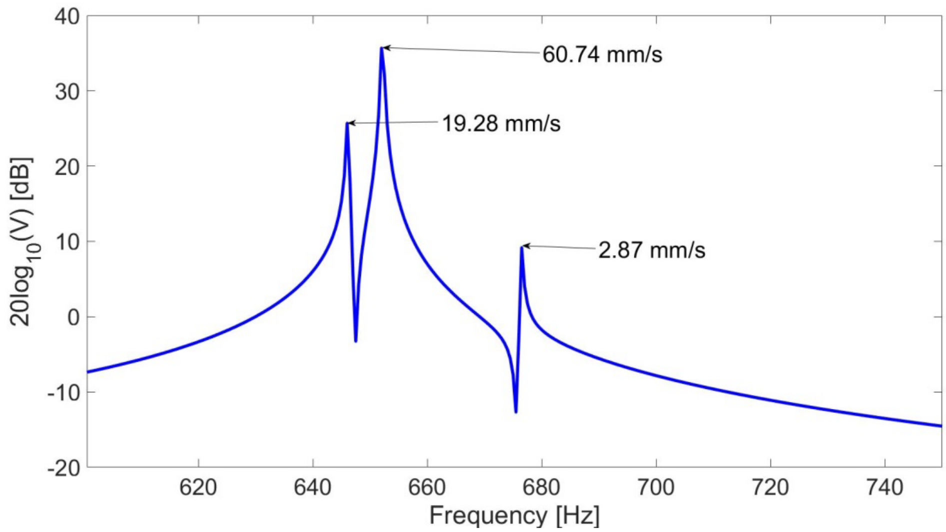

Figure 7: L/Lo = 1 Frequency Response

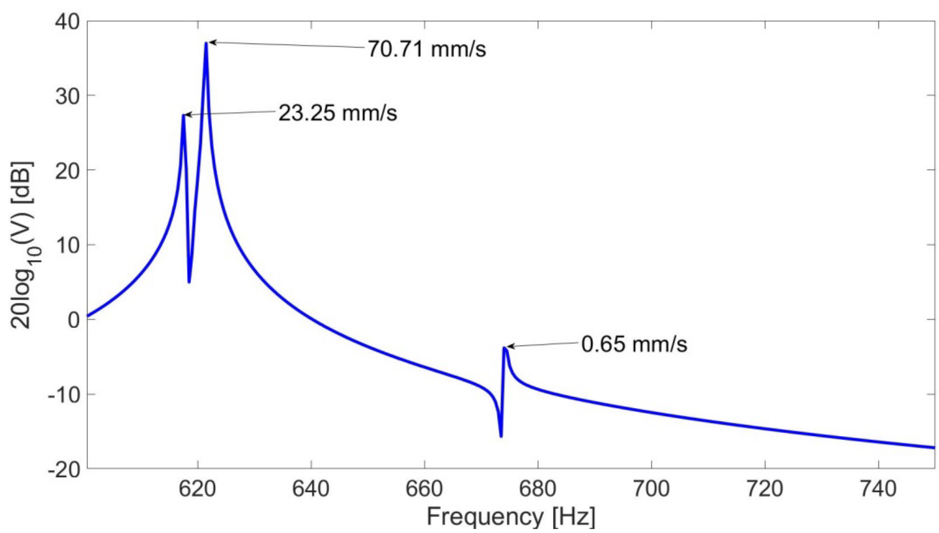

Figure 8: L/Lo = 1.025 Frequency Response

Looking at the first graph, the two modes of the cantilevers are approximately 130 Hz above the build plate, resulting in little interaction between the modes. As the length of the cantilevers continued to increase, the build plate frequency shifted and interacted the most at 98.5% the nominal length, seen in how the magnitudes in the first and third mode being equal. Similarly, as the length continued past that of the nominal length, the build plate frequency shifted above that of the cantilevers.

To determine the relationship between the properties of the build plate and the respective coupling between the cantilevers and the build plate, the properties of the build plate were varied for the next series of tests. Knowing that the resonant frequency is proportional to the square root of the ratio of young's modulus to the density, Equation 1, three configurations of cantilevers were used, seen in Figure 10, and the resulting eigenfrequencies of the structure were recorded.

$$f \propto \sqrt{\frac{E}{\rho}} \tag{1}$$

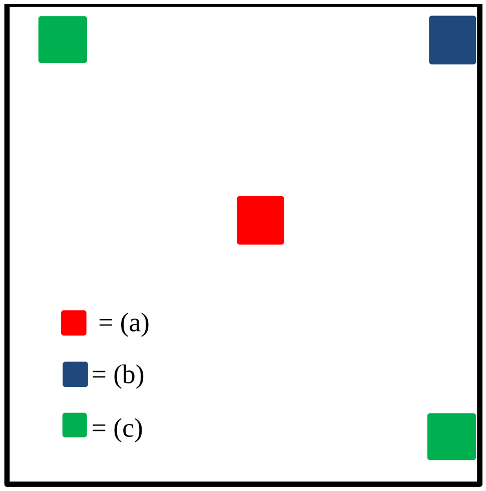

Figure 9: Cantilever Configurations.

These three configurations encompass the highest and lowest locations of deformation in the build plate: the corners and middle, respectively. The motivation for this is that the coupling should be highest when the difference of deformation is highest. Referring to Equation 1, the two main tests that were conducted were keeping the ratio of stiffness to density to be the same but varying their magnitudes by the same amount, and varying the stiffness while keeping density to be nominal. For each test the difference between configurations (b) and (c) against (a) were recorded as a function of the build plate stiffness as well as the deformation of the build plate.

The first test involved varying the stiffness to density ratio from 0.1 to 100 times the nominal ratio. With this test the first modal frequency of the build plate should theoretically stay the same whereas the cantilever frequencies should change due to the change in deformation of the build plate. Figures 10 and 11 show the difference between the configurations when the stiffness to density ratio was constant.

In addition to plotting the eigenfrequency difference, a theoretical difference of density was plotted as well considering studies have already down that a difference in engineering properties because of processing parameters also yields a difference in eigenfrequencies. [4]

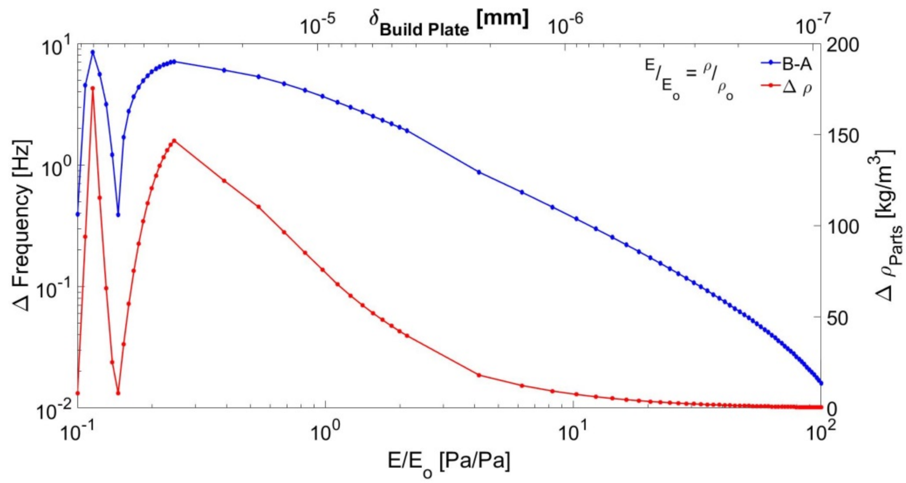

Figure 9: Eigenfrequency difference between configurations (b) and (a) along with theoretical density difference as function of stiffness ratio.

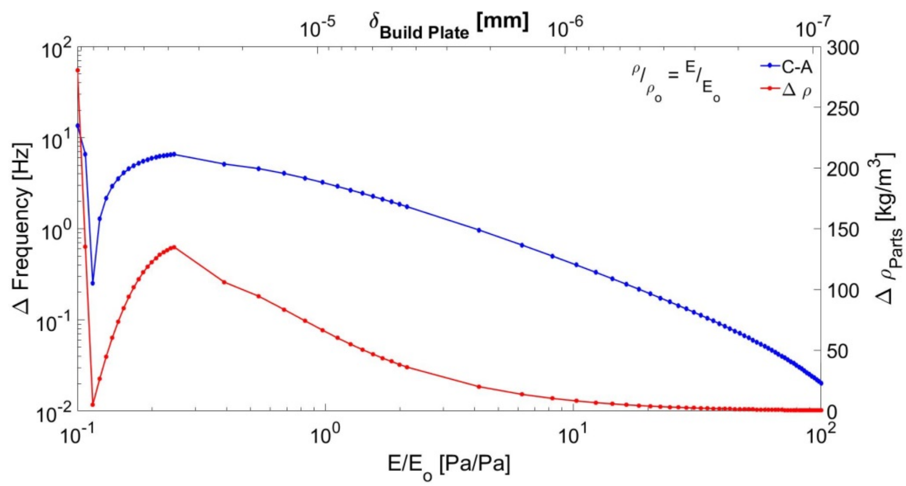

Figure 10: Eigenfrequency difference between configurations (c) and (a) along with theoretical density difference as function of stiffness ratio.

From the graphs, as the build plate's stiffness and density both increased, the difference between the configurations converged towards zero. This is due to both the build plate frequency shifting above that of the cantilevers as well as the deformation of the build plate decreasing as the stiffness of the plate increased.

The next test involved varying the stiffness from 0.5 to 100 times the nominal stiffness but having the density remain constant at the nominal value. Figures 12 and 13 show the eigenfrequency difference as well as the theoretical density difference.

By varying only the stiffness, the build plate frequency varied below and above the cantilever frequencies. This creates two significant differences from the first test: the build plate and cantilevers couple together as well as the mode shape of the build plate being affected as the stiffness increases. The change in the mode shape is the reasoning behind why even though the build plate frequency was increased above that of the cantilevers, the difference between the configurations does not approach zero as the stiffness continuously increases.

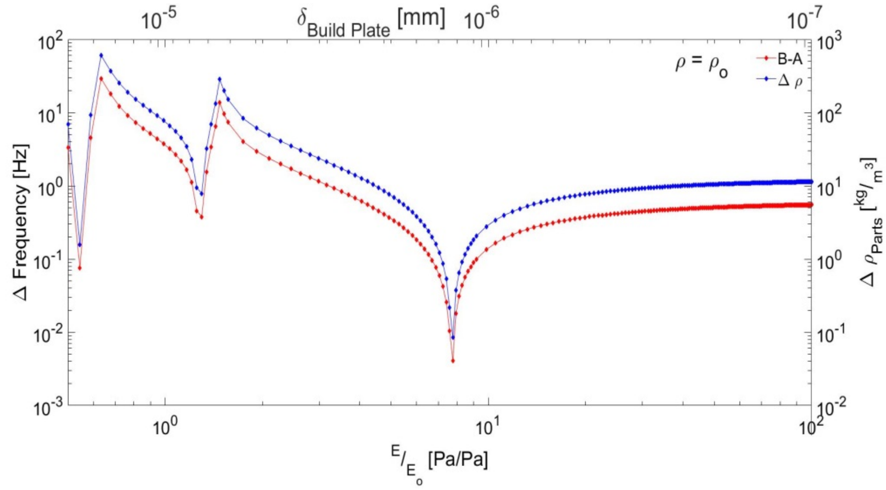

Figure 11: Eigenfrequency difference between configurations (b) and (a) along with theoretical density difference as function of stiffness ratio.

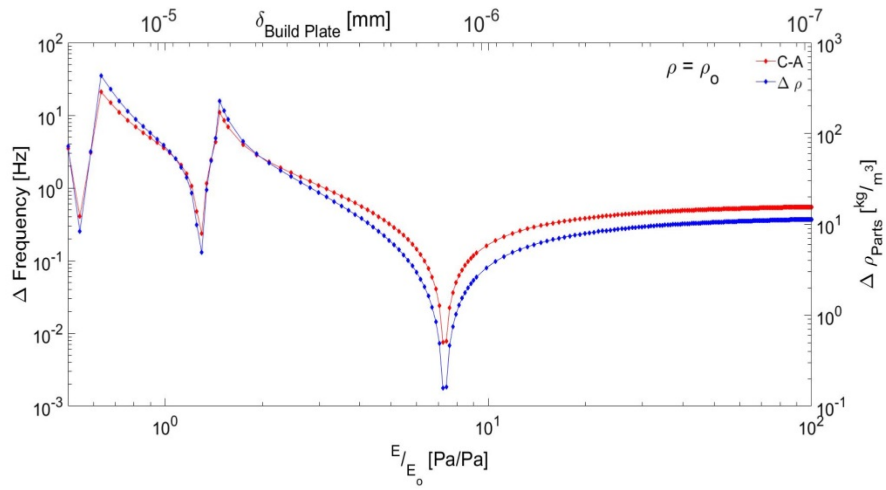

Figure 12: Eigenfrequency difference between configurations (c) and (a) along with theoretical density difference as function stiffness ratio.

The second test results are heavily dependent on the ratio of the stiffness. As stated earlier, the mode shape of the structure as the stiffness increases changes to the point to where the difference between the frequencies crosses effectively zero and then converges towards a constant value as the stiffness continues to increase. From this, the ability to differentiate between two cantilevers and a single cantilever is difficult if the build plate is stiffened without adding appreciable mass.

The results from the third test do not show similar behavior as the first test: the coupling response did not converge toward 0 as the build plate frequency became farther and farther away from that of the cantilevers. In addition, the only points at which the difference in eigenfrequencies was small was due to the mode shape change which is unmerited due to the transition point being at the discretion of the processing the simulation results since there is no clear ratio that signifies when the mode shape changes. Some reasons as to why the build plate frequency trend does not remain true is to the fact that the build plate's mass approaches that of the cantilevers when its frequency increases; this causes the cantilevers and build plate to not be independent of each other in terms of mass. Because of this, the influence of the cantilevers shifts the frequency of the build plate even more; smearing the eigenfrequency results.

With the three tests in mind, a potential solution to the coupling effect between parts can be minimized by increasing the build plate frequency above that of the cantilevers by increasing both the stiffness and density. An obvious way to achieve this solution is to simply make the build plate thicker. To test the effectiveness of increasing the build plate thickness, the eigenfrequencies of configurations (a) and (c) were recorded and plotted as a function of the additional build plate thickness. Figure 14 shows the resulting eigenfrequencies of both configurations.

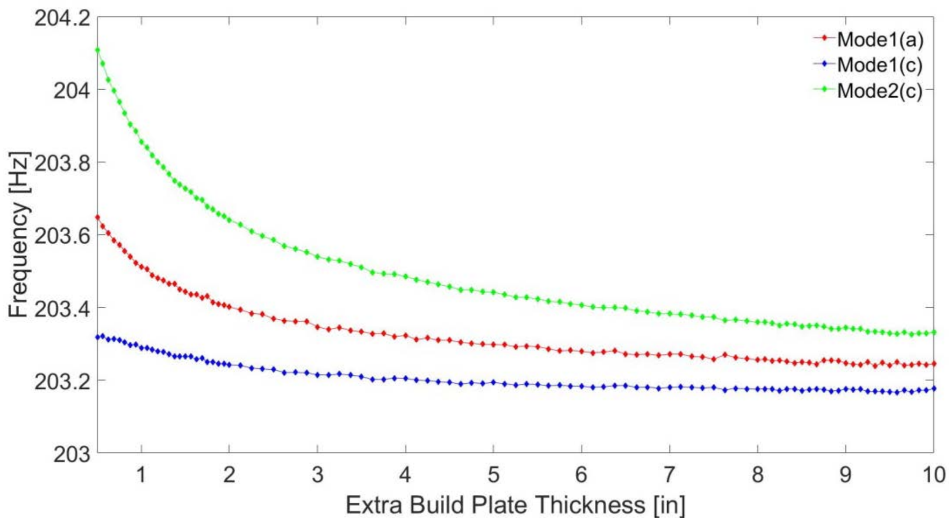

Figure 13: Eigenfrequencies as function of build plate thickness.

The difference between the first and second eigenfrequencies of configuration (c) against configuration (a) was inversely proportional to the square root of the thickness of the build plate. With this in mind, tolerances of 0.1% and 0.05% between frequencies were chosen to show the behavior of the configurations as the thickness of the build plate changed; the resulting thicknesses that yielded these success criterions were 2.75" and 7.625", respectively. Figure 15 shows the FRFs of the configurations at nominal, 2.75", and 7.625" additional thickness.

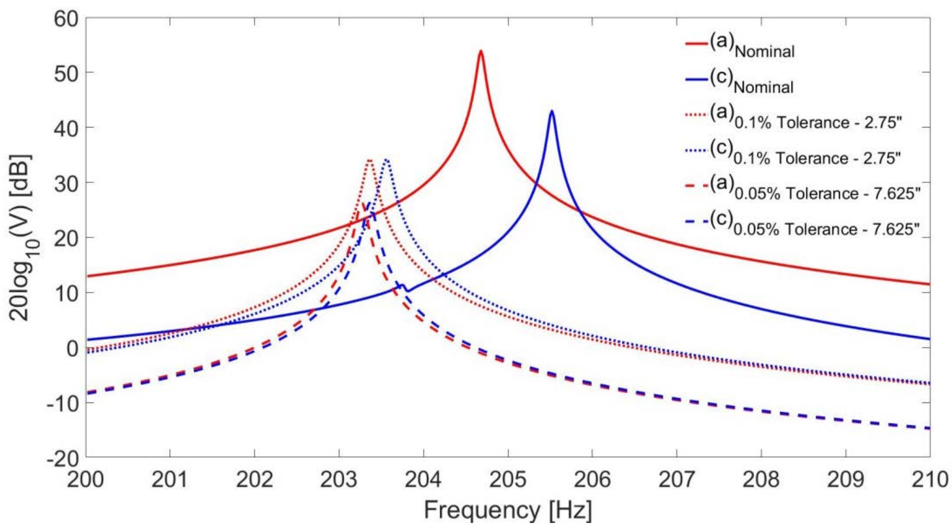

Figure 14: FRFs of configurations (a) and (c) as thickness of build plate changed.

There are two distinct trends that occur in Figure 15. The first being that as the build plate thickness increased, the out of phase amplitude became insignificant to the point of not being seen in the FRF. The second trend being that the difference between configurations progressed from 0.84 to 0.2 to 0.1 Hz. With this in mind, the difference between the eigenfrequencies can be reduced, making it easier to fingerprint defective from nominal parts.

With the results from increasing the geometry of the build plate itself, it begs the question about the impact of bolting the plate to a heavier object. A plate was created that was 60” × 60” and attached to the bottom of the nominal build plate. The thickness was set to be 1” and the frequency response for both configurations was recorded and can be seen in Figure 15.

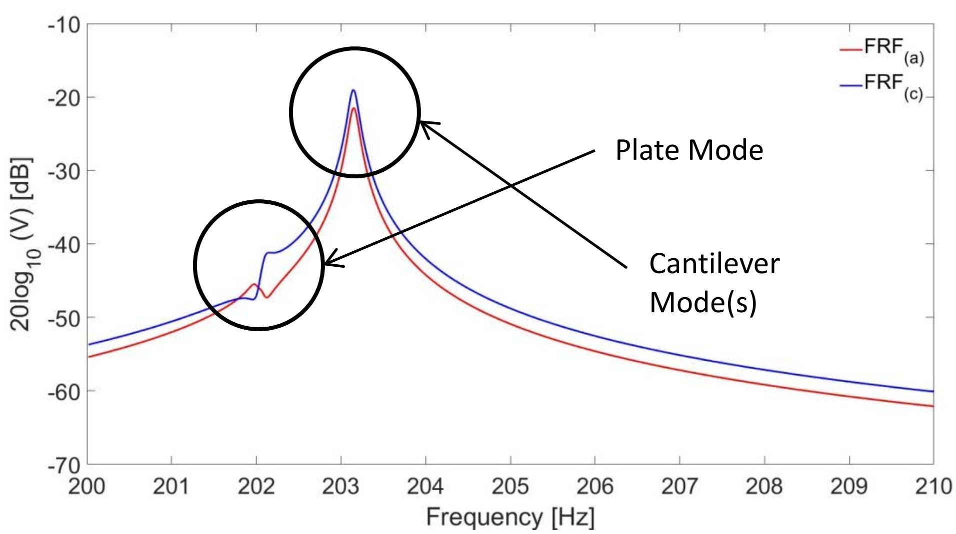

Figure 15: FRF of (a) and (c) with plate attached to bottom of build plate.

As predicted, the coupling effect was reduced to the point to where the FRFs of (a) and (c) were almost on top of each other. The underlying reasoning for this can be seen in the deformation of the build plate itself. Since the build plate was bolted to a heavier mass, the deformation of the build plate was reduced substantially. With bolting the build plate to a heavier plate, the simulation results almost match the same shape as the theoretical boundary condition results. The only difference is that with the 60” by 60” plate, it had a resonant frequency near that of the cantilevers, resulting in the second peak seen in both configurations. The only downside to this behavior is that the driving force required to displace the stiffening plate would require powerful equipment. Further research will be conducted to optimize the topology of the stiffening plate to encompass lattices to minimize the overall weight of the plate, while keeping the stiffness to density ratio relatively constant to maintain the same frequencies of the cantilevers attached to the build plate.

To showcase the scenario of the deformation from a boundary condition perspective, the build plate was modeled with a fixed support on the top and bottom surface. Figure 16 shows the resulting FRFs of (a) and (c). As predicted, with the deformation of the build plate set equal to zero, the difference between the resonant frequencies is also zero.

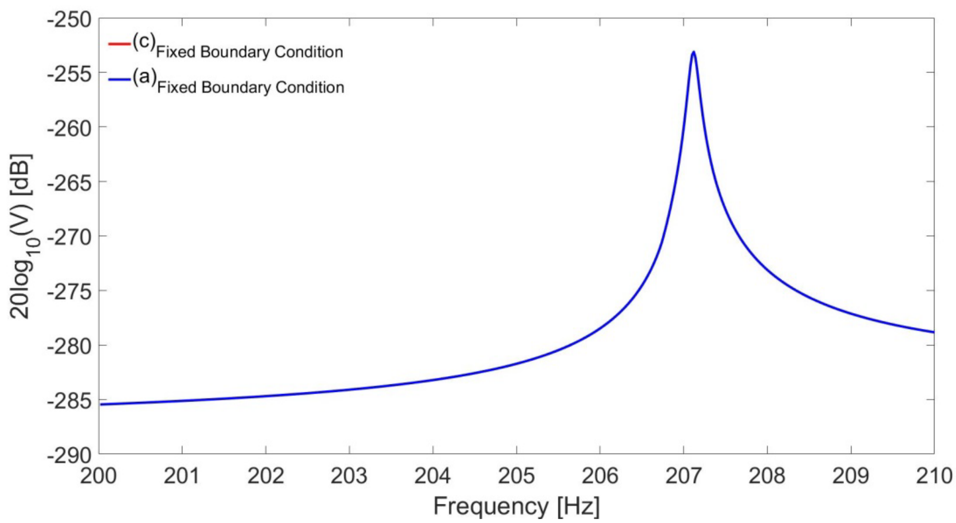

Figure 16: FRF of configurations (c) and (a) with fixed boundary condition.

3. SUMMARY AND CONCLUSIONS

From the findings in this report it is certain that increasing the stiffness of the common build plate that parts are attached to mitigates the coupling effect. To facilitate this behavior, the thickness of the build plate was varied as well as bolting the build plate to a heavier plate. The results from both of these simulations show that the coupling behavior was minimized with bolting the build plate to a heavier plate as opposed to changing the geometry of the build plate itself. As a direct result, validating parts in terms of frequency response is made more accurate by increasing the stiffness of the build plate by meaning of bolting it to another structure.

4. ACKNOWLEDGMENTS

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