Authentication Sensing System Using Resonance Evaluation Spectroscopy (ASSURES)

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ABSTRACT

This paper describes an ongoing instrument development project to distinguish genuine manufactured components from counterfeit components; we call the instrument ASSURES (Authentication Sensing System Using Resonance Evaluation Spectroscopy). The system combines Laser Doppler Vibrometry with acoustical resonance spectroscopy, augmented with finite element analysis. Vibrational properties of components, such as resonant modes, damping, and spectral frequency response to various forcing functions depend strongly upon the mechanical properties of the material, including its size, shape, internal hardness, tensile strength, alloy/composite compositions, flaws, defects, and other internal material properties. Although acoustic resonant spectroscopy has seen limited application, the information rich signals in the vibrational spectra of objects provide a pathway to many new applications. Components with the same shape but made of different materials, different fatigue histories, damage, tampering, or heat treatment, will respond differently to high frequency stimulation. Laser Doppler Vibrometry offers high sensitivity and frequency bandwidth to measure the component's frequency spectrum, and overcomes many issues that limit conventional acoustical resonance spectroscopy, since the sensor laser beam can be aimed anywhere along the part as well as to multiple locations on a part in a non-contact way. ASSURES is especially promising for use in additive manufacturing technology by providing signatures as digital codes that are unique to specific objects and even to specific locations on objects. We believe that such signatures can be employed to address many important issues in the manufacturing industry. These include insuring the part meets the often very rigid specifications of the customer and being able to detect non-visible internal manufacturing defects or non-visible damage that has occurred after manufacturing.

Keywords: additive manufacturing, authentication, defect detection, acoustic resonance spectroscopy, laser Doppler vibrometer

1. INTRODUCTION

The supply chain for manufactured components in industrial and military systems can often be complex, involving many different suppliers and individuals for materials, machining, finishing, and inspecting. At almost any stage, contractors and subcontractors can cut costs by altering manufacturing and inspecting procedures as well as incorporating materials that have not undergone extensive treatment and inspection. In extreme cases counterfeit components find their way into expensive and critical systems. This becomes a serious problem when system failure can result in mission failure, serious delays, great expense, or especially loss of life. Practical, inexpensive inspection methods are needed to authenticate components in such systems. The problem has become even more challenging with the introduction of extremely complex components made possible by additive manufacturing (AM). AM components often include complex surfaces, internal structure, and material properties that are not accessible by normal non-destructive means, making them even more difficult to inspect. AM is often based on creating the part "layer by layer" and defects can and do occur for a variety of reasons in between layers, which if large enough in size or number can significantly decrease the mechanical properties of the part to a point where the part should be rejected for inclusion in the final product.

This paper describes an ongoing instrument development project to distinguish genuine manufactured components from counterfeit components; we call the instrument ASSURES (Authentication Sensing System Using Resonance Evaluation Spectroscopy). ASSURES is based upon the fact that every object has a unique vibrational spectrum that depends upon the mechanical properties of the material, size, shape, internal hardness, tensile strength, alloy/composite compositions, flaws, defects, and other internal material properties. It is virtually impossible for two objects that are not identical to have the same vibrational spectrum. Therefore, the vibrational spectrum can act as a unique signature and enable authentication of a component.

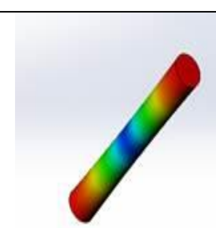
ASSURES combines Laser Doppler Vibrometry (LDV), acoustical resonance spectroscopy [1,2] (ARS), and finite element analysis (FEA) to measure the vibrational spectrum of an object under inspection in a quick, straightforward manner. The non-contact feature of the vibration measurement enables collecting information from any or all points on an object, providing an almost unlimited amount of information describing the component. ARS has become widely researched in recent years to measure the elastic properties of materials and to distinguish substandard products from good ones [3]. It was employ by the pharmaceutical industry to detect counterfeit drugs [4,5] and in the nuclear industry to detect tampering in nuclear containers [6]. Although ARS is an active field, its application in non-destructive inspection (NDI) is still in the early stages and the information rich signals in the vibrational spectra of objects are yet to be fully exploited. ASTM standard E2001-98 [7] provides general recommendations for evaluating the integrity of metallic and nonmetallic components. A "fingerprint" is established for a standard by identifying specific resonant peaks, and peak shifts, splits, and other variations are interpreted as deviations from the standard.

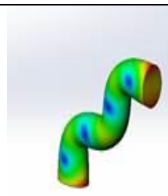
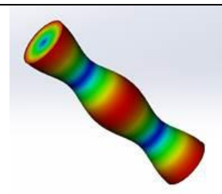
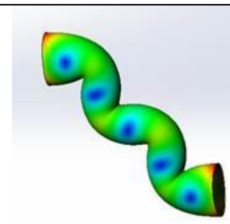
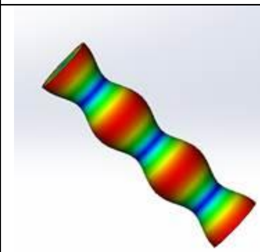
Many practical questions must be answered in this research to make the concept useful and applicable to real problems. How repeatable is a measurement for the same object? How sensitive is ASSURES for component changes, and how does this compare with changes caused by unacceptable variations due to tampering, counterfeiting, and defects? How much does an acoustic spectrum change for normal, acceptable component to component variations? Can the method be simplified enough to make it practical for counterfeit detection? What is the simplest, most repeatable way to efficiently put acoustical energy into a component, so that excitation does not change the results?

2. COMPUTER MODELING OF SAMPLE PARTS

Our strategy was to begin with the simplest objects, like cylinders and cubes for which we could produce supporting finite element analysis that is easy to interpret, compare with, and augment the experiments. We compared results from cylinders of copper, aluminum, and two types of steel. FEA showed that the resonant modes are the same, but, as expected, occurred at significantly different frequencies for the different metals. Experiments confirmed this. Table 1 provides FEA examples of the mode structure and resonant frequencies for eight different resonances for steel.

Table 1. UCI FEA predictions for 5.875" Steel.

Mode #	**7 & 8**	**9**	**10 & 11**	**12**
Origin	Bending, 1st harmonics	Stretching, 1st harmonics	Bending, 2nd harmonics	Axial stretch without Radial expansion
Wavelength/size	0.5	0.5	1	0.5
Frequency (kHz)	4.6	10.4	11.6	16.7
Geometry				

Mode #	13 & 14	15	16 & 17	18
Origin	Bending, 3rd harmonics	Stretching 2nd harmonics	Bending, 4th harmonics	Stretching, 3rd harmonics
Wavelength/size	1.5	1	2	1.5
Frequency (kHz)	20.4	20.7	30.0	31.1
Geometry				

Clearly the FEA models provide a quick way of selecting optimized measurement points, excitation points and frequencies that can identify small anomalies. A key consideration is that an FEA model can be produced quickly when a CAD file of the component is available. This should be the case especially for almost all commercial components.

The FEA modeling can also be used to show the effects of using different materials and of small changes in the dimensions of the part. Table 2 shows the natural frequencies of a 6” x 1” cylinder of aluminum and alloy steel, respectively.

Table 2. Calculated Resonant Frequencies of a 6” x 1” metal cylinder of aluminum and alloy steel.

	Resonant Frequency (Hz)	
Mode Number	**Aluminum 6061**	**Alloy Steel 4140**
7	4,600	4,652
9	10,087	10,374
12	16,552	16,740
13	20,082	20,363

The FEA modeling also showed that for a 6” alloy steel cylinder, reducing the length by 1/8” (~2%) caused the resonant frequencies to reduce by about 3-4%.

3. EXPERIMENTAL MEASUREMENTS

Figure 1 shows the experimental setup. The part to be measured was placed on a small piezoelectric transducer (PZT) that was driven by a function generator with a swept frequency from 3 kHz up to 30 kHz. The induced vibration was measured by a laser vibrometer (LaserPoint LP01-HF from Optical Measurement Systems Corporation) that can measure vibration frequencies up to 100 kHz, with a frequency resolution better than 1 Hz. The measured velocity vs. time was digitized with a data acquisition module, and the vibration spectrum was calculated and displayed on a laptop computer.

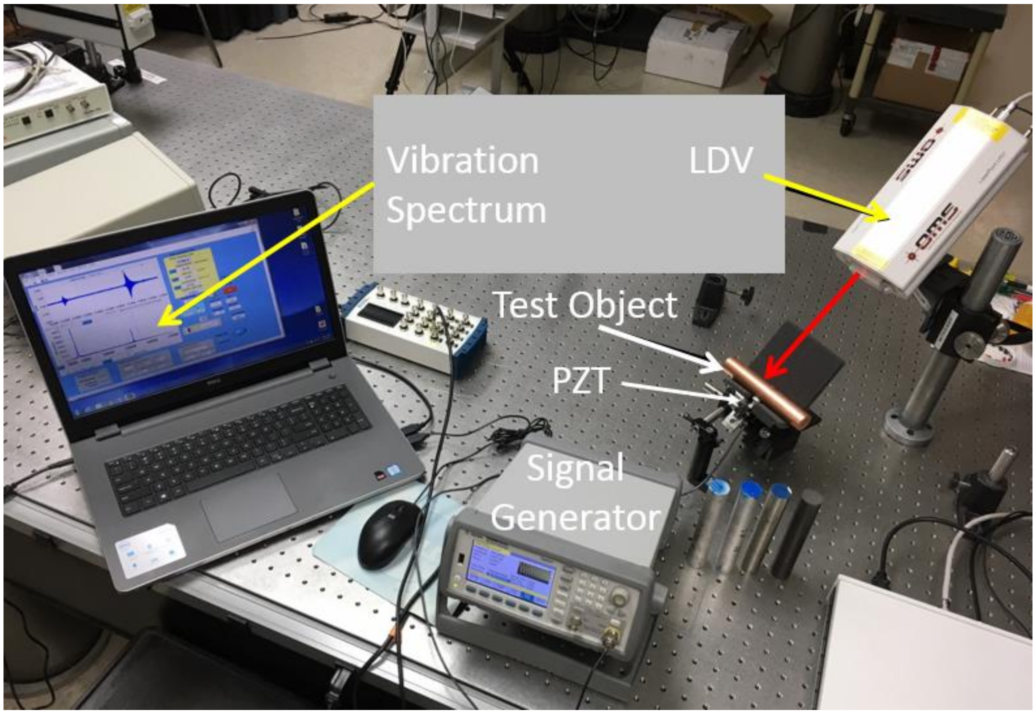


Figure 1. Experimental Setup for measuring the acoustical spectrum of a metal cylinder.

The first experiments used metal cylinders that are 6" long and 1" in diameter, made of aluminum, copper, steel, and stainless steel. As predicted by the FEA modeling, each cylinder produced a frequency spectrum of several discrete lines, and small frequency shifts were observed for each material (see Figure 2).

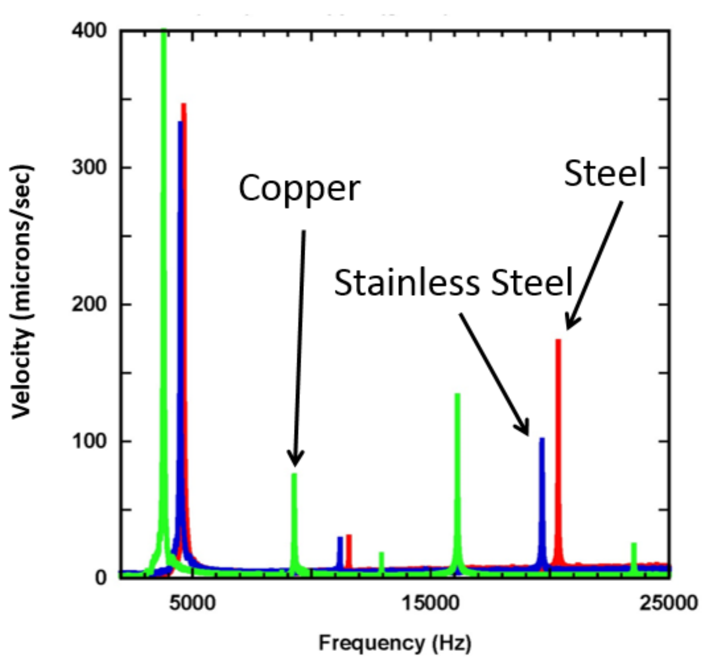


Figure 2. Measured vibration spectra for 6" cylinders of copper (green curve), steel (red), and stainless steel (blue).

Cylinders of Different Lengths

The vibration signature of two aluminum cylinders of slightly different length (150 mm and 155 mm) was also easily distinguishable, as shown in Figure 3.

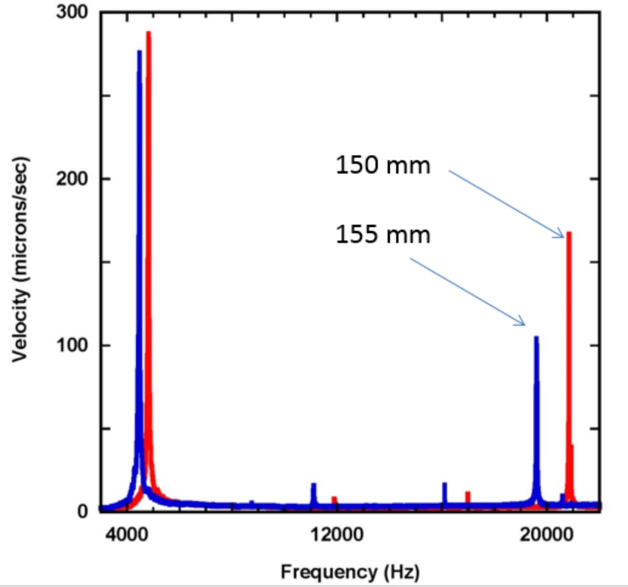


Figure 3. Measured vibration spectrum of cylinders of length 150 mm (red curve) and 155 mm (blue).

Measurement Reproducibility

In order to be a practical tool for component verification, it is necessary for the vibration measurement to be reproducible. The first test was to verify the long term stability of the measurement. With a cylinder left in the test fixture, measurements were taken over a span of several hours. The results shown in Figure 4 show the largest peak shifted about +/- 7 Hz during the day. Note that the FWHM of this spectral peak is about 23 Hz.

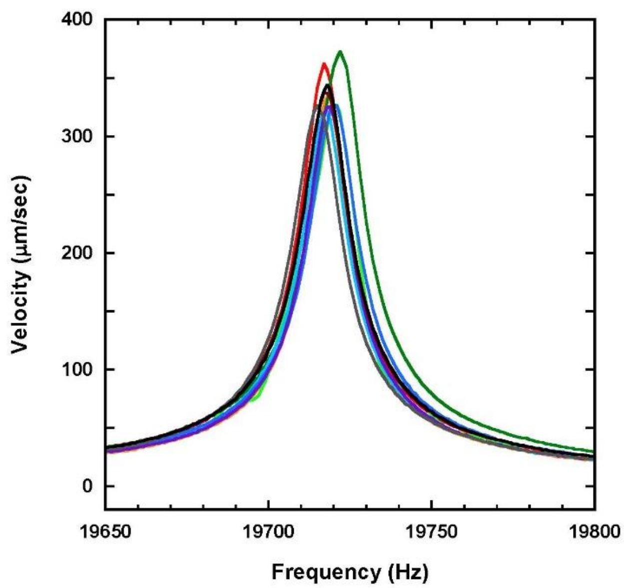


Figure 4. Long term stability of the vibration spectrum. Each curve shows a measurement taken at different times during one day.

The next reproducibility test was to remove and replace the metal cylinder from the test fixture. In each case, the cylinder re-positioned "by eye", so that that exact position may have changed by one or two millimeters. The results, shown in Figure 5, show that the reproducibility was within +/- 4 Hz.

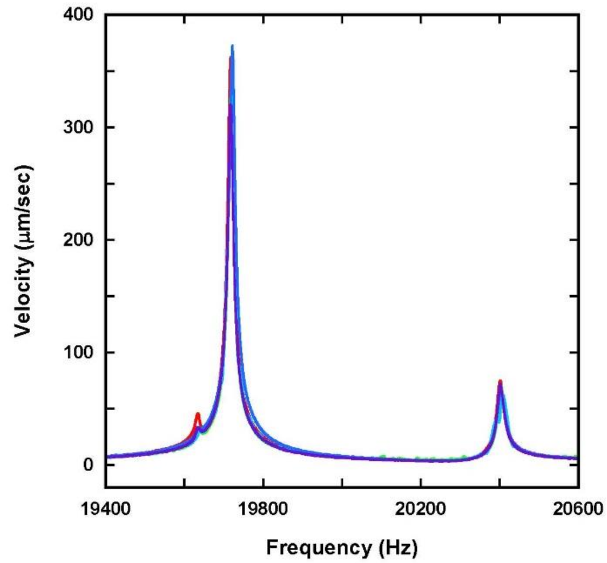
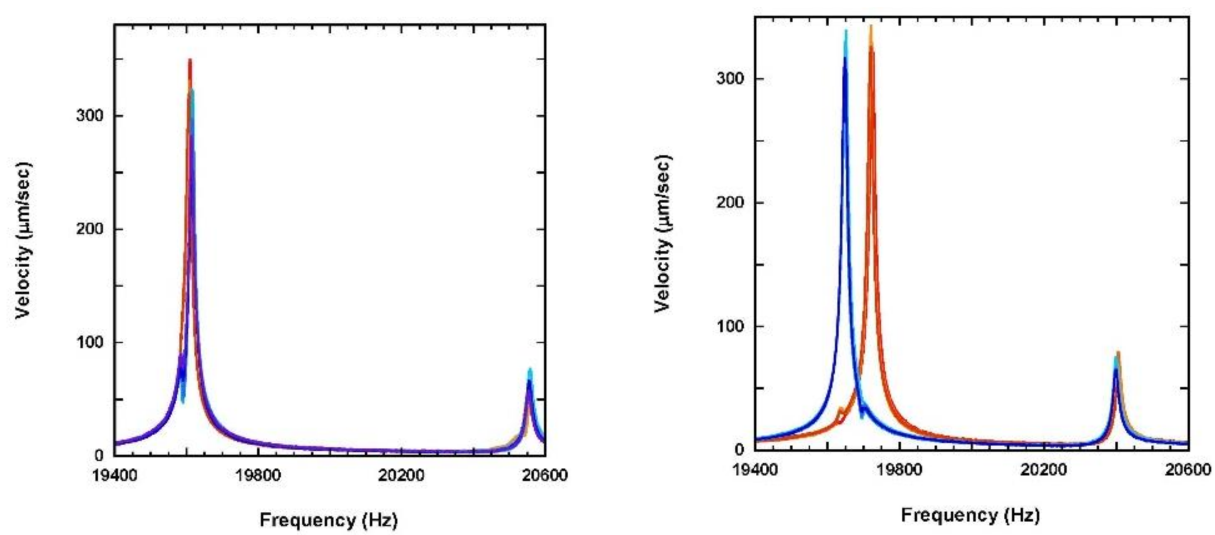


Figure 5. Effect of removing the cylinder and then re-positioning it.

Defect Detection

To study the ability to detect small changes in the cylinder, holes of different diameters were drilled into the cylinders. First, an aluminum cylinder of length 155.2 mm long and diameter 25.45 mm was tested. A hole was drilled with a 2.36 mm drill bit perpendicular to the wall at approximately 39 mm from the edge, at a depth of about 5 mm. Measurements were made on the drilled cylinder in two orientations – one with the PZT excitation parallel to the alignment of the drilled hole, and one with the cylinder rotated so that the PZT excitation was perpendicular to the drilled hole. (Figure 6).



(a) (b)

Figure 6. Comparing the spectrum of (a) unmodified with (b) modified cylinder. The red curve shows the spectrum when the excitation is parallel to the drilled hole, while the blue curve is when the excitation is perpendicular to the hole.

Vibrational spectra of a T-slotted aluminum extrusion

Moving on to more complex components, we selected an aluminum extrusion for testing (Figure 7). The T-slot is a 45 mm (width) aluminum extrusion, with a mean length of 117.2 mm. It weighs 182.8 g, and additionally it has three ø=7.24 mm holes, all drilled in one direction.

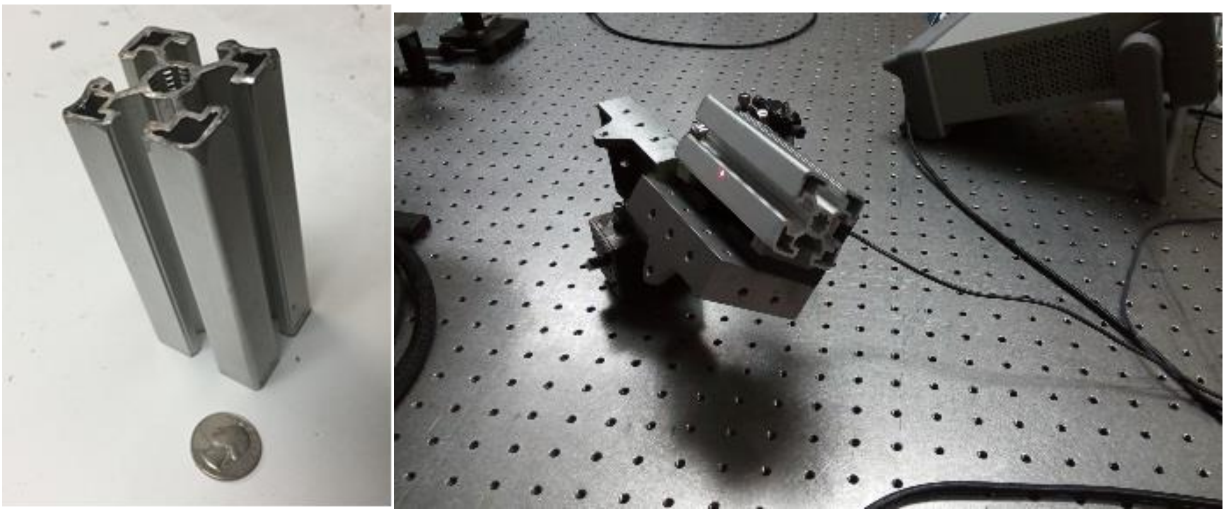


Figure 7. Aluminum Extrusion as a more complex component.

The spectra were measured using the setup shown in Figure 1. As expected, this part shows a much richer and complex spectrum than the metal cylinders. Figure 8 presents two (red and blue) separately measured spectra for the whole 3-30 kHz region (left) and an expanded view for 8-11 kHz (right):

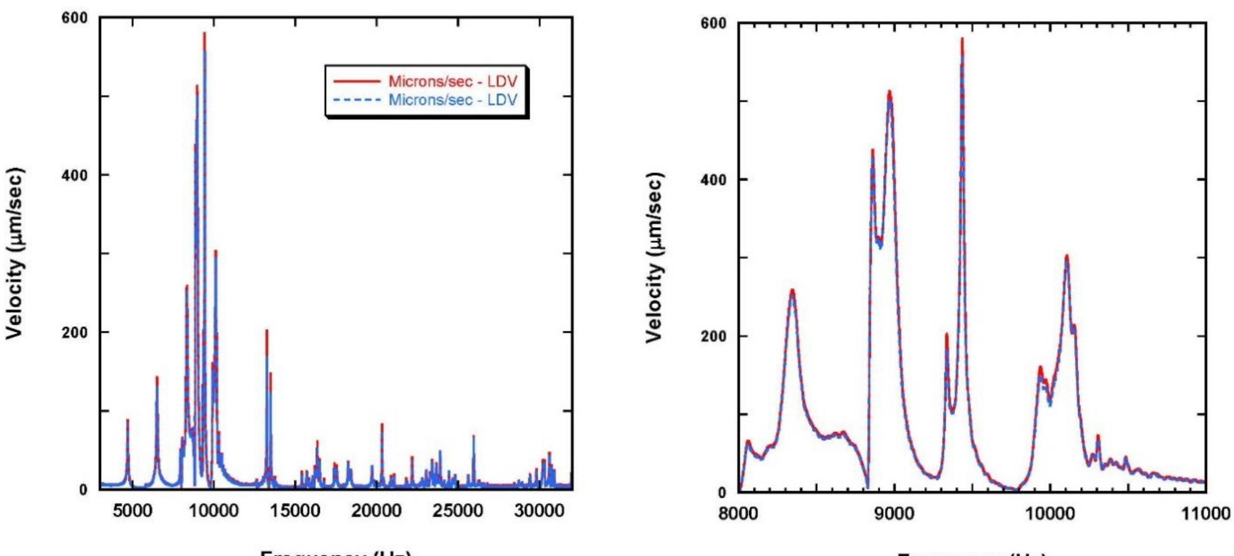


Figure 8. Vibrational Spectrum of a complex aluminum extrusion.

To introduce a small change in the component, we used a screw (1/4-20, 1.5" long) in the middle hole (there are three holes) with various levels of tightening and different plastic washers to vary "coupling". Figure 9 shows some preliminary results, which illustrate that the resonance spectra are very sensitive to these variations.

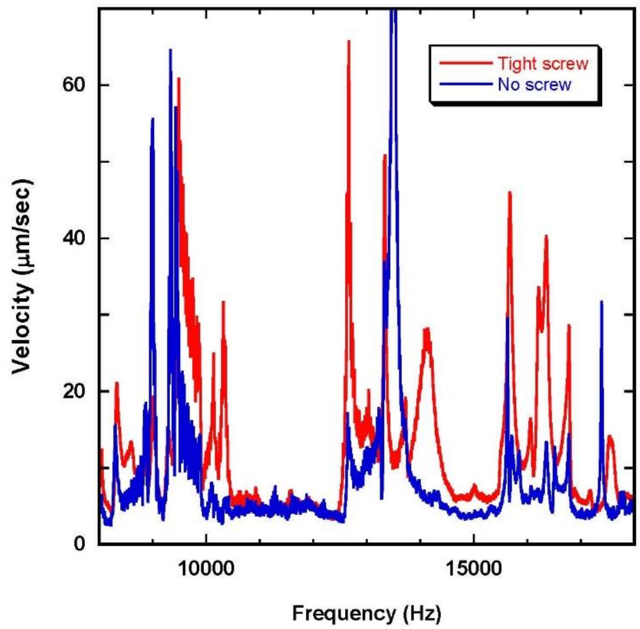


Figure 9. Acoustical spectrum for a T-Slotted extrusion with (red) and without a screw (blue) in the component.

Figure 10 provides another example of how the vibration spectrum changes with small changes to the part. This graph shows the spectrum for three conditions – no screw, a tight screw, and a screw with plastic washers.

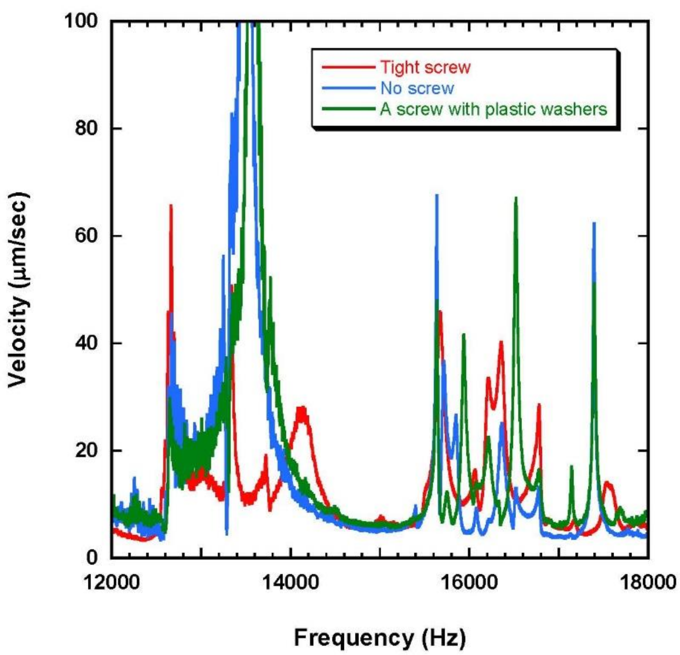


Figure 10. Acoustical spectrum of the extruded component with different changes.

4. CONCLUSIONS

Our experiments and computations so far have allowed us to make some important conclusions. ASSURES can produce reproducible vibrational spectra for components to within a few Hertz. This degree of resolution enables detecting very small changes in the structure, weight, and anomalies of metal components. The vibrational spectra of more complex components contain much more information than for simple components like cylinders and this can be used to advantage.

We have demonstrated the potential of ASSURES for detecting small changes in manufactured components. So far we have demonstrated the method on both simple and complex structures including metal cylinders and extrusions. The method was shown to provide a unique vibrational signature that can identify changes in material, stress, and size.

5. FUTURE WORK

In subsequent work we will apply the methods developed in the project to additive manufacturing components and develop signal processing algorithms that will distinguish small differences in authentic and counterfeit components.

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