ADDITIVE MANUFACTURING OF LOCALLY RESONANT COMPOSITE METAMATERIALS

Irfan M. Raza[1], Lorenzo Iannucci[1], Paul T. Curtis[1,2]

[1]Imperial College London,Department of Aeronautics, Exhibition Road, SW7 2AZ London, UK
Emails: irfan.raza@imperial.ac.uk, lo.iannucci@imperial.ac.uk, p.curtis@imperial.ac.uk
[2]Defence Science and Technology Laboratory, SP4 0JQ, Porton Down, Salisbury, UK

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Abstract

This article introduces a custom built multi-material 3D printer that is capable of depositing three different materials during one print. The printer utilises both continuous and droplet direct-write methods to deposit a UV cure plastic adhesive, latex rubber, and SAC solder metal in one single object. The printer is fully controlled via LabVIEW, allowing all aspects of the printing process to be adjusted. The purpose for this printer is to facilitate the manufacture of composite acoustic and elastic metamaterials.

1. Introduction

Additive manufacturing has existed as a method of making 3D objects since 1984 [1]. The field has expanded rapidly in recent years with various different printing methods being created, and the 3D printing hardware becoming substantially more accessible. The process of being able to make an object layer by layer using only the material you need has allowed various complex shapes and features to be made, which traditional manufacturing techniques could not achieve. In addition to this clear advantage, the ability to make a small batch number of components has meant that there has been strong adoption of the additive manufacturing techniques for the creation of prototypes and ageing components where the tooling no longer exists. Whilst the majority of devices can only deposit one material, more advanced machines are being created that allow the creation of parts with multiple materials[1]. However, these multiple material machines use methods that limit the number of materials that you can use in a single print, and high initial hardware costs discourage the experimentation of these printers to fabricate with new materials. There are many potential uses for a multi-material 3D printer, one off which is the manufacture of acoustic and elastic metamaterials.

Metamaterials are periodic, micro-engineered composite objects that are able to manipulate propagating waves in a manner that a homogeneous material cannot. These manipulations include the ability to stop a propagating wave, or bend it in such a manner that it can be redirected towards or around an object, otherwise known as wave focusing and wave cloaking [2]. Various different designs of metamaterials exist [2] that can operate in either the electromagnetic or the acoustic/elastic wave regimes. For elastic wave applications, locally resonant metamaterials (LRMs) are favoured due to their ability to manipulate waves with wavelengths 2 magnitudes larger than the periodicity of the LRM, as well as their ability to show negative effective density relatively easily [3]. The typical LRM design involves a dense core, coated in a soft flexible material, typically rubber, all held in place by a stiff but light matrix material[4, 5].

In this project, we bring these two fields of study together by attempting to print a LRM with a custom built 3D printer, that utilizes both continuous and droplet based direct-write printing methods[6, 7], which will allow it to build parts with up to three different materials. The benefits of using these two

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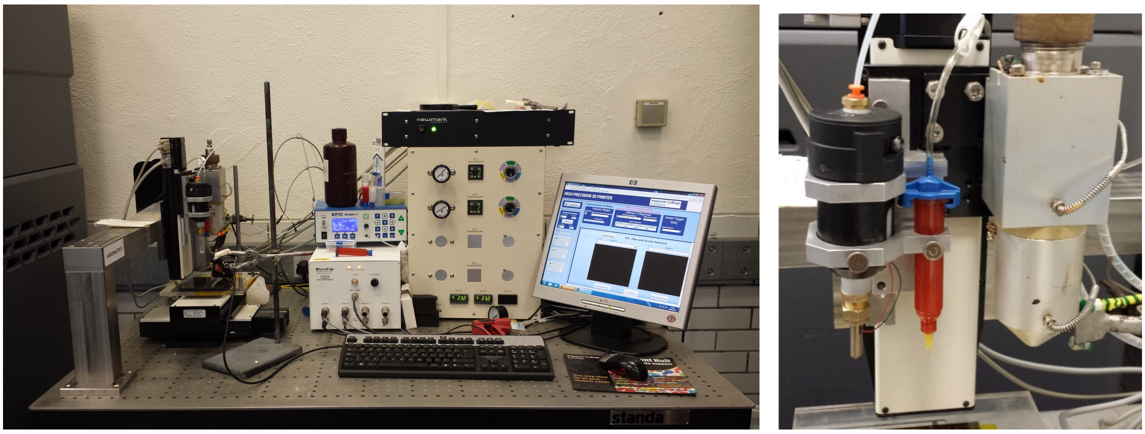
direct-write methods is that they facilitate the use of different materials better than other methods do, and they are also capable of achieving a high resolution and accuracy in the final printed parts. The printer is fully controlled by a custom program designed in LabVIEW, and can process STL files which facilitates the wider use of the printer. The ability to print with three different materials and two different methods presents the possibility of making smaller and more complex LRM designs, which it is hoped will increase their adoption into industrial applications.

2. Printer Setup

The printer was designed to deposit a range of different types of material. Of the various printing capabilities, direct-write methods have proven some of the most adept for multi-material printing [1]. As such there are 3 different nozzles; 2 droplet direct-write devices (aka inkjet nozzles) and 1 continuous direct-write system (see Fig.1(a) for the printer setup and Fig.1(b) for the nozzle configuration).
The inkjet nozzles are provided by Microfab and are of a piezoelectric design. Microfab recommends that the maximum viscosity of the material being deposited does not exceed 20mPas. To increase the potential range of materials that can be printed, one of these inkjets is part of the PolyJet system which allows the printing material to be heated up to 240°C. This is to reduce the viscosity of a material to bring it into the acceptable range for inkjet printing. The second inkjet nozzle does not heat up and prints with a material a room temperature. The nozzles are connected to a signal generator which can send different signals to each device, allowing one material to be printed at a time or simultaneously. In addition, the nozzles are connected to both a compressed air supply and a vacuum supply to ensure the correct back pressure for printing.



(a) Printer Setup (b) Nozzle configuration

Figure 1. Custom 3D printer layout

The Polyjet nozzle is set up to print with a SAC solder. The composition of this solder is Sn96.5Au3 Cu0.5. It has a melting point of 217°C, well within the range of the Polyjet's heating capability. The solder hardens upon cooling.
The room temperature inkjet nozzle will deposit a latex rubber material that has been recently developed [8] to be printed via the inkjet method. This latex rubber cures by drying at room temperature.
The continuous direct-write nozzle is part of the EFD Nordson Ultimus V system. A compressed air supply is connected to the Ultimus V control box, which feeds a controlled air pressure to a 10cc syringe containing the material to print. The material is extruded through the nozzle at the end of the syringe by a plastic plunger. The Ultimus V system applies a small vacuum after each deposition to ensure correct deposition amounts if the material to be printed has a low viscosity. This nozzle will print Permabond UV625 which is a UV cure adhesive. Cure times for this material are in the order of seconds.

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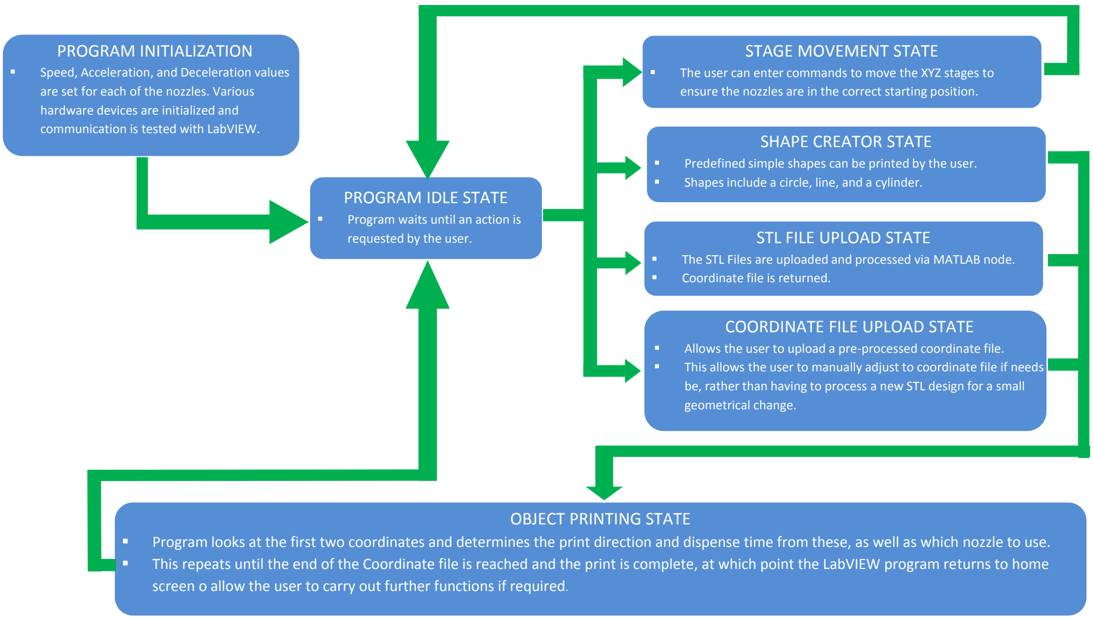
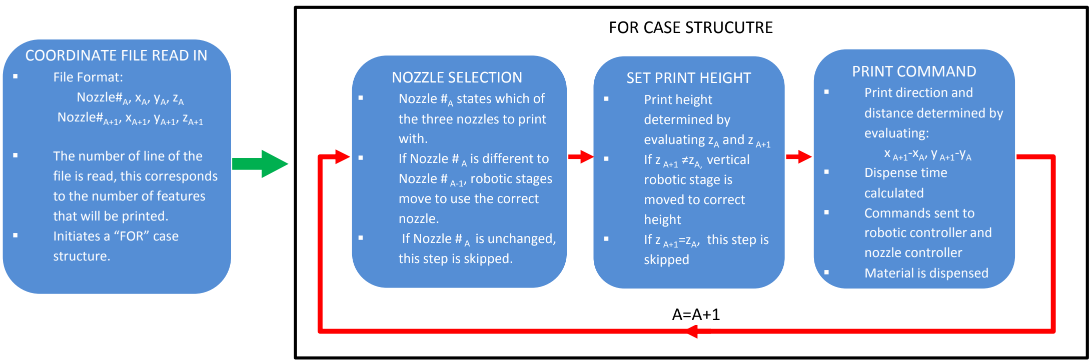
The movement of the nozzles is carried out using Newmark Systems XYZ linear stages. The three stages can be operated independently and have a quoted accuracy of 3μm and a repeatability of 0.5μm. The three nozzles are attached to a vertical stage which moves in the Z direction. The substrate platen is attached to X and Y stages. As such, the item being built moves under the correct nozzle to be used and as the material layers build up, the height of the nozzles are increased relative to the platen. The acceleration, deceleration, and velocity of the stages are controlled by the user and are set prior to printing. The robotic stages are set upon an optical table in order to dampen out unwanted vibrations during the print. A silent air compressor provides the pneumatic pressure that needs to be applied to the 3 different nozzles.

A LabVIEW program was created to control the 3D printer and allows for full control of the printing process. The user specifies the various printing parameters including the speed of the stages and the pressure of the pneumatic syringe prior to initiating the program. The user is requested to upload the STL files into the program, one for each nozzle that will be used. LabVIEW sends these files to MATLAB which then processes the STL files and creates a command file which is then read by LabVIEW. Based upon the coordinate file, LabVIEW sends the signals to the various pieces of hardware to allow the object to be printed (see Fig.2). The print can be paused if a nozzle's reservoir needs to be refilled or the user wants to inspect the partially built object for quality and defects before proceeding.



(a) An overview of the main LabVIEW printer control program.



(b) Schematic of the Object Printing State stage in the control program.

Figure 2. Schematic of the custom made LabVIEW printer control program.

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Processing of STL files is carried out by a custom MATLAB program which creates nozzle path commands for the printer. The MATLAB program works by reading in the STL geometry and identifying the maximum and minimum X, Y, and Z values of the part. Within these points, a grid is created according to a user defined resolution. A point-cloud plot of the part is created by identifying which points lay in the object and which are outside the object. This is determined by vector geometry. The program then identifies the shell of this point-cloud and writes the nozzle path commands, building the part from the base up. The resolution of the point-cloud representation of a part directly affect the number of the points the nozzle will go to. The resolution can be varied independently for each material in a part to take account of the different nozzle capabilities. The benefit of this system is that is works well when different parts are made of different materials in one object. The program has proved very effective at resembling the correct geometry and identifies gaps or voids in the object well.

3. Printed Multi-Material Design

The printer has been used to print with each of its nozzles individually to verify that each worked correctly. With the continuous direct write nozzle, several materials were printed using the smallest nozzle diameter available (100μm). These material were all UV curable, however it was observed that viscosity of some the materials were very low, meaning the material would run before they had been cured by the UV light source. Altering the nozzle speed and pneumatic vacuum did help alleviate some of these issues but meant slow printing speeds. When larger designs were printed, the cured object showed material run in the areas where it had been deposited first and hence there was a need for a more viscous material. The Permabond UV625 UV curable adhesive has a gel like consistency and maintained its deposited shape well when printed on a glass substrate until it could be cured. It also has a high strength and was suitable to use as the matrix component for the composite metamaterial.
The SAC solder was deposited using the PolyJet nozzle. The PolyJet's nozzle and reservoir device was heated to 225°C which melts the solder, a process that takes approximately 20 minutes prior to printing. The molten solder then passes through a 7μm stainless steel filter to remove any particulates or debris in the reservoir. This has proved more tricky to print with as this is typically done with an inert gas supply near the tip of the nozzle to stop the solder from oxidizing. For this reason printing with the solder has proved more difficult. Successful droplets were generated when the solder was deposited immediately following a small cleaning purge of the nozzle. A suitable substrate needs to be found as the droplets formed do not adhere well to glass.
The room temperature inkjet nozzle deposits the Litex T71S20 rubber. This is a material which, when mixed with a small amount of triethylene glycol monomethyl ether (TGME), has successfully been printed using an inkjet method [8]. The TGME is used to delay the drying time of the rubber to stop the material getting clogged in the nozzle. This will form the soft material that will coat the dense core for the metamaterial. The rubber material cures upon exposure to air and as such there is a risk the nozzle will get blocked whilst another material is being deposited. In instances where the nozzle was blocked,a small amount of Toulene was applied to the tip of the nozzle, followed by short purging of the material through the nozzle. The time taken to print can be adjusted using the settings in the LabVIEW program and so it is hoped that by speeding up the print the need to unblock this nozzle will not be required.

A simple square multi-material design was made and manufactured on the printer. The design was printed using Permabond UV625 which was deposited first, then the SAC solder was deposited second, and the Litex T71S20 was the last material deposited. (see Fig.3).

The printer deposited 4 layers of the UV cure adhesive. The material does have some minute air bubbles inside as is visible in Fig.3, but these were present in the material before depositing and are not introduced as a result of the printing process. Despite their presence, the resin still had suitable strength and maintained its shape well. Acoustically, the presence of the air bubbles could cause some scattering of

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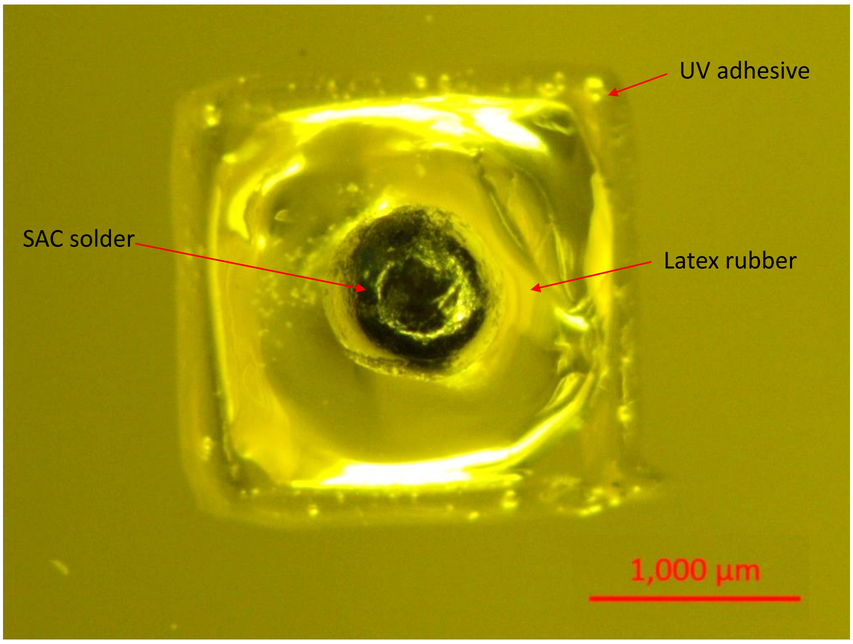

Figure 3. An example of a printed composite material. This is a simple square design with 2mm length sides made from a UV cure adhesive, SAC solder, and rubber.

sound waves but this will only affect sound frequencies where the wavelength is of a similar scale to the distance between the air inclusions, which are higher than the frequencies the metamaterial will be designed for and so will not affect the performance of the final printed metamaterial.
The SAC solder deposited well onto the glass substrate and maintained its shape well. As stated previously, the solder does not adhere well onto the glass substrate and so there is a potential risk of the deposited material moving around. When printing for a metamaterial, the solder will be printed on a rubber substrate which initial trials show this should reduce the risk of the deposited material moving around.
In [8], satellite formation of the rubber proved to be an issue and decreased the resolution of the printed rubber. This was not an issue when depositing the rubber as shown in Fig.3 as the resin and solder has already been printed and the rubber nozzle was used to deposit the material to fill the void between the two materials by allowing the rubber to flow until it came into contact with the other materials. This method of printing with the rubber as the final step will be adopted where possible. Another issue with the printed rubber, although not clearly evident in Fig.3, was the evidence of crack formation as the colloidal solution dries. Experimenting using small drops of the rubber solution which had been pipetted onto a glass substrate showed that any cracks that had formed during the drying process could be filled in when fresh rubber solution was deposited. This will have to be accounted in the printing strategy when printing a full metamaterial design.

Each of these materials cures in a different manner. The cooling and UV curing methods and quicker than the drying method for the latex rubber and indeed this is a rate limiting factor for the speed of the printer to make an object. This justifies the need to have a printing strategy when attempting to print with multiple materials. Single material printers can simply follow the standard process of deposit a material to form a layer of an object, cure it, and repeat for the next layer. With multi-material printers like the one presented, the deposition methods, deposition speed, and curing rate for each material need to be understood well and then programmed into the printer to achieve a successful print. For instance, when printing with the Permabond UV625, after each layer is deposited, the printer needs to move the platten

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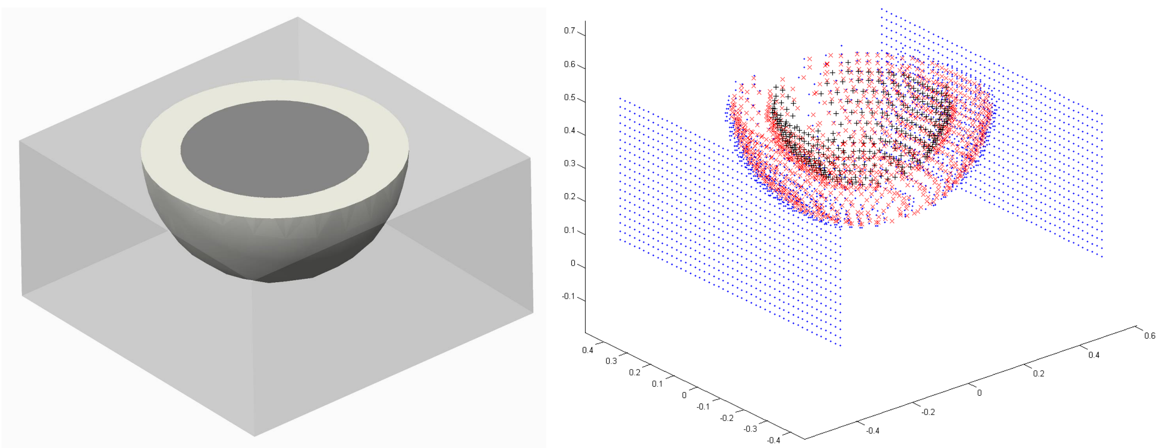
to allow the UV light source to cure the material, but this action is not necessary for the the curing of the rubber or solder materials. A summary of the materials that will be pritned is shown in Table 1.

Table 1. Printed Material Summary

Material	Nozzle Type	Cure Method	Metamaterial Component
Permabond UV625	Continuous direct-write	UV	Matrix
Litex T71S20	Room temp. Inkjet	Solvent evaporation	Coating
Sn96.5Au3 Cu0.5 Solder	Heated PolyJet	Cooling	Core

4. Proposed Metamaterial Geometry and Future Work

The printer will be used to make a LRM with a design similar to that first proposed by Liu [5] whereby the core and the coating are both spherical. Other non spherical designs have been studied showing the spherical design is the best for in-plane wave attenuation [9]. As such the proposed LRM's core and coating will remain spherical. One proposed design, which is ambitious due its small unit cell size, will have the core material have a diameter of 520μm and the thickness of the rubber coating is 110μm (see Fig.4(a)). The length of one side of the unit cell cube is 1 mm. The first band gap is observed during the vibration mode which equates to the displacement of the spherical core. Other attenuation bands are observed at higher vibration modes which equate to oscillations in the rubber layer however these typically have narrower band gaps.
With the geometry specified above, the proposed metamaterial should have its first band gap in the region 10kHz -11.43kHz (see Fig.5). The frequency spectrum diagrams shown in Fig.5 are generated by performing a modal analysis, evaluating points along the boundaries of the irreducible Brillouin zone (IBZ) for the cubic unit cell [2, 9]. The vertices of the IBZ are represented by the characters: Γ,M,X, and R.



(a) A cross section of a cubic unit cell for a proposed LRM design, with side lengths of 1mm. The core material is SAC solder, coated in rubber, all within a UV cure adhesive matrix material.

(b) A visual representation of a print command file generated for the model shown in Fig.4(a), used by the custom LabVIEW control program (see Fig.2), where each point represents a coordinate for one of the 3 nozzles to print to.

Figure 4. Proposed metamaterial design.

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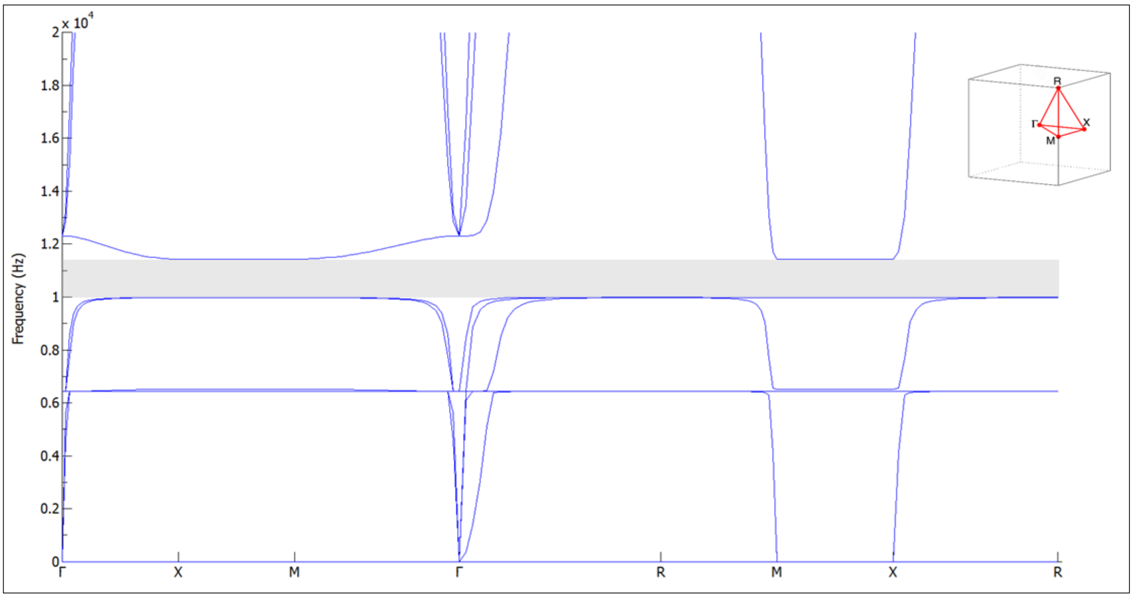

Figure 5. Frequency spectrum diagram of a proposed LRM, generated by performing modal analyses at the bourndaries of the IBZ, represented by the characters: Γ,*M*,*X*, and *R*. [2, 9]. For this LRM, the diagram shows a band gap in the region between 10-11.43kHz.

The main focus for the short term is to successfully print the proposed metamaterial design and test it using an impedance tube. Looking at longer term ambitions, there are various applications for a multi-material printer of this type. One such application is to make an active metamaterial by replacing the solder core with a magnetic material. As the core oscillates it would induce a small current in adjacent wires which opens the possibility of utilizing the printer to make energy harvesting metamaterials. Ferro-fluid has been successfully printed using an ink-jet method already [10] and could be utilised for this purpose.

5. Conclusion

A custom 3D printer has been built that has utilized both continuous direct-write and ink-jet printing methods to print three different materials in one object. The materials printed are Permabond UV625 UV cure adhesive, Litex T71S20 rubber, and Sn96.5Au3Cu0.5 solder. The printer is controlled by a custom made LabVIEW program that allows all aspects of the print process to be customized. The program uses a point-cloud method to process part geometry and copes well with multiple material models. A simple square design was printed which shows that it is possible to print all three different materials together, but has also highlighted to need to have a printing strategy in order to print the different materials together and take account of their resolution and curing method. This will be used to to make a locally resonant type metamaterial which with a unit cell size of 1mm, and should achieve a band gap between 10kHz and 11.43kHz.

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