COBEM 2021 26th International Congress of Mechanical Engineering
ABCM Associação Brasileira de Engenharia e Ciências Mecânicas
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-2334
ON THE POTENTIAL OF INJECTION MOULDING FOR THE PRODUCTION OF LOCALLY RESONANT METAMATERIALS

Kristof Steijvers
KU Leuven, Campus Diepenbeek, Department of Mechanical Engineering, Wetenschapspark 27, 3950 Diepenbeek, Belgium
DMMS core lab, Flanders Make
kristof.steijvers@kuleuven.be

Claus Claeys
Wim Desmet
KU Leuven, Department of Mechanical Engineering, Celestijnenlaan 300B box 2420, 3001 Heverlee, Belgium
DMMS core lab, Flanders Make
wim.desmet@kuleuven.be
claus.claeys@kuleuven.be

Philip Eyckens
Flanders Make, CoDesignS core lab, Oude Diestersebaan 133, 3920 Lommel, Belgium
philip.eyckens@Flandersmake.be

Lucas Van Belle
KU Leuven, Department of Mechanical Engineering, Celestijnenlaan 300B box 2420, 3001 Heverlee, Belgium
DMMS core lab, Flanders Make
lucas.vanbelle@kuleuven.be

Elke Deckers
KU Leuven, Campus Diepenbeek, Department of Mechanical Engineering, Wetenschapspark 27, 3950 Diepenbeek, Belgium
DMMS core lab, Flanders Make
elke.deckers@kuleuven.be

Abstract.

Locally resonant metamaterials have recently emerged as promising lightweight solutions for noise and vibration control. These materials allow the creation of stop bands, frequency ranges of strong noise and vibration reduction, by the addition or inclusion of resonant structures on or in a host structure on a sub-wavelength scale. As the currently used techniques for the production of LRMs are not suited for mass production, this paper investigates the suitability of the well-established injection moulding production process for the creation of LRMs. This conventional production process comes with a multitude of advantages, such as low cycle times, low cost for mass production and high repeatability, which make it highly appealing for the manufacturing of LRMs. Based on several resonator designs which have been tailored for the injection moulding process, multiple mould inserts are manufactured after which the repeatability of the injection moulding process is quantified by assessing produced resonator geometry and vibration responses. The measured resonance frequencies show that the injection moulding process is highly repeatable, although the material and process settings can influence the resonator dynamics. Compared to finite element method simulation results, additional update steps can be of use to increase the agreement between experimental and numerical results.

Keywords: *vibro-acoustics, metamaterials, injection moulding, manufacturing*

1. INTRODUCTION

In the field of noise and vibration engineering, the potential of locally resonant metamaterials (LRMs) as lightweight noise and vibration control solutions has been widely demonstrated (e.g. Liu et al., 2000, Claus Claeys, 2014, Sangiuliano et al., 2019). By the addition or inclusion of resonant structures on or in a host structure on a sub-wavelength scale, stop bands can be created, which enable creating frequency ranges of strong noise and vibration attenuation. For the manufacturing of LRMs, additive manufacturing (AM) techniques are often used as they are suited for the manufacturing of complex geometries and features. Nevertheless, AM techniques suffer from geometric inaccuracies and material property variations which influence the resonance frequencies of the resonant elements (C. Claeys et al., 2016, Jimenez et al., 2018). These small deviations due to the AM process can lead to non-negligible deviations in the dynamic properties of the LRM, resulting in off-design or deteriorated LRM performance. Moreover, mass-production of LRMs using AM techniques is impractical as these production processes remain expensive and do not reach the desired throughput for commercial applications, in particular for large scale structures (Wu et al., 2019).

In view of mass production, thermoforming can be used for the production of LRM panels (de Melo Filho et al., 2019). While the use of thermoforming as mass production method was successfully demonstrated, an additional milling step was needed to create the resonant structures. Moreover, the hard to control local thinning of the sheets during the forming process led to a large spread on the resonance frequencies causing off-design and less robust peak performance of the LRM panel. Alternatively, injection moulding (IM) can be used for the production of LRMs. This production process comes with low cycle times and costs when used for mass production along with a better repeatability compared to additive manufacturing. In a first attempt, insert injection moulding has been used to manufacture individual resonators, successfully demonstrating the use of IM for the production of add-on LRM solutions (Yu et al., 2019).

Regarding mass production of LRMs using IM, this research aims to investigate the repeatability of the IM process in view of dynamic performance. Therefore, individual resonators are manufactured, which can be added to a host in order to create an LRM. For all resonators, the forced vibration responses are measured after which the resonance frequencies are determined. In order to obtain a robust LRM performance, the variation on the resonance frequencies of the produced samples should be small. Section 2 discusses the resonator and mould insert design, taking into account both injection moulding and measurement procedure constraints. In the following section, the most important injection moulding parameters for the production of the resonators are discussed. In Section 4, a reusable measurement platform is introduced which is used for the dynamical characterisation of the resonators, followed by an explanation of the used measurement procedure. Section 5 discusses the repeatability of the measurement approach and the production process. Eventually, in Section 6, a general conclusion is given, followed by future research goals.

2. RESONATOR AND MOULD INSERT DESIGN

Two types of resonators with an out-of-plane mode shape are designed, taking into account specifications of an in-house available mould. The finite element method (FEM) is used to tune the eigenfrequency of the desired mode for each resonator design in the frequency range between 200-600 Hz as LRMs are highly suitable for targeting the hard to address low-frequency range (Claus Claeys, 2014). In order to quantify the repeatability of the IM process in view of LRM manufacturing, individual resonators are produced and their resonance frequencies are measured.

2.1 Mould characteristics

The resonators are produced using an in-house available mould which makes use of mould inserts. These inserts have dimensions as shown in Figure 1a and can be replaced in order to manufacture a different product with the same mould. As the insert is only placed in the moving side of the mould, the parting line will be situated on the edge of the product, limiting the resonators to 2D designs to avoid undercuts when demoulding. The mould has several ejector pin locations available which can be used to eject the resonators as illustrated in Figure 1b. In the injection side of the mould, two hot runner needles are present which allow the use of multiple injection locations to fill the insert cavities. Based on these mould constraints, a separate insert is designed for each resonator geometry such that both the injection points can be used for the same resonator and a single resonator will be produced each process cycle.

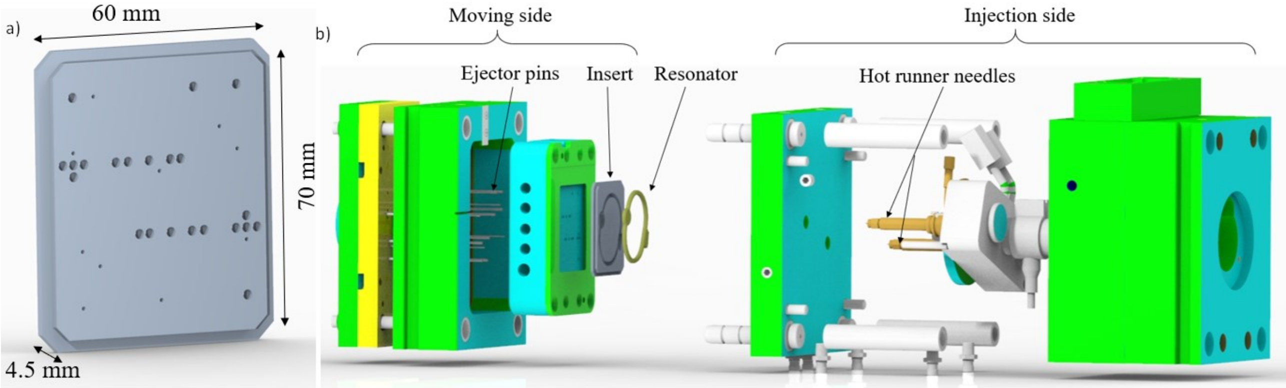

Figure 1: a) Mould insert, b) overview of the available mould

2.2 Resonator design

In view of creating vibro-acoustic metamaterials and metamaterial partitions which can be used for noise and vibration attenuation, the resonant structures are typically tailored to create bending wave stop bands, since bending waves contribute most to sound radiation. Hence, in this work, two resonator types are considered which enable such stop bands by having an out-of-plane resonant mode. For the first design, a cantilever beam resonator as in (Van Belle et al., 2017) was considered, targeting the first bending mode (Figure 2a). For the second design, a ring-shaped resonator with a top mass was created, which has an out-of-plane mode (Figure 2b). In order to satisfy manufacturability considerations, both resonator designs are tailored for the IM process: a draft angle is foreseen, sharp corners have been rounded and a maximum wall thickness of 3 mm was maintained to avoid the occurrence of voids during the injection moulding process. In addition, the foot of both resonators is tapered to suit the reusable measurement platform for resonance frequency verification, as explained in Section 4. The targeted eigenmodes of both resonators with clamped front and back side of the foot are calculated using Siemens NX using a quadratic solid finite element (FE) model with an element size of 1.5 mm and applying the material properties provided by the material supplier datasheets for polypropylene (PP) (*SABIC*, n.d.) and acrylonitrile-butadiene-styrene (ABS) (*NOVODUR P2H-AT - Novodur*®, n.d.). This results in the cantilever beam resonator of Figure 2a with an out-of-plane resonance frequency of 221.7 Hz and 285.4 Hz for the PP and ABS material respectively. For the ring-shaped resonator, the eventual resulting out-of-plane mode is tuned at 432 and 556.1 Hz for PP and ABS respectively.

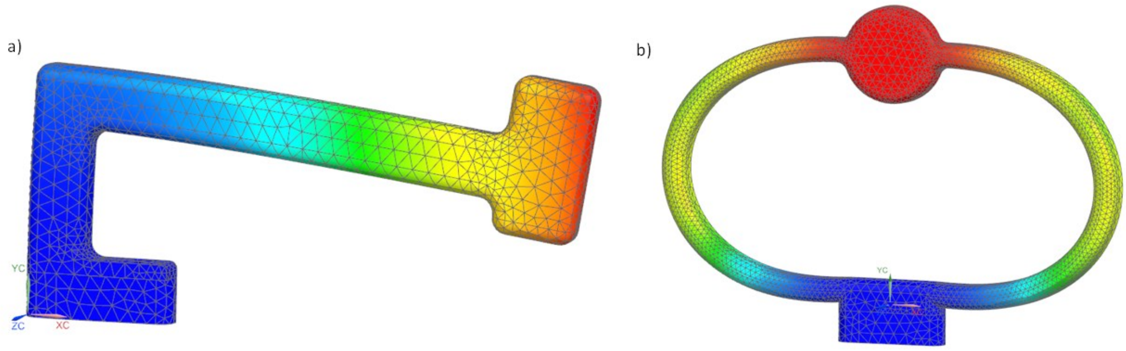

Figure 2: FE model of the a) cantilever beam resonator and b) ring resonator targeted 1st out-of-plane mode

2.3 Insert design and production

Based on the above defined resonator designs, two mould inserts have been produced which contain a resonator-shaped cavity for the cantilever beam and ring resonators, respectively (Figure 3a and b). In order to be able to investigate the influence of the selected injection location on the product filling and resonance frequency, both resonator cavities overlap with the two injection locations of the mould as indicated by the orange crosses. Furthermore, the resonator cavities are placed in the insert such that several existing ejector pin holes can be used to ensure product demoulding. Both mould inserts have been milled in an in-house workshop after which they have been grinded to create a perfectly flat closing plane and the correct insert thickness. The latter is particularly important to avoid the products to flash at the end of the filling cycle; this occurs when the polymer material leaks between the two mould sides, resulting in excess material attached to the product.

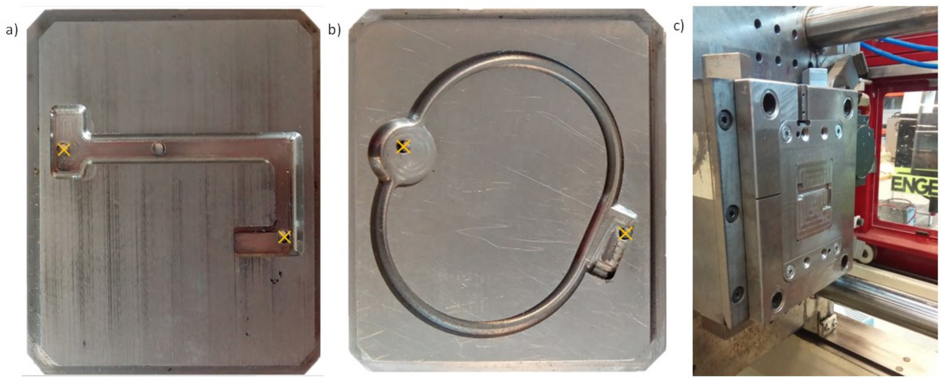

Figure3: a) Cantilever beam insert, b) ring insert, c) cantilever beam insert attached to the mould,

3. RESONATOR PRODUCTION

After the resonator design and insert production, the resonators are manufactured with the injection moulding process. This Section briefly discusses the injection moulding process cycle, followed by the main process settings used for the resonator production.

3.1 Injection moulding process

The resonators are produced with a Demag Ergotech IntElect 50/330-100 electric injection moulding machine with a maximum closing force of 500 kN and a 440 mm diameter long screw with a diameter of 22 mm which is heated in 5 sections (including the nozzle). During the process, a four-step cycle as illustrated in Figure 4 (Xie et al., 2011) is followed. First, a reciprocating screw melts the polymer while it is simultaneously mixed into a homogeneous mass by the rotation of the screw (plastification). Next, the plastic is injected into the mould cavity at a certain speed, until the cavity is almost filled (injection). Then, at the switching point, the process changes from speed-controlled to pressure-controlled were the product is entirely filled at a certain packing pressure (packing). After the packing time, the product cools down and solidifies further while the screw is dosing the next shot of material. After the cooling time, the mould opens and the product is ejected (demold) after which the cycle starts again.

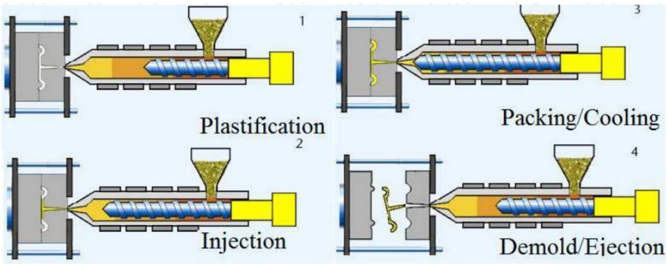

Figure 4: Process cycle of the injection moulding process (Xie et al., 2011)

3.2 Injection moulding parameters

The main injection moulding process parameters used for the resonator production in this work are listed in Table 1. The injection speed is set as a linear decreasing profile instead of a constant value to avoid burning of the product at the end of the filling. The process settings are the same for both resonator designs as the cavities are rather small with respect to the screw volume. The ring resonator has a higher volume, but the dosing volume was not increased with respect to the beam resonator as the ring still seemed successfully filled during the packing time. Based on the material datasheets, only the ABS material was dried for at least 3 hours at a temperature of 80 °C before injection moulding.

Table 1: Injection moulding process settings for both resonators in PP and ABS

Setting	PP	ABS		Setting	PP	ABS	
Nozzle temperature	240	240	°C	Dosing volume 3	4.56	4.56	cm³
Mould temperature	40	70	°C	Injection speed 3	3.8	3.8	cm³/s
Dosing volume 1	9.503	9.503	cm³	Dosing volume 4	4.18	4.18	cm³
Injection speed 1	19	19	cm³/s	Injection speed 4	1.9	1.9	cm³/s
Dosing volume 2	5.702	5.702	cm³	Switching volume	3.8	3.8	cm³
Injection speed 2	15.2	15.2	cm³/s	Packing pressure	30	30	MPa

4. MEASUREMENTS

The repeatability of the process, which is important to obtain a robust LRM performance, can be captured by verifying the dynamic response of the resonators. Therefore, after the production of several resonator batches in both the ABS and PP material, the resonator mass is assessed and the resonance frequency of each sample is estimated by forced response measurements. Then, the repeatability of the injection moulding process is quantified. After introducing the measurement platform in Section 4.1, the measurement procedure is explained in Section 4.2.

4.1 Measurement platform

To obtain the resonance frequency of each sample, the resonator is excited at the resonator base by an electromagnetic shaker while the vibration response is measured at the resonator mass using a laser doppler vibrometer. In order to measure multiple resonators simultaneously, a modular platform is used which is able to clamp multiple resonators at once and does not exhibit any modes in the frequency range of interest of the resonators. Hence, a reusable aluminum platform with 16 clamping slots was designed. This platform has outer dimensions of 12 x 12 cm, a thickness of 15 mm and is equipped with milled-out tapered slots in which the tapered resonator foots can be clamped as shown in Figure 5a. This clamping system is able to correct for small dimensional differences in the resonators as the tapered slot is longer than the resonator foots, so smaller resonators are clamped further in the slots than larger ones. These geometric differences can occur when using different materials with a different shrink rate for the production of the resonators.

Important in view of obtaining reliable measurement results is that the plate behaves rigid in the frequency zone of interest (200-600 Hz). Also the attachment to the shaker should be rigid. To achieve the latter, 3 bolts are used to make the clamping on the shaker sufficiently rigid, providing a fixture over a larger area as compared to the use of a single bolt in the middle of the plate. To verify the platform's modes and its first eigenfrequency in particular, a dynamic FEM simulation is performed in Siemens NX. The plate mesh consists of 10887 CTETRA 10 elements, for the aluminium material, a mass density of 2711 kg/m^3, Young's modulus of 68.98 GPa and a Poisson coefficient of 0.33 are applied. The nodes around the middle circle of 25 mm have been fixed to represent the clamping. The numerical solution indicates a first tilting plate mode around 3100 Hz (Figure 5b) which is sufficiently far away from the frequency range of interest for the tuned resonator frequencies. Eventually, the predicted platform mode was verified by measuring its response, resulting in a measured first resonance frequency around 2900 Hz (Figure 5 c). This slightly lower frequency can be explained by the simplified modelling of the clamping of the platform and possible small deviations in material properties.

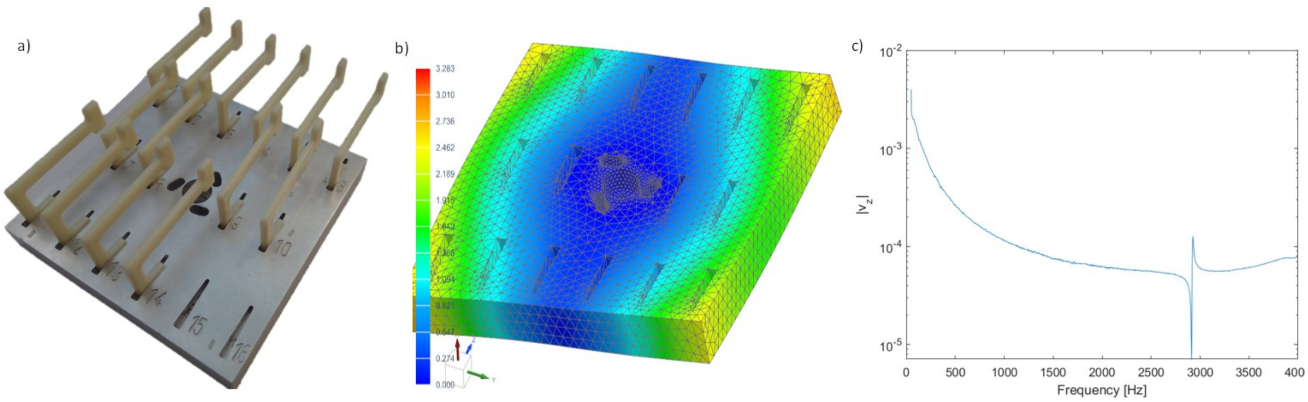

Figure 5: a) Measurement platform with clamped ABS cantilever beam resonators, b) predicted first eigenmode of the plate around 3100 Hz, c) experimentally measured plate velocity, the first plate mode occurs around 2900 Hz

4.2 Measurement procedure

The sample mass and resonance frequency of the produced resonators (2 geometries, 2 materials) have been measured to quantify the process repeatability. For the mass, all samples are weighted on an analytical balance with a resolution of 0.1 mg. The resonance frequencies are measured by exciting the measurement platform with resonators fixed in all slots with the help of a shaker, while white noise was used as excitation signal. The response velocity was captured at the moving masses of the resonators by a laser doppler vibrometer. The frequency range of the measurements was fixed at 50-1000 Hz with a resolution of 625 mHz. All resonance peaks were determined in Simcenter Testlab in a postprocessing step.

Before the process repeatability can be quantified, the repeatability of the measurements should be assessed. The clamping of the resonators on the platform might be influenced by the force used during their assembly as well as by manufacturing differences of the platform slots. First, a single resonator is fixed in a specific slot and is measured 20 times without reassembling the resonator on the platform in between the measurements in order to estimate the accuracy of the laser vibrometer and the used settings. Secondly, 16 resonators are fixed on the platform using all slots. 20 measurement runs are done with a reassembling step of the resonators in the same slot between each run to estimate the repeatability of the clamping system. For the above measurements in the framework of the measurement repeatability, PP beam resonators are used, which have been injected at a constant injection speed of 19 cm^3/s.

For the validation of the injection moulding process variability, 50 resonators of each type, injected with the injection speed profile in both materials and for both injection point locations (in the foot and mass of the sample) were measured.

5. RESULTS AND DISCUSSION

This Section discusses the results of the resonance frequency and mass measurements of the resonators. First, the repeatability of the measurement platform is assessed, followed by the repeatability analysis of the IM process for the ABS and PP beam and ring resonators.

5.1 Repeatability of the platform

First, the plate with 1 PP beam resonator fixed in a slot was measured to assess the repeatability of the measurements. When repeatedly measuring the resonance frequency without reassembling the resonator in the slot between each measurement, the standard deviation on the measurement results was defined at 1.16 Hz, almost double the measurement accuracy of 625 mHz.

Next, the platform fully filled with PP beam resonators was measured 20 times with a reassembling step between each measurement. The results are given in Figure 6. The boxplots indicate that the spread on the measurements is slightly increased as compared to the standard deviation of 1.16 Hz by the reassembling of the resonators, however the measurements are still repeatable. A higher measurement resolution might yield more accurate quantifications of the platform repeatability, yet the spread on the results is already satisfyingly small. For resonator K, the spread is higher than the other resonators. This could indicate that slot 10 does not provide a good clamping for the resonators or that the resonator was not clamped properly due to a poor filling of the resonator foot. However, this large spread disappears when measuring other beam resonators in the same slot on the platform, indicating that resonator K has a deviating foot geometry, resulting in a less repeatable clamping condition.

Finally, the 16 samples were clamped in other slots to identify possible slot-dependencies of the measurements. Here, the differences between the measurement in the new slot and the measurement in the previous slot is calculated for all the samples and plotted in Figure 6 b. It can be seen that the spread on the measurements is not larger than in Figure 6 a.

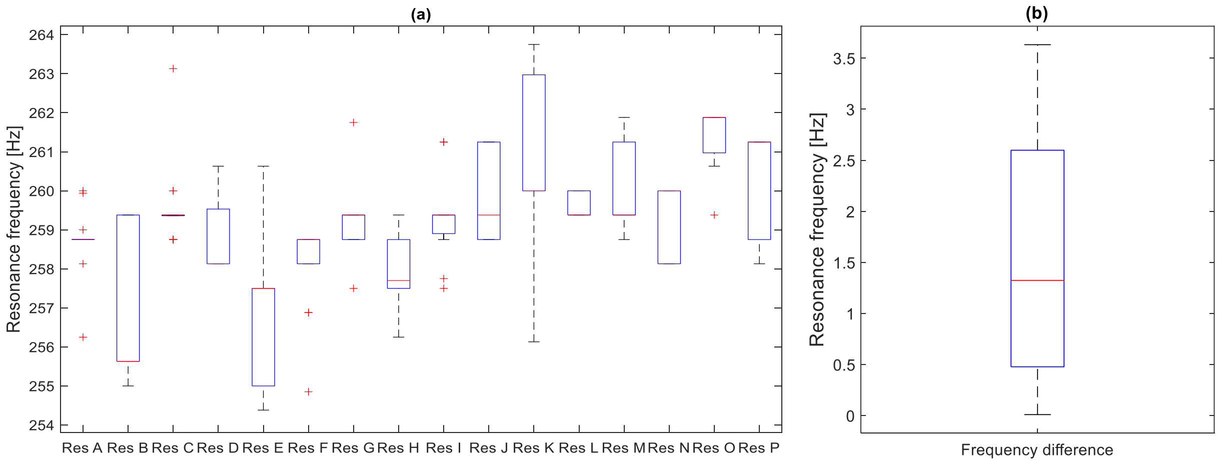

Figure 6:Box plots of the measurement results of the a) out-of-plane resonance frequencies of the PP cantilever beam resonator over 20 measurements with a reassembly step between each measurement, b) frequency differences of the resonator measurements in different clamping slots

5.2 Repeatability of the injection moulding process

For each type of resonator and material, the resonance frequency and mass were measured for 50 resonators which results in the outcomes of Figure 7. Both resonator designs were injected in the resonator foot and mass separately. For the ABS beam resonators (Figure 7a), the standard deviation of the product mass is significantly lower for both injection locations (respectively 1.5 & 5.6 mg) compared to the PP beam resonators (19.1 & 10.7 mg). This can be caused by the higher linear shrinkage of the PP material (1.6 %) compared to ABS (0.4-0.7 %), which means the PP beam needs more polymer filling during the packing phase of the injection moulding process compared to the ABS beam. As the polymer is already cooling in the mould during the packing time, it starts to solidify, hindering the entrance of more material into the insert cavities. The smaller spread for ABS compared to PP is not well represented in the beam resonance frequencies (Figure 7b). This might indicate that also spread on the stiffness is present. Further, no differences in mass or resonance spread occur with respect to the used injection point.

For the ring resonators, a higher spread on both the mass (Figure 7c) and resonance frequency (Figure 7d) of the PP rings is observed compared to the ABS rings. Further analysis of the PP ring samples showed that voids were present in the samples due to a poor filling of the products. As mentioned in Section 3, the resonators have a higher volume than the beam resonators but seemed well-filled during the packing time of the injection cycle. Due to the narrow legs of the ring resonator, the solidification of the ring is enforced, making it even harder to further fill the product during the packing time. Hence, the PP ring resonators should be produced again with a higher dosing volume to achieve better filled products. Furthermore, the foot-injected PP ring resonators have on average a higher resonance frequency than their mass-injected counterparts (Figure 7d). According to the inverse relation between mass and frequency, the frequency should increase with decreasing moving mass. This is the case as the mass-portion of the ring is not filled properly in case of foot-injection. The mass is the furthest point of the flow path and the narrow ring legs start to solidify rapidly, resulting in a lower mass and higher frequency for the foot injected ring samples.

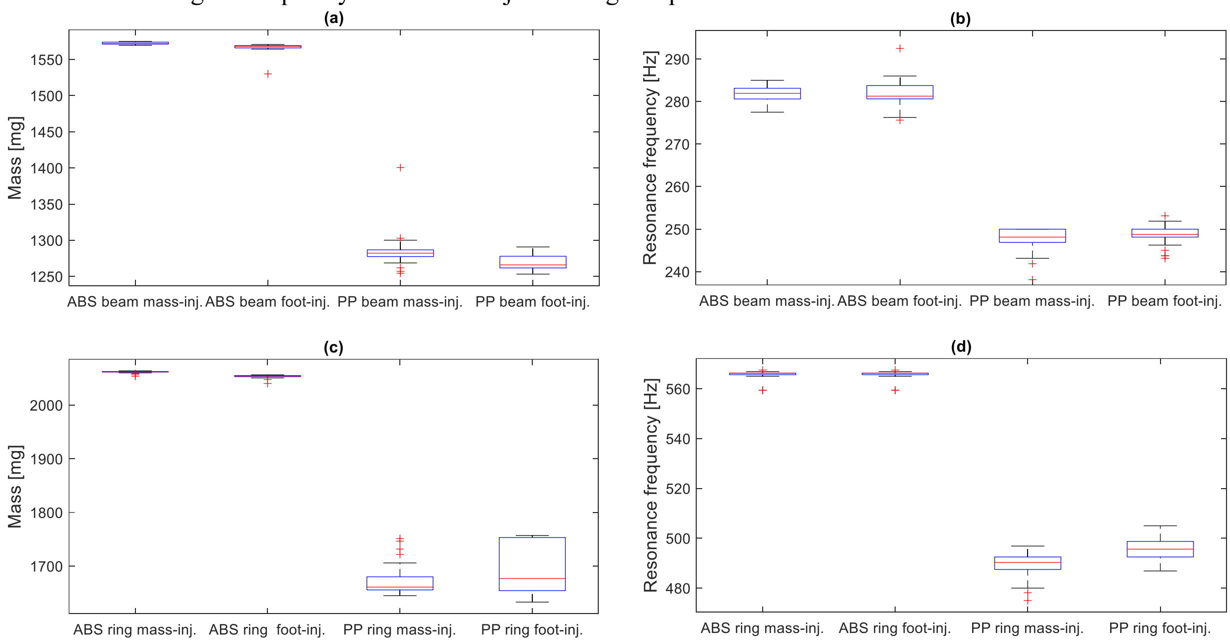

Figure 7: Box plots of the measurement results of the a) cantilever beam mass, b) cantilever 1st out-of-plane beam bending frequency, c) ring mass and d) first ring transverse bending frequency

Additionally, a comparison between the experimentally measured and numerically calculated resonance frequencies using the provided material properties is shown in Table 2. For the ABS material, a good agreement between numerical and experimental results is obtained. For the PP beam and ring resonators, the numerical results yield lower resonance frequencies than the experiments. This can partly be compensated by adding the volumetric shrinkage of the PP material to the FEM model by scaling the geometry, making the beam and ring arms shorter which increases the resonance frequencies. However, further material parameter updating will be needed to match both results. In future work, injection moulding simulations such as Moldex 3D (*Moldex3D | Plastic Injection Molding Simulation Software*, n.d.) can be used to further incorporate these injection moulding related effects in the numerical predictions.

Table 2: Comparison between numerical and experimental resonance frequencies

Resonator type	Numerical [Hz]	Experimental [Hz]
Beam PP	221.7	248.2
Beam ABS	285.4	281.8
Ring PP	432	492.7
Ring ABS	556.1	565.7

Comparing the PP beam resonators of this Section with the samples of Section 5.1, it can be noticed that the resonance frequency is on average 10 Hz lower while the masses are on average 25 mg lower (Figure 8). As the mass of the PP beams of Section 5.2 is associated with the lowest first bending frequency, it follows that the materials stiffness should be lower in order to explain these results. As both beam batches are measured at different room temperatures (20°C and 27°C respectivley), the young's modulus of the beams of Section 5.2 can be decresaed, causing the resonance frequency to decrease as well. This needs further investigation.

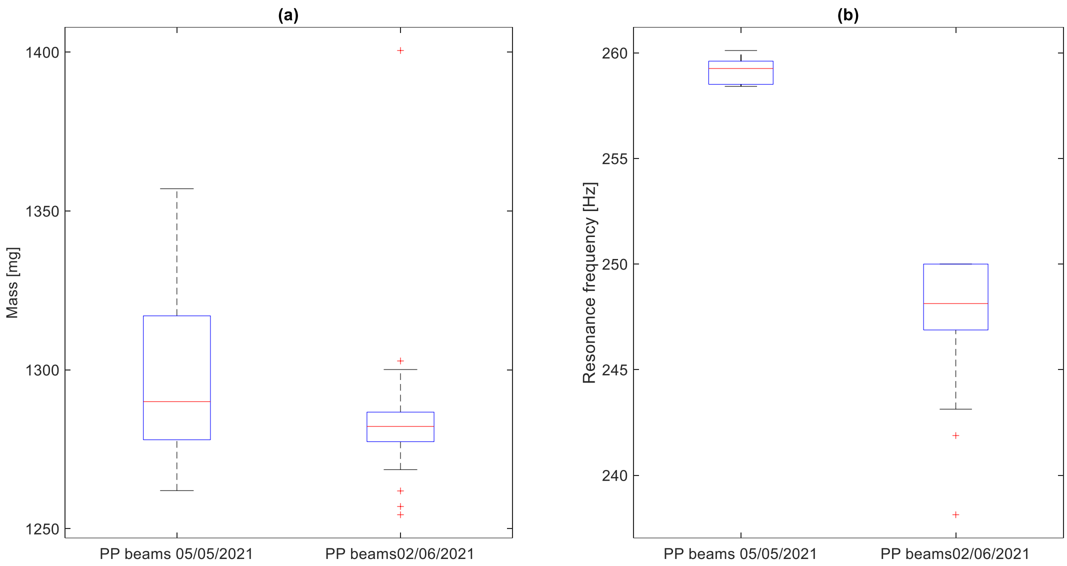

Figure 8: Box plots of the measurement results of the a) PP beams mass and b) PP beams resonance frequency measured at different room temperatures

6. CONCLUSION

Since LRMs are not yet mass producible nowadays, this research aims to take a first step towards the use of injection moulding as an enabling production process. A first verification of the repeatability of the commonly used injection moulding process for dynamic properties, relevant for LRM design, is performed. This study considered two different resonator designs and two different materials. It is shown that the injection moulding process can be a repeatable process in terms of dynamic product behavior. A good product filling is, however, required to obtain the best repeatability. Good agreements between experimental and numerical resonance frequency are obtained, although a clear need is identified for additional material and geometry updating steps. Further investigations will have to reveal whether there is an influence of the measurement temperature on the dynamic behavior of the resonators. In general, this study uncovers that injection moulding is highly interesting for the production of resonators in a repeatable way, taking a first step towards mass production of LRMs.

7. ACKNOWLEDGEMENTS

Internal Funds KU Leuven are gratefully acknowledged for their support.
This research was also partially supported by Flanders Make, the strategic research centre for the manufacturing industry.
VLAIO (Flanders Innovation & Entrepreneurship Agency) is also acknowledged for its support.
The research of L. Van Belle (fellowship no. 1271621N) is funded by a grant from the Research Foundation – Flanders (FWO)

8. REFERENCES

Claeys, C., Deckers, E., Pluymers, B., & Desmet, W. (2016). A lightweight vibro-acoustic metamaterial demonstrator: Numerical and experimental investigation. *Mechanical Systems and Signal Processing*, *70–71*, 853–880.

Claeys, Claus. (2014). *Design and analysis of resonant metamaterials for acoustic insulation*. KU Leuven.

de Melo Filho, N. G. R., Claeys, C., Deckers, E., & Desmet, W. (2019). Realisation of a thermoformed vibro-acoustic metamaterial for increased STL in acoustic resonance driven environments. *Applied Acoustics*, *156*, 78–82.

Jimenez, N., Romero-Garcia, V., Pagneux, V., & Groby, J.-P. (2018). *Technical limits of 3D printing by stereolithography techniques in the design of subwavelength perfect acoustic absorbers* (p. 26).

Liu, Z., Zhang, X., Mao, Y., Zhu, Y. Y., Yang, Z., Chan, C. T., & Sheng, P. (2000). Locally resonant sonic materials. *Science*, *289*(5485), 1734–1736.

Moldex3D | Plastic Injection Molding Simulation Software. (n.d.). Retrieved January 26, 2021

NOVODUR P2H-AT - Novodur® favorable buying at our shop. (n.d.). Retrieved June 9, 2021

SABIC. (n.d.). June 9, 2021

Sangiuliano, L., Claeys, C., Deckers, E., De Smet, J., Pluymers, B., & Desmet, W. (2019). Reducing Vehicle Interior NVH by Means of Locally Resonant Metamaterial Patches on Rear Shock Towers. *SAE Technical Papers*, *2019-*

June(June), 1–10.
Van Belle, L., Claeys, C., Deckers, E., & Desmet, W. (2017). On the impact of damping on the dispersion curves of a locally resonant metamaterial: Modelling and experimental validation. *Journal of Sound and Vibration*, *409*, 1–23.
Wu, X., Su, Y., & Shi, J. (2019). Perspective of additive manufacturing for metamaterials development. In *Smart Materials and Structures* (Vol. 28, Issue 9, p. 093001). Institute of Physics Publishing.
Xie, L., Shen, L., & Jiang, B. (2011). Modelling and Simulation for Micro Injection Molding Process. In *Computational Fluid Dynamics Technologies and Applications*. InTech.
Yu, J., Nerse, C., Lee, G., Wang, S., & Kyoung-Jin, C. (2019). Mass production applicable locally resonant metamaterials for NVH applications. *Proceedings of the 26th International Congress on Sound and Vibration, ICSV 2019*.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.