A Non-Destructive Evaluation System for Additive Manufacturing based on Acoustical Signature Analysis with Laser Doppler Vibrometry

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ABSTRACT

Every object possesses a unique acoustical spectrum/signature that is determined by its dimensions, materials, defects, and history. The signature can be read and analyzed by exciting the part and scanning the surface using Laser Doppler Velocimetry (LDV). Defects, tampering, inferior materials, and spec failures change the signature and can be detected by reading the signature. Finite element analysis (FEA) employed with the computer design and knowledge of material makeup of an object can predict its signature. Additional security is possible by programming a hidden authentication key printed during manufacturing. Such a readable signature offers many opportunities, especially in additive manufacturing. This paper describes the development and potential applications of this photonic tool.

Keywords: Authentication, Certification, Non Destructive Testing, Counterfeit detection, Process monitoring

Introduction

Parts manufactured by additive manufacturing (AM)[1] typically suffer from a combination of defect types that can inhibit the functional performance of a part. Most AM parts inspection methods are destructive, time-consuming, complex, expensive, do not perform in-situ, and are not easily applicable in the field. There is a critical need for a capability to ensure repeatable product quality throughout the industry[2]. Available methods for qualification and certification of AM parts lack essential feedback and process monitoring capability, requiring additional online/off-line quality control techniques to supplement them. New approaches are needed for real-time, in-situ quality assurance of parts manufactured in earth and space environments.

Our previous research has established the feasibility of an authentication procedure based on the concept that every object is a unique vibrational system that can be categorized by its vibrational spectrum. It is virtually impossible for two objects that are not identical to have the same vibrational spectrum, so this spectrum can provide a unique signature and digital code that matches and identifies specific genuine components. This research is developing and testing a non-destructive evaluation method based upon acoustical signatures that can perform in-situ, and post production and is equally applicable to both metallic and non-metallic AM. Vibrational properties of components, such as resonant modes, damping, and vibrational frequency response depend strongly upon the mechanical properties of the material, including its internal hardness, tensile strength, alloy/composite compositions, flaws, defects, and other internal material properties, and they respond differently to various forcing functions. Components with the same shape but made of different materials, different fatigue histories, damage, or heat treatment will respond differently to high frequency stimulation and can be distinguished by detecting changes in vibrational signature.

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We reported the early stages of this research last year[3], which demonstrated the feasibility of combining Laser Doppler vibrometry (LDV) with vibrational resonance spectroscopy to extract sufficient acoustical information from a part to determine when it is acceptable and not. This paper describes subsequent research that tested the concept on real AM components, developed tools to speed up data interpretation and is exploring extension of the concept to in-situ measurement for process control.

The research is testing the concept through experiment and computer simulation. Component samples ranging from acceptable to unacceptable will be produced and fully analyzed with complex inspection and diagnostic tools to verify the mechanical and structural properties, and the associated acoustical signatures will be correlated with various stages of contamination and defects. We will determine how well the acoustical signature of a reference part can be used to certify additional parts arising from subsequent production. We will show how such a system can be interfaced with a printing machine and operated in a space environment.

Acoustic Resonance Spectroscopy has become widely researched in the past twenty years to measure the elastic properties of materials[4], to distinguish substandard products from good ones, to detect counterfeit drugs[5] and to detect tampering in nuclear containers [6-8]. However, no one to date has refined and fully exploited the information rich signals that exist and can be detected in the vibrational spectra of complex objects during and after manufacturing, and no one has attempted to employ this diagnostics in-situ, in additive manufacturing, or in space.

Conceptual System

Figure 1 shows how Laser Acoustic Resonance Spectroscopy (LARS) is employed. The LDV has high sensitivity and frequency bandwidth to measure the component's frequency spectrum, without physical contact and without attenuation issues or restrictions on location that limit existing ARS technology to small components, since the LDV beam can be aimed anywhere onto the part. Since AM components are manufactured layer by layer, there exists an exposed layer at the end of each printing scan that is available for inspection scanning with LARS, so it has potential for use both on and off-line, providing in-process monitoring and feedback as well as *post mortem* analysis with the same system. LARS can provide online layer/trace monitoring enabling rapid identification of defects as they are generated before the run is finished saving time, energy, and materials and possible defects correction by introducing layer compensation algorithms. LARS evaluation could occur after each layer is bonded (enabling corrective actions to be taken right away) but can also be done after a batch of layers and even when the process is completed.

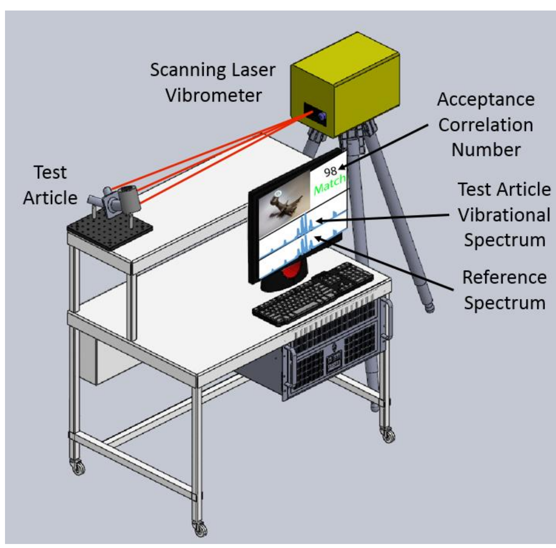

Figure 1. Conceptual design of the LARS system for component inspection.

Figure 2 taken from our previous analytical work, demonstrates the different predicted vibration signatures of a one-inch cube as small slots (either 0.5" x 0.05" or 0.5" x 0.01") are present, representing a type of defect or abnormality that needs to be detected. All these cases can be monitored and mapped in detail with a LARS system, providing a unique signature for each component. We have employed FEA for different materials and more complex shapes showing the presence of detectable differences and signatures that characterize these differences. Defects and anomalies can cause resonant frequencies to broaden, split or add new resonances for certain bands. When only the material properties are changed, all frequencies are shifted with little if any effect on the spectral pattern. Therefore, changes in the material properties as well as defects are detectable and distinguishable with this approach. If this concept proves feasible, it would provide a tool for in-situ process monitoring as well as a relatively simple, quick method to certify finished components.

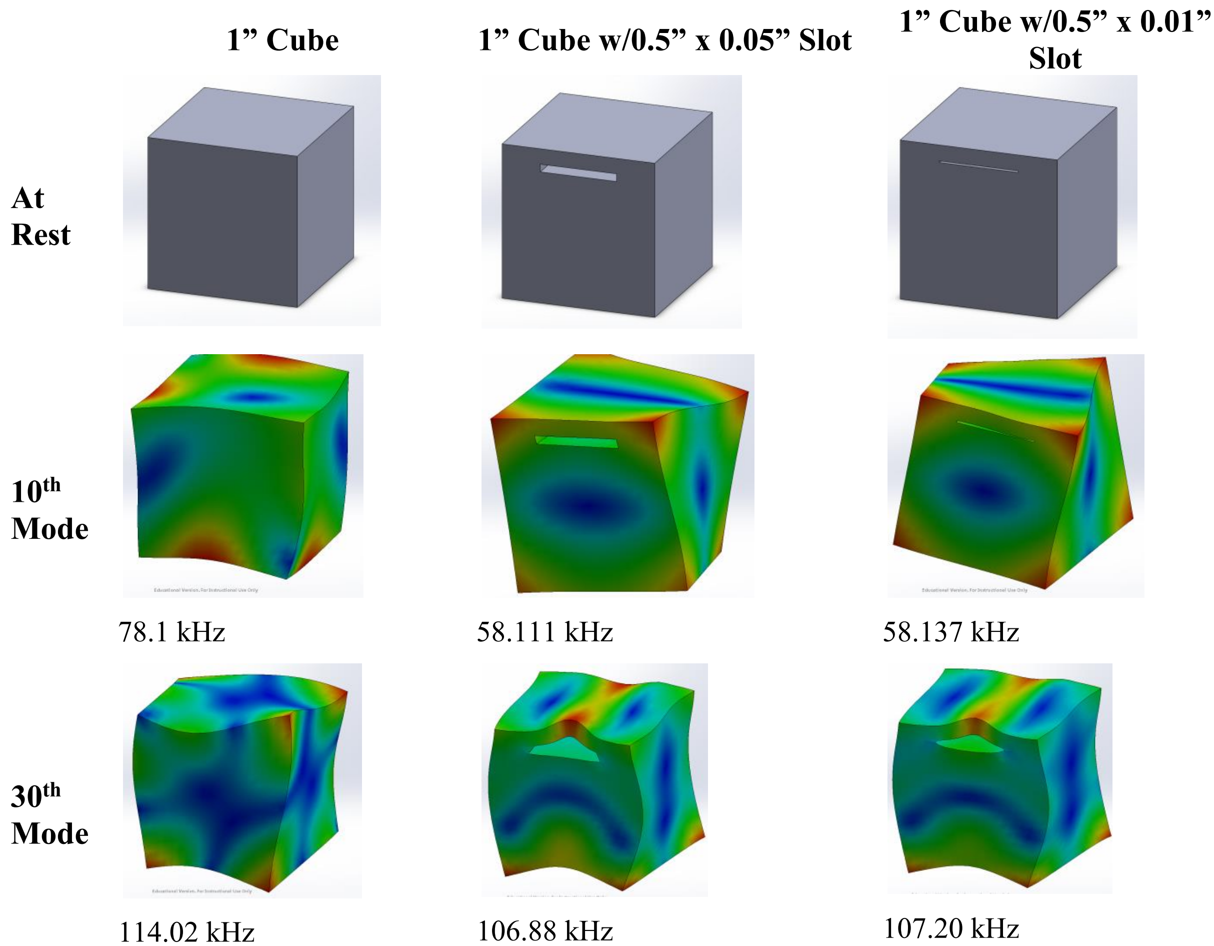

Figure 2. Simulated vibrations of a 1” cube with slots, illustrating the unique vibration signatures.

Laser Doppler Vibrometry

Laser Doppler Vibrometry (LDV) is a non-contact method to measure the vibrational characteristics of an object. LDV works by aiming a laser beam at an object, and combining the light scattered from the object with a reference beam onto a photo-detector. The motion of the object imposes a frequency change (the Doppler Effect) on the scattered light, and this frequency change can be demodulated to extract the velocity vs. time of the moving object. The key benefits of LDV are its extremely high sensitivity (sensing displacements on the order of picometers is possible), and its precise frequency measurement.

Figure 3-5 show an actual setup used to examine various AM materials.

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Figure 3-A preliminary prototype breadboarding

One of the most challenging parts of the design is the component holder, since we do not always know exactly what the shape of the object it must hold will be. Nebulous sources of resolution loss include how the component is placed, oriented, supported, and excited. Ideally, the component should be suspended in space touching nothing, which is largely impossible. So the best approach is to minimize its connections to anything. So far, the best holders we have used incorporate some type of soft mount or foam that isolates it from the mount and alignment pins to enable removing and replacing the part repeatably. Our current sample holder enables acquiring vibrational bands of some 20-25 Hz FWHM with a reproducibility within an overall interval of approx. 7 Hz, and we can detect a “defect” that accounts just for a 0.6 g decrease (from 212.5 to 211.9 g) in the sample’s weight, less than 0.3% with a shot-to-shot jitter within ±3 Hz.

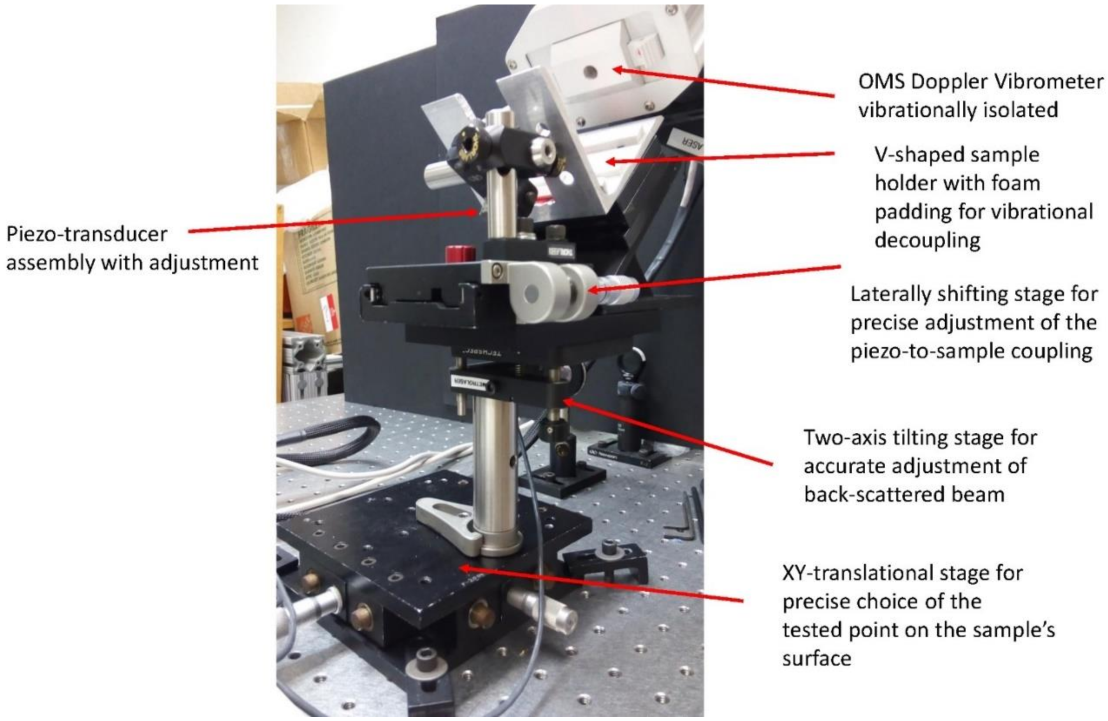


Figure 4-Explanation of various adjustments for LARS Prototype

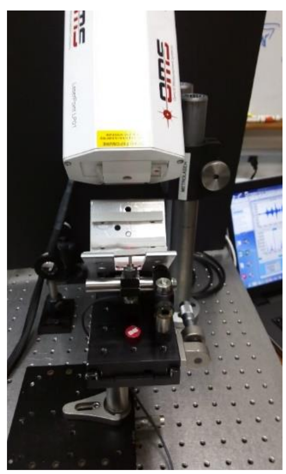


Figure 5-Component mount showing the foam isolating pads and piezo electric exciter

Figure 6 shows a typical AM component under test and **Figure 7** is a sample acoustical signature.

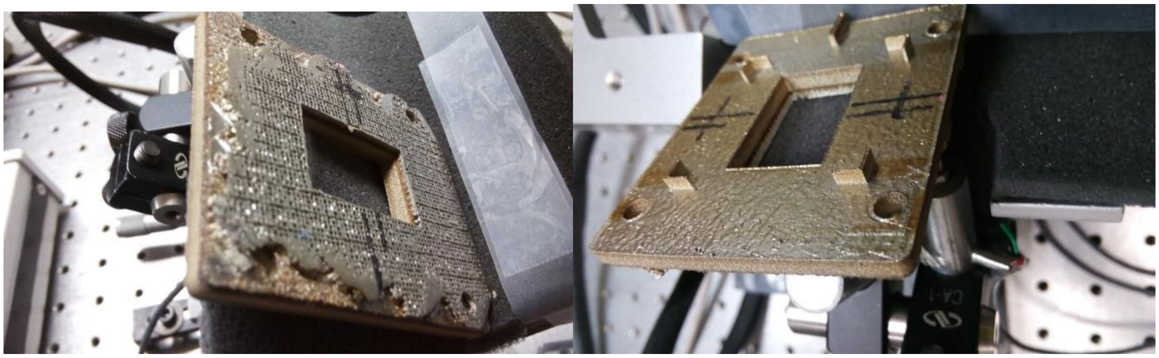


Figure 6-Printed plastic component under examination

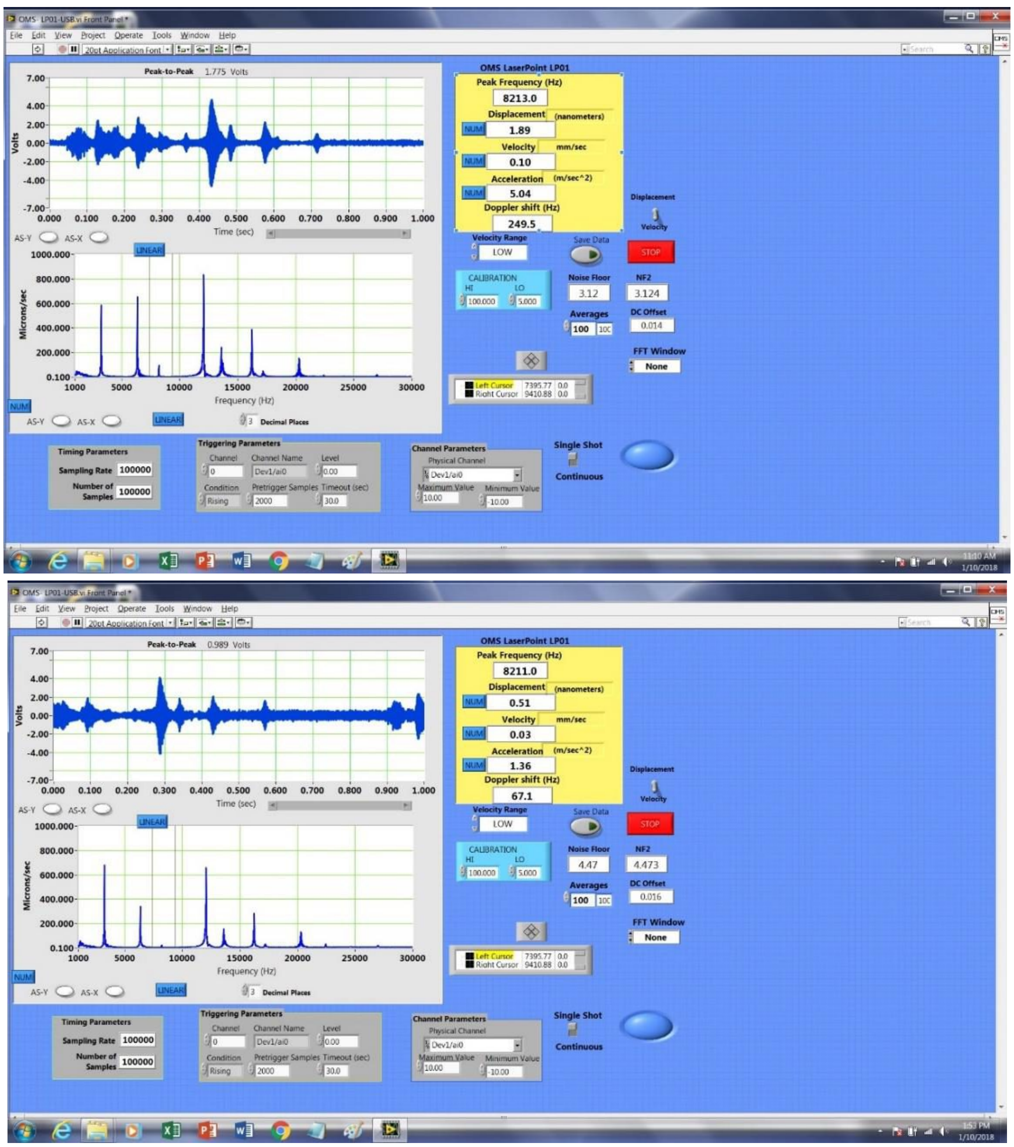


Figure 7-Typical acoustical spectra of a plastic AM part being modified

Figure 8 shows the typical acoustical signature of a complex AM component wherein slight changes were made to the component by enlarging a drilled hole in the component. On the left, the entire spectrum is displayed up to 20 KHz. The figure on the right is an expanded view of the resonance near 17.5 KHz, showing a clear distinction between the components response as the drilled hole is modified.

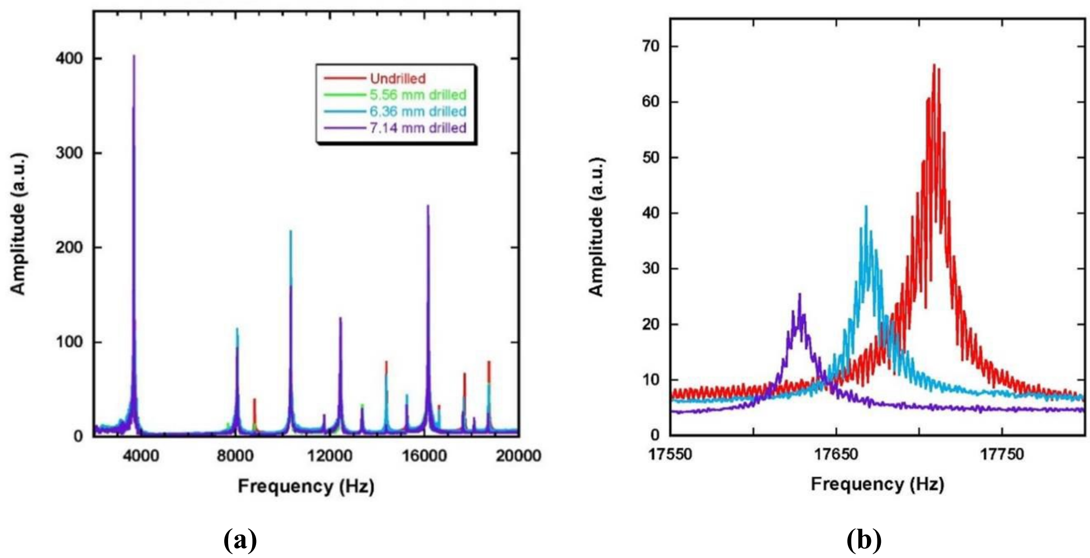


Figure 8. Vibrational spectra of an AM component with incremental increases in a small drilled hole diameter (left, center, and right as the drilled diameter is increased from 5.56 to 6.63 to 7.14 mm). (a) Entire vibrational spectrum; (b) Enlarged view of the peaks near 17.7 kHz.

Although our previous work focused on metallic parts, the FEA methods developed are equally applicable to non-metallics and the metallic results can be roughly scaled to non-metals using $(F/M)^{1/2}$, where F is Young's modulus and M is mass density.

To verify that the proposed concept can be useful in defect detection, it will be necessary to test the system with representative test samples, ideally with samples having different degrees of quality, all the way down to visible damage. We will begin with multiple samples of a non-metallic AM component with varying defect levels and types over a range from acceptable to unacceptable and to determine the detectability of such changes with LARS, which will provide vibrational signatures of AM components both during and after manufacture. We will achieve this by at least two methods, 1) programming defects into the CAD files, and 2) purposely contaminating materials used in manufacturing.

Samples that contain a wide range of controlled defect types and densities are being manufactured and analyzed by the UCI Institute for Design and Manufacturing Innovation (IDMI). The reference test samples will be fully analyzed with complex inspection and diagnostic tools to verify the mechanical and structural properties of the sample and then the LARS system will be used to complete a vibrational spectral database of a part at various stages of contamination purposely introduced during the additive manufacturing process. We will finally determine how well the spectral signature of the part correlates with the changes in the properties of the part and how well the signature certifies additional parts after production. We will determine the feasibility limit of detecting the onset of a defect during manufacturing and simple measurements to detect anomalies occurring during the printing process, and finally to certify/confirm additional similar or "identical" components in large numbers without employing complex and expensive NDI or destructive testing methods.

In-Situ Monitoring

We have extended the research to determine feasibility of integrating LARS into the AM process for NDE for both in-situ and post production. This requires integrating the instrument shown in **Figure 1**, into an additive manufacturing set up, by viewing through a window (**Figure 9)** (or otherwise) and directing the laser beam to the surface being manufactured without interfering with the printing process. The second challenge is to enable acoustical excitation of the part during manufacture without interfering.

Acoustical excitation can be achieved either through the mount for the part or through the air to the part in various stages of manufacturing. In metallic AM machines a laser scans and fuses a metallic powder layer to the emerging part, layer by layer. In non-metallic AM machines, like FDM, a scanning head deposits new material, layer by layer onto the emerging part. After each layer is fused, that surface is available for scanning by the LDV. We are exploring all options for accessing the surface with the LDV, what is optimum, and how it varies with different AM processes

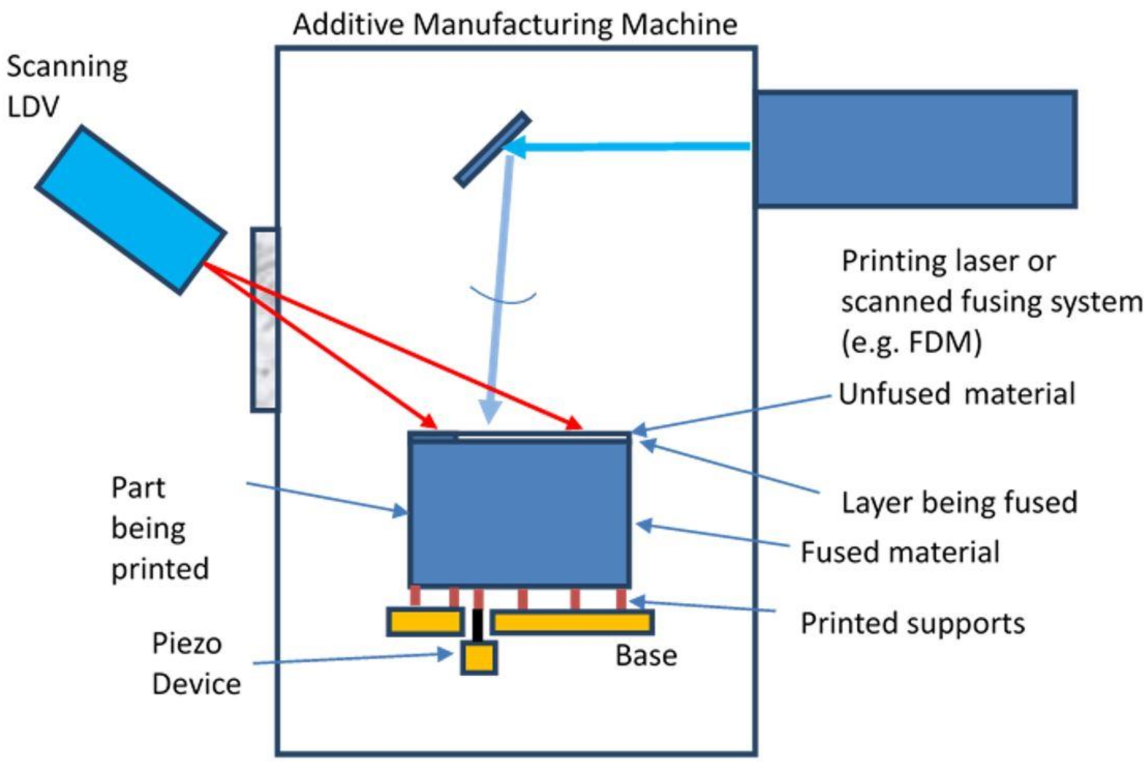


Figure 9. Conceptual Use of LARS in Additive Manufacturing.

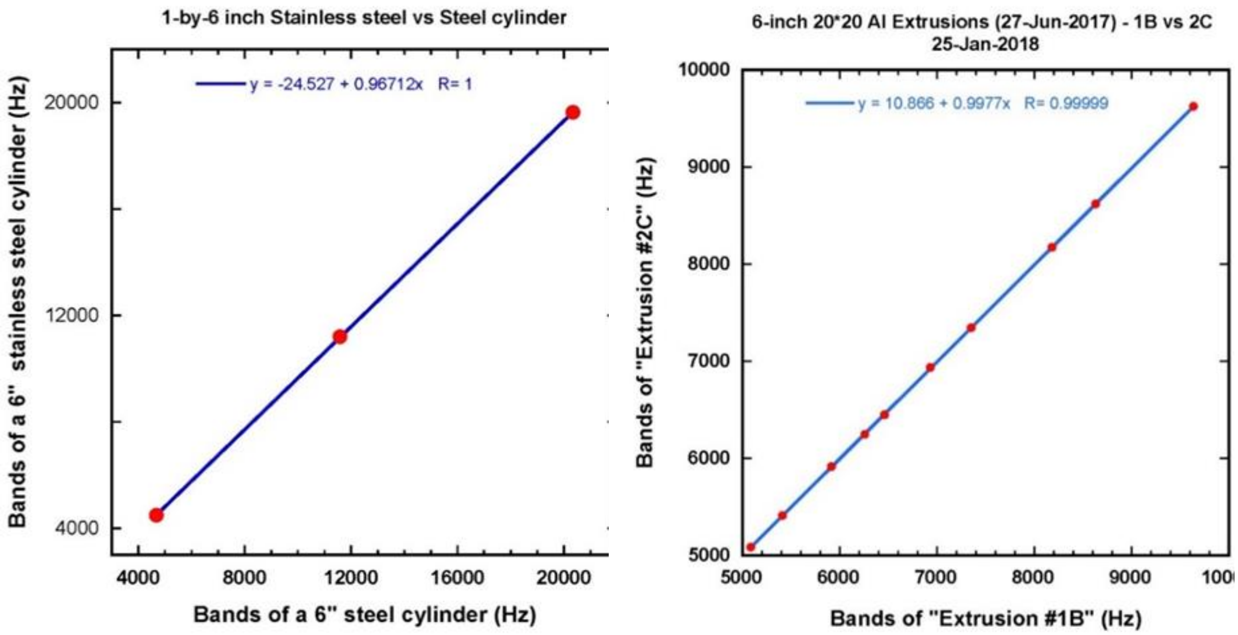
We have employed a variety of excitation methods including sound transmission through the air to the part, piezo-electric transducers that touch the part, sonic hammers, and pulsed lasers. Exciting the part with a speaker designed to focus sound has the benefit of non-contact. The chosen method must transfer realistic and relevant acoustical energy to the part without interfering with the manufacture. The excitation would be applied after a layer is bonded and before the next layer is started and should not interfere with the manufacturing process, although nanometer surface movements are detectable with LDV and are not expected to interfere in any event. Methods for contacting the excitation device to the part must be integrated into the AM machine and the printing process. One possible method is to print an energy transfer channel from the exciting device directly to the part being printed.

Decision Tools

In the course of our experimental studies, we have searched for optimum decision tools to assist an inspector in using the vast amount of information available in acoustical signatures. A few examples are given here. Three types of information contained in acoustic spectra are 1. the resonant frequencies, which are completely defined by the part's geometry and material, 2. the relative amplitudes of the spectral peaks, which are sensitive to both the excitation and testing mode, and 3. frequency broadening, which is influenced by both the fine features of the material, such as the ratio of the elastic (real) to the inelastic (complex) components of the Young's modulus, and the experimental (instrumental) conditions, e.g., vibrational coupling of the part and the part-holder.

Vibrational coupling broadens the frequencies and should be reduced to a minimum. Line broadening caused by an increase in the inelastic (complex) component of the Young modulus may be induced by variations in the AM protocols and, therefore, provides an exciting option. Variations in the shape of the spectrum (relative amplitude ratios) by varying excitation and data collection mode are potentially a very strong differentiating instrument.

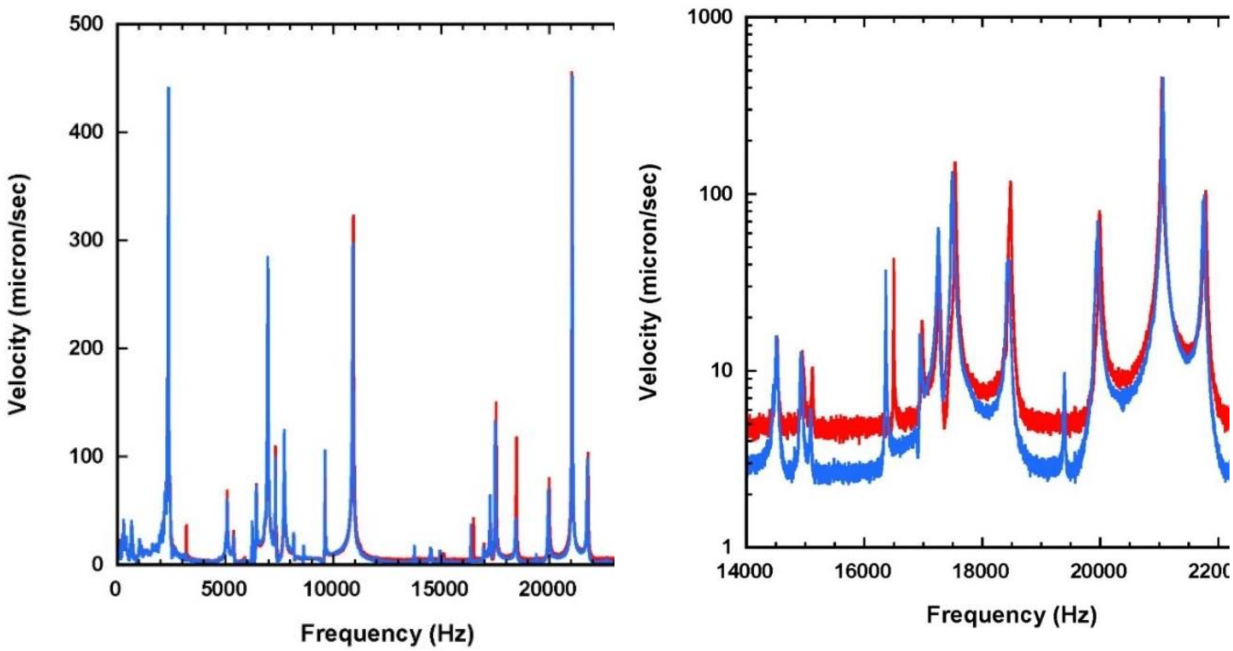
To explore the effects of altered material parameters, we compared geometrically identical parts. **Figure 10** shows a correlation curve for two identical parts with the y-axis being the positions of observable bands measured on one part vs. the correspondent bands (x-axis) measured on the other. The slope in such a correlation is expected to equal unity, if the ratio of E (elastic modulus) to ρ (density) for the two materials is the same, and to differ from unity if the materials differ. The left panel presents the data for two cylinders of identical geometry made of two different materials, while the right panel presents the data for two extrusions of the same material (aluminum) and coming from the same batch (and expected to be of the same geometry, at least within the accuracy of weight and lengths). The inserts in both panels show the results of the linear fit. In both cases, the correlation coefficient (i.e., the measure of quality of the linear approximation) is equal to one, signaling an excellent fit. The slopes in the two panels are different: 0.967 (in the left) vs. 0.998 (in the right). The difference might look small; but it is statistically significant, and the difference from unity, which is the main point of interest, is 3.3% vs. 0.2%, i.e. more than an order of magnitude.



(a) **(b)**

Figure 10. Comparing vibrational resonances of two identical parts of (a) different materials and (b) two identical ones (a more complex geometry, an extrusion, with more measurable bands in the right panel).

When a point-defect affects the positions of some but not all bands, it is easier to detect with a different discrimination procedure, illustrated in **Figure 11** To simulate a point-like defect in a complex-shaped part, an aluminum extrusion was analyzed before (blue) and after (red) a small hole was drilled in it. Clearly the two signatures are different, but how can we transform the spectrum into readily usable *information* to aid the decision-making algorithm?



(a) **(b)**

Figure 11. Effect of a small "defect" on the vibrational spectrum of an extrusion.

We observe three categories of changes: 1) minor variations that fall within the expected statistical inaccuracies, 2) suspiciously large deviations that may indicate an important difference, and 3) variations that are so large that the difference is unexplainable and indicate an "altered" part.

To highlight the vital differences, the same data is presented in a different format. Over the full spectrum, the majority of the bands (in blue) fall within one standard deviation, signaling a natural variability. However, two outliers provide reason for suspicion and the excessively large frequency shift around 17 kHz (in red) confirm with high confidence that the part is different from the reference sample.

Figure 12 illustrates yet another tool that we plan to exploit: an ability to use the data obtained by FEA simulation from a CAD file.

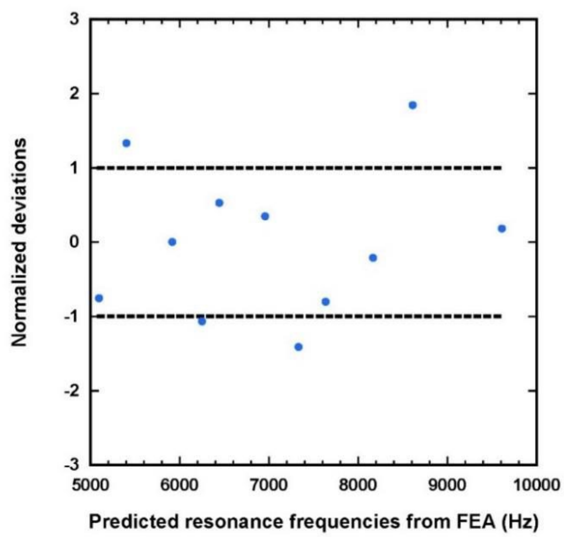


Figure 12. Measured spectral deviations from those predicted from FEA.

Figure 13 provides further details. The reference can be generated by FEA simulation based on a CAD file. As expected, both slope, at 0.9985, and the correlation coefficient, at 0.99999, are close to unity. The former signals that the material parameters correspond to the ones promised by the manufacturer, while the correlation coefficient illustrates the accuracy of the FEA algorithm. As previously discussed, given a CAD file for a part, we can calculate the resonances. Comparing calculated and measured values provides an obvious decision tool.

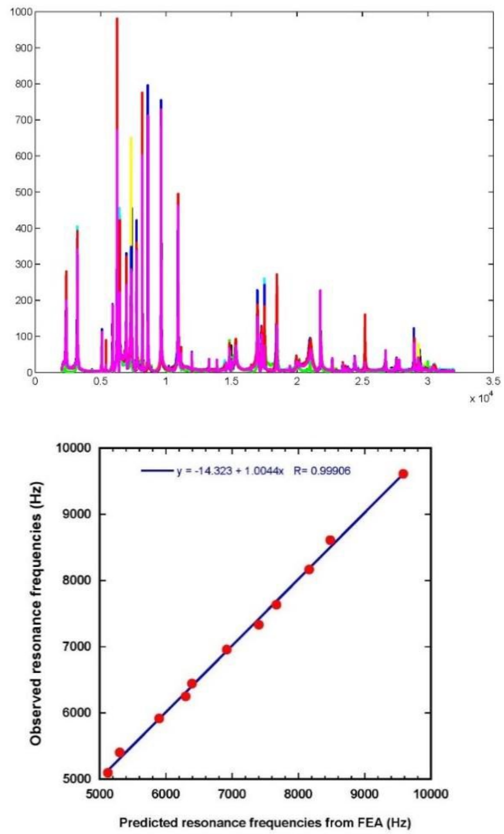


Figure 13. Comparing vibrational resonances of a part (left panel, several spectra superimposed) with the corresponding bands' positions predicted by FEA.

Another concept that could be equally promising in decision-making tools is to tailor the input spectrum in a more sophisticated manner to look for specific responses by varying excitation and testing positions. Like interrogating a criminal suspect, questions are carefully designed to look for specific responses. This idea would be especially applicable for components in which a validation key had been programmed for inclusion during manufacturing.

Preliminary Conclusions

Our experiments and computations so far have allowed us to make some important conclusions. We can produce reproducible vibrational spectra for components to within a few Hertz. This degree of resolution enables detecting very small changes in the material, structure, and anomalies of AM components predicted by FEA. The vibrational spectra of more complex components contain much more information and many more resonances. These are very sensitive to material properties and defects. It is highly likely that a hidden signature can be programmed into an AM component for use in authentication.

Future Work

We will continue to establish the method sensitivity to detecting specific anticipated problems in a range of AM components during and after manufacture, and will construct a field prototype and test it on real world problems.

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