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Acoustics of tearing Velcro

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Abstract

The distinctive sound of a tearing Velcro has been investigated experimentally. We have constructed a rig that can tear a Velcro in a repeatable way at specified speeds. Tearing leads to the snapping of the hooks and loops of a Velcro, which induces vibrations of the base on which the Velcro is attached. We show that this is the main source of noise and present some new designs to reduce Velcro sound.

Keywords: hook and loop fastener, noise, noise reduction

Velcro sound

1 Introduction

Velcro is a trade name of a self-adhesive material otherwise known as a hook and loop fastener. It is popular for its light weight and strong adhesion, and therefore is used in clothing and household applications. However, it also emits a distinguishable sound when its two sides are pulled apart. The origin and properties of the sound are interesting for several reasons. Firstly, the distinctive nature of the sound alone merits its investigation. Secondly, understanding how the sound is produced would allow us to attenuate it and therefore develop a quiet Velcro, which would possibly be a high-value product as the noise emanating from the fabric is perceived as a drawback in many applications, e.g. military clothing. Finally, a lung disease called interstitial pulmonary fibrosis manifests itself as a Velcro-like sound [1]. Thus understanding the Velcro sound could aid in its diagnosis.

In this paper we present the first physical model for Velcro sound, validate it against experiments and suggest designs for quieter Velcro.

2 Experimental setup

In order to measure the sound from a tearing Velcro in a repeatable way, a Velcro pulling rig was constructed (figure 1). It consists of a stepper motor, which powers two inverse lead screws. Consequently, the two Velcro-holding clamps can be pulled apart at a specified velocity. A microphone is used to record the sound.

The stepper motor was used, as it is precisely controlled from the computer. However, it also emits the tonal noise, which interferes with the recordings. Therefore, Wiener noise filter was used to remove this noise and make the data usable. The comparison of spectra of the recordings before and after filtering is shown in Figure 2.

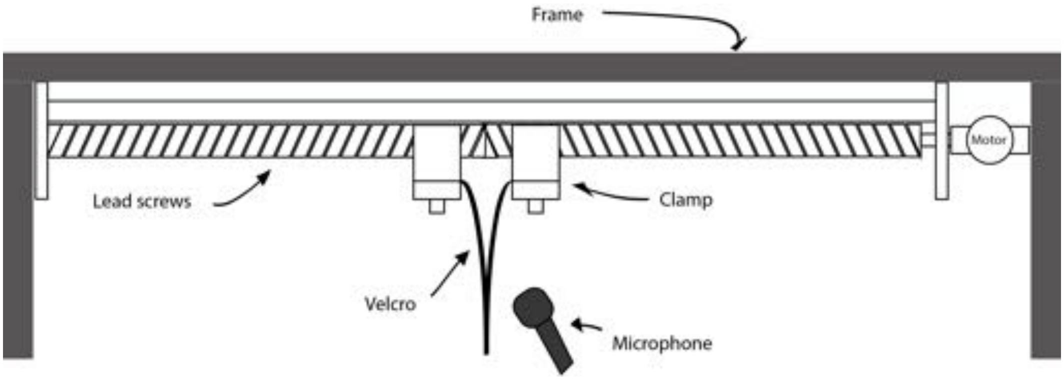

Figure 1: Schematic of the Velcro pull rig

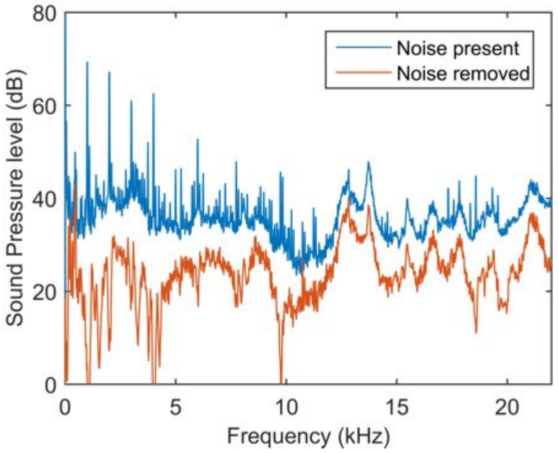

Figure 2: Velcro sound before and after removing motor noise

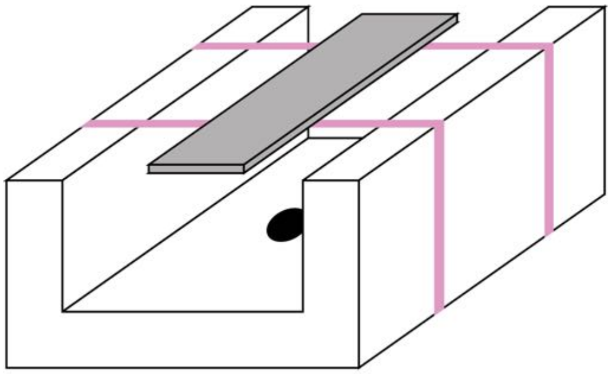

Figure 3: Schematic of a beam vibration rig, used for impulse response testing.

3 Experimental results and discussion

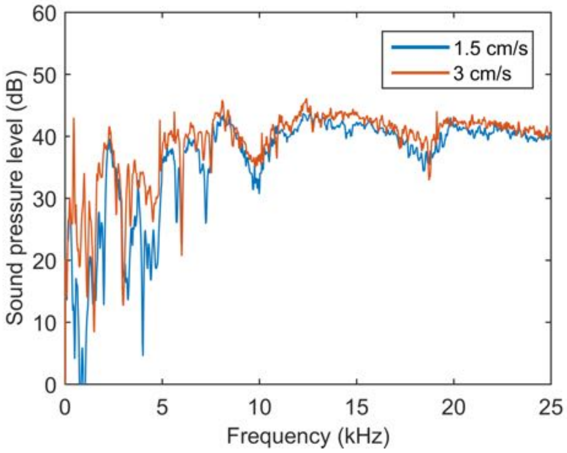

Figure 4: Comparison of Velcro sound frequency spectra obtained via Fourier transform for different testing velocities

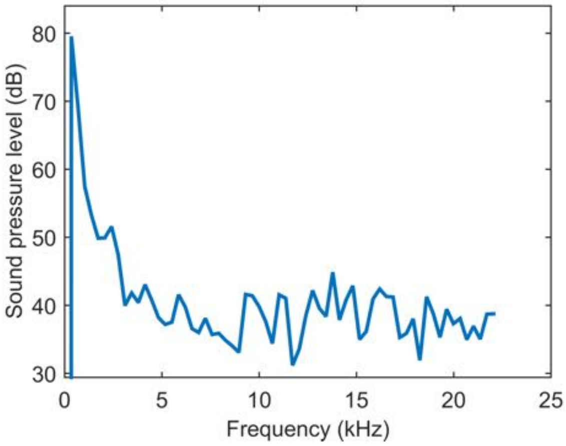

Figure 5: Frequency composition of an isolated hook-loop connection snap

3.1 First model: sound generation by hook-loop snap

Our first hypothesis was that the sound from a Velcro comes from the vibration of the hooks and loops initiated by the individual hook-loop snaps as the Velcro is pulled apart. As a result, each snap is expected to contribute identically to the frequency composition of Velcro sound. Hence, the frequency spectrum of the continuous tear should look similar to the one recorded from a single connection snap.

To test this hypothesis, we used a woven Polyester Velcro with the following dimensions (length $l = 105$ mm, width $b = 20$ mm, thickness $d = 0.45$ mm) (hereafter referred to as a simple Velcro) . The spectrum of the continuous tear (Figure 4) has clearly defined sound frequencies which are consistent within different recordings of the same sample. The FFT of a single snap, obtained by taking a very small segment of the Velcro and carefully pulling apart a single hook and loop connection, is shown in figure 5. The spectrum from the single snap is dominated by low frequencies, that are attributed to 50 Hz electromagnetic waves. The spectra at higher frequencies is mostly white noise. This result suggests that the vibration of the hooks and loops themselves is not the main source of Velcro noise.

Another observation was made by fastening the Velcro on a 2 mm thick aluminium plate, so that the new sample is of the same area, but has an aluminium base. This way the total number of hook-loop connections, total area of the sample, and hooks (loops) themselves are same for both samples. By assumption that sound is generated in these connections being snapped, the two samples are expected to sound similarly. However, the two sounds were very different qualitatively and quantitatively (Fig. 4 vs. Fig. 6). Therefore, not only snap is not the major sound source, but also changing properties of the base influences the sound.

3.2 Second model: snap induced base vibration

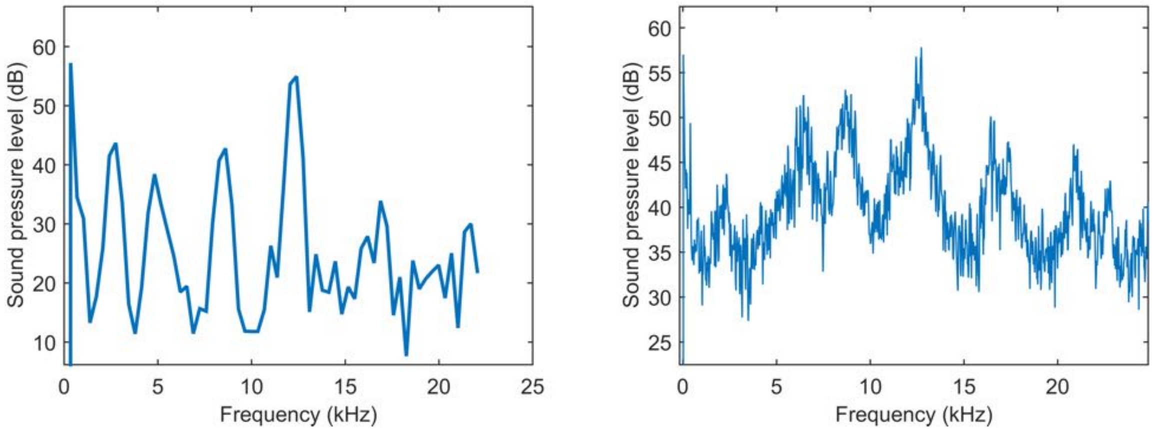

Figure 6: Frequency composition of (a) hook-loop connection snap (b) continuous tear of Velcro with aluminium base

In order to capture the base dependence, samples with different bases were created. In this section simple Velcro is compared to Velcro with a 2 mm Alumininum base.

Firstly, the sound emitted from a single snap (figure 6(a)) using the aluminium base sample is compared to that of continuous tear (Fig. 6(b)). There are clear peaks in the spectra and as these frequencies match, they are assumed to be dependent on the vibration of the base. Moreover, it also shows that a continuous tear can indeed be modelled as a series of snaps, as each snap carries similar sound composition as that of the whole-length tear.

Contrary to what was observed in Figure 5 and explained in Section 3.1, this snap results in a definite sound with clearly expressed frequencies. However, this difference is explained by low damping of aluminium, as a single snap is able to induce base related effects. Therefore, in Figure 6(a) not only hook-loop, but also base action is shown, while in Figure 5 base effects are not induced due to high damping of fabric. Still, a conclusion can be drawn that a single snap is capable of inducing a sound, which is similar in composition to that of continuous tear.

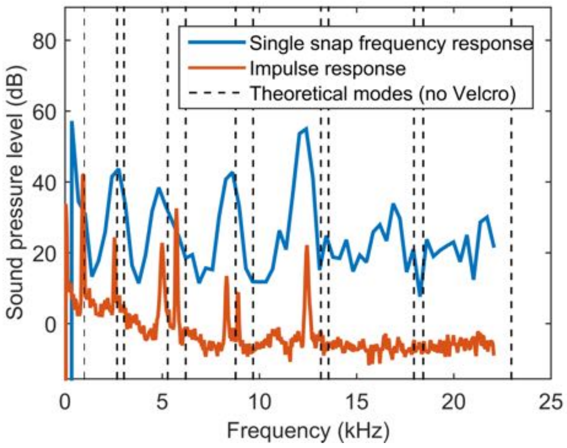

Figure 7: Comparison of Velcro sound frequencies and impulse response of the base. Dashed lines show theoretical resonant frequencies for the sample without Velcro

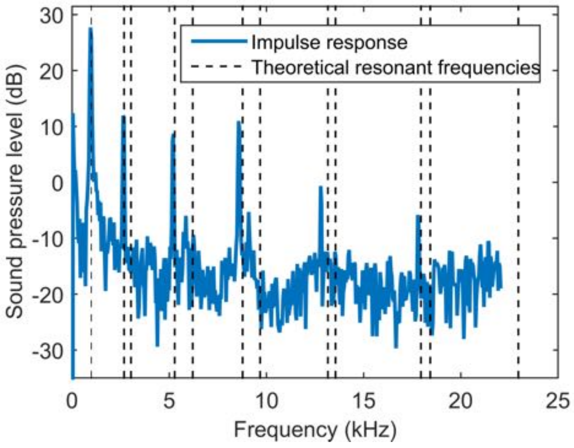

Figure 8: Comparison of impulse response of an aluminium base without Velcro and its theoretical resonance frequency

We propose (hypothesis 2) that the process of sound generation from a tearing Velcro is as follows: connection snap induces an impulse on the base, thus vibrating the base. The base vibrates predominantly at its resonant frequencies and this vibration radiates as sound.

To show that a snap induces impulse on the base, a beam vibration test is performed on one side of the aluminium Velcro sample using the rig shown in figure 3. The rig consists of a frame with a cavity, and a microphone fastened on the bottom of it. Above the cavity two rubber bands are stretched. The sample is placed on top of the rubber bands. This way, free vibration of the sample is not constrained by the support. The impact on the sample is provided via a hammer, and the vibration is recorded by the microphone. This test is guaranteed to only display the vibration properties of the base, as the provided impulse is external, and hook and loops are not involved. The response in frequency domain is plotted in orange on Figure 7. It is compared to an FFT of single impulse snap (blue). The two responses show identical frequencies. This proves that the major sound components are from the base vibration. Hence, a snap only induces an impulse for the base.

The next step is to show that the impulse on the base induces the vibration at resonant modes.

We observe that by comparing mode shapes and frequencies to impulse response test results. Figure 9 shows resonant mode shapes and their frequencies, obtained by computer simulation for 2mm thick aluminium plate of required dimensions. The frequencies are also shown as dashed lines in Figure 7, as comparison to the impulse response. It is seen that the test results and theoretic frequencies are close. The offset is present due to the extra mass of hooks and loops, which reduces the natural frequencies of a pure aluminium base. The theoretical calculations were done only for the aluminium base, without connectors.

To verify this is indeed the case, an impulse response test was also performed on a plain aluminium base. The result shown in Figure 8 confirms this, as the overlap is perfect.

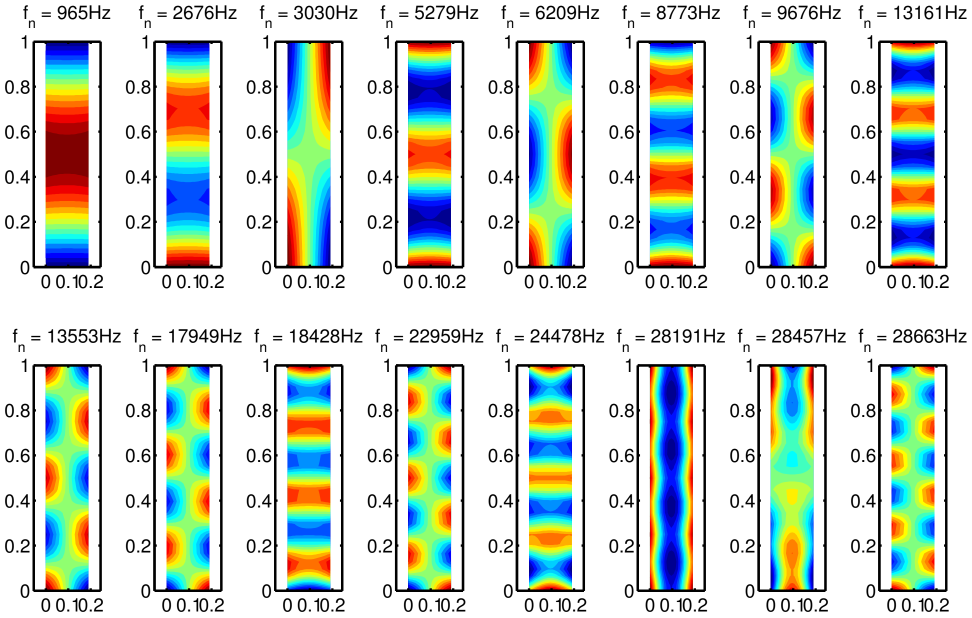

Figure 9: Mode shapes and respective vibration frequencies for 105 mm x 20 mm x 2 mm aluminium plate

4 Quiet Velcro

In this section we aim to make the Velcro quieter. As the sound originates from the vibration, parameters that govern vibration frequencies are explained. For a rectangular plate with small thickness there are two types of vibration modes: bending and torsional.

For a rectangular beam, the vibration frequencies are expressed by

$$f_{bending} = \frac{\alpha^2}{2\pi L^2}\sqrt{\frac{EI}{\rho A}} = \frac{\alpha^2}{2\pi L^2}\sqrt{\frac{Ed^2}{12\rho}}$$

where α is a coefficient, depending on the boundary conditions and a number of nodal points. E is the stiffness of the beam, I is the second moment of area and ρ is the density.

The resonant frequencies of the torsional modes are given by:

$$f_{torsional} \propto \frac{d}{bL}\sqrt{\frac{E}{(1+\nu)\rho}}$$

where ν is the Poisson's ratio for the material.

Hence, the resonant frequencies for the plate vibration depend on its geometry and material.

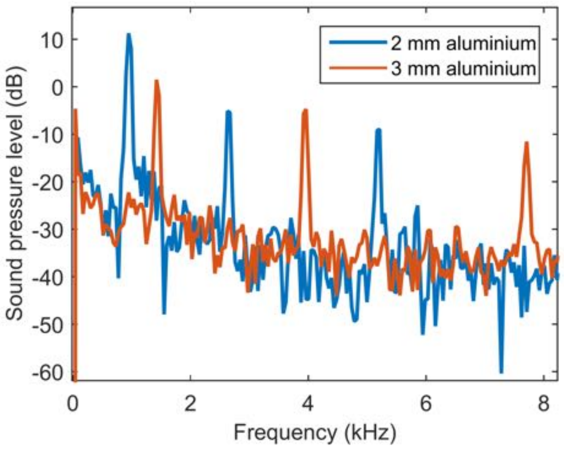

Figure 10: Comparison of 2 mm aluminium base Velcro and 3 mm aluminium base Velcro impulse responses.

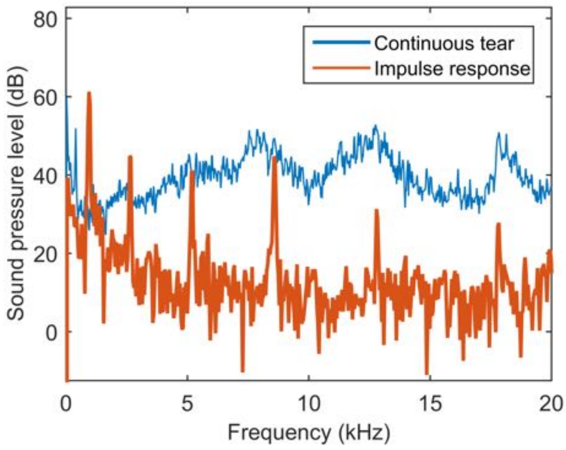

Figure 11: Comparison of continuous tear and an impact at 20% length from the edge. 3 mm aluminium base Velcro

4.1 Variation in geometry

A 3 mm thickness aluminium base Velcro was made to verify sound frequency scaling with thickness. Single impact and continuous tear tests were performed on this sample. Given that this sample is identical to the previously used 2 mm thick sample in all respects with the exception for the thickness, it was expected that the sound frequencies would scale by the thickness ratio. This expectation was confirmed by impulse response tests on the two bases of interest. Figure 10 shows the consistent scaling of the respective mode frequencies. In addition, the response from a single impact was contrasted with the sound of continuous tear (Figure 11). Very good alignment of the frequency peaks is observed. Thus, the net effect of changing the base thickness is that the natural frequency increases by the thickness ratio.

To observe the variation with length of the sample, the 3 mm base was cut into 6 segments, so that the total size of the base is the same, but the length of individual segments is $L/6$. The initial hypothesis was raised that the sound frequencies from this sample would be higher and

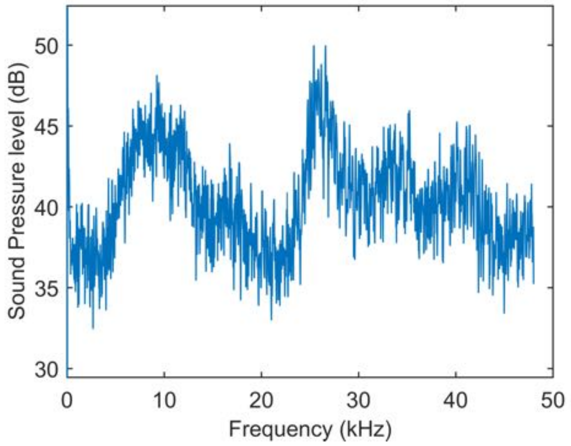

Figure 12: Frequency spectrum of continuous tear, segmented 3 mm aluminium base sample

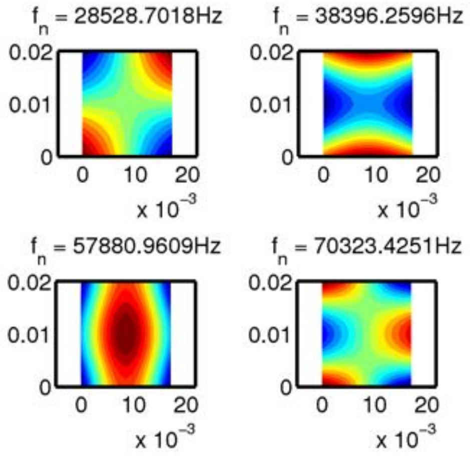

Figure 13: Mode shapes and respective vibration frequencies for 17 mm x 20 mm x 3 mm aluminium plate

more distantly spaced, resulting in fewer tones falling within human hearing range. Thus, the sound would appear quieter.

Simulated vibration modes are shown in Figure 13. As expected by theory, resonant frequencies are higher for the smaller sample. The first theoretical bending mode is found at 38.3 kHz and the first torsional mode at 28.5 kHz. The recorded frequencies of continuous tear are shown in Figure 12. The peaks at 26.5 kHz and 35.3 kHz are offset from estimations due to extra hook and loop mass, but otherwise show a very good match between theory and experimental results.

The additional frequency of 9.2 kHz is also strongly expressed, and it is not attributed to the aluminium part of the base. However, for the adjacent pieces of the base not to touch each other during the peeling motion, small gaps of the original Velcro base were left uncovered. It is proposed, that the vibration induced in these regions is expressed by 9.2 kHz frequency.

The frequencies in the most sensitive hearing region are expressed weakly for this sample. Hence, the emitted sound is much quieter than for the samples analysed before. The same observation is made qualitatively. Also, because of high natural frequencies only a few vibration modes fall in the hearing range. This property also contributes to why the sound appears quiet.

4.2 Material selection

As the vibration frequencies depend on E/ρ, we want to select materials that would give the optimal stiffness to density ratio. To make Velcro quieter, we aim to shift the resonant modes to ultrasound. This way although the sound will be present, it would be not observable to human ear. The chart for the material selection is shown in Figure 14. Constant E/ρ lines are shown in dashes. According to this chart, aluminium is already among the best choices for high sound frequencies. Interestingly, leather exerts very low frequency vibrations, suggesting that leather base would result in a very loud Velcro. Fabrics generally used for Velcro bases are expected to have similar properties, and thus it is one of explanations why generally Velcro is loud. Finally, vibration of polymers such as acrylic or nylon are expected to be somewhat lower than aluminium, but higher than simple Velcro.

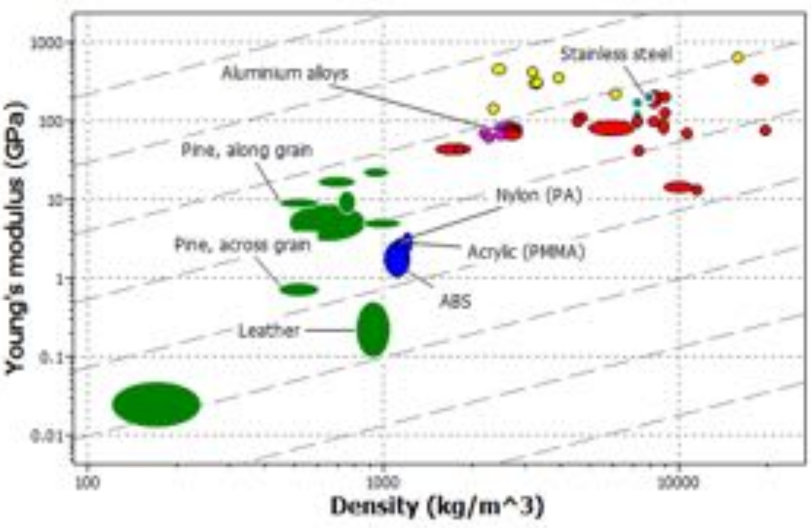

Figure 14: Materials selection chart. Guidelines show the direction of constant E/ρ and thus materials lying on the same guideline are likely to give identical natural frequencies. Natural frequencies increase in the directions up and to the left of the guideline, and decrease down and to the right. Colour coding: yellow = technical ceramics, red = non-ferrous alloys, green = natural materials, blue = polymers, turquoise = ferrous alloys, pink = glasses.[3]

Figure 15 shows impulse responses for the two bases, indeed giving a fixed ratio of 2.6 for the respective modes. Such low natural frequencies of Acrylic imply that more vibration modes have frequencies within the hearing range. Qualitatively the sound is observed much louder than for aluminium samples, but quieter than the reference sample. Both are expected, from stiffness to density ratio.

In addition, due to amorphous microstructure of Acrylic, the impact is easily dissipated compared to metals. This results in shorter vibration of an Acrylic sample, and the sound is thus less “ringing” is noticeable.

In Section 2 the experimental setup was described to provide consistency and repeatability. However, the Wiener noise filtering was observed to reduce the mean sound intensity in an undefined way. To compare SPLs in a consistent way, the peeling was done by attaching a weight of 4.5 N to one side of the Velcro. The recorded intensities are shown in Figure 16. As expected from qualitative observations, the reference sample was louder than the segmented

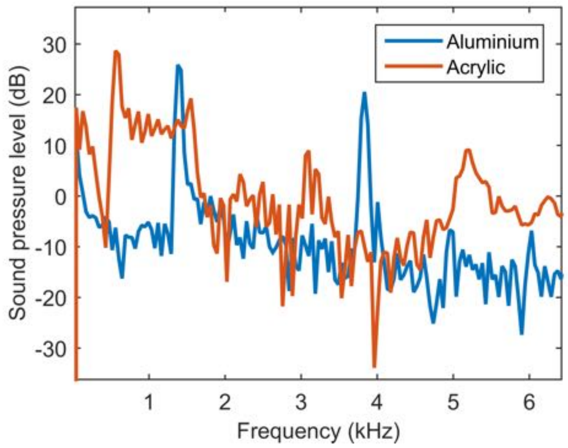

Figure 15: Impulse responses for aluminium and acrylic samples

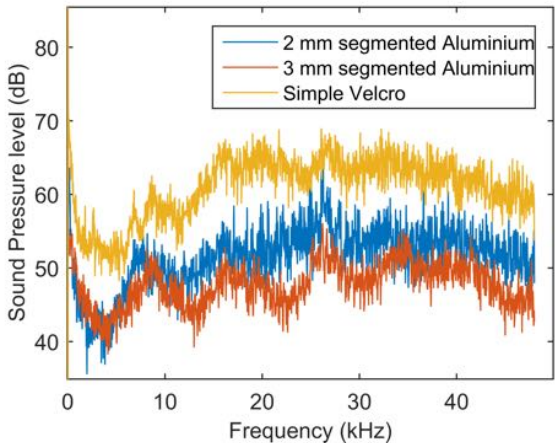

Figure 16: Sound pressure levels for different samples

base samples. The 3 mm segmented aluminium base sample was the quietest.

5 Conclusions

Velcro sound is generated because of the vibration of the base on which the Velcro is attached. The vibration is induced by the snapping of the hooks and loops as the Velcro is pulled apart. Sound is radiated predominantly at the resonant frequencies of the base. Not all the resonant modes and frequencies are excited. Bending modes are more readily exciting than the torsional ones. Higher modes require more energy to be excited and are more damped than the the lower-order modes. Thus the first few resonant modes are observed in the sound spectra. The sound can be manipulated by changing the base. This paves the way for designing a quieter Velcro as demonstrated in the paper.

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