ACOUSTIC METAMATERIALS: NOISE AND OVERHEATING IN RESIDENTIAL BUILDINGS

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1 INTRODUCTION

The need to balance overheating risk and exposure to noise has recently become an increasingly common issue and is now at the forefront of residential building design. This has resulted in the publication of the '*Acoustics, Ventilation and Overheating: Residential Design Guide*'[1] (hereafter the AVO Guide) in January 2020.

This paper presents an overview of the potential for addressing the noise and overheating challenge through the use of emerging technologies and approaches to construction. Specifically, it focuses upon the initial development of a novel form of passive ventilation based around the integration of acoustic metamaterials. The work has initially been centred around the design of an external acoustic shutter which incorporates metamaterial technology into its basic design, the aim being to provide levels of traffic noise reduction while also allowing air movement.

A prototype shutter has been developed and was sent for laboratory testing in February 2020. A summary of the initial findings and test results is presented, alongside a discussion of the practical applications for the shutter. Finally, the paper discusses the opportunities for future development of the shutter, along with the potential for integrating holistically designed environmental control solutions within factory produced building elements as part of the off-site manufacturing process.

2 BACKGROUND

2.1 Impact of noise on health and economy

It is well documented that exposure to too much noise can result in adverse health effects. This is not new; it was estimated as early as 1996 that up to twenty percent of western European citizens were at risk of health effects due to noise[2]. More recent research estimates that more than 1 million healthy life years are lost across western Europe annually as a result of environmental noise; with traffic noise ranked as the second greatest environmental health risk[3].

These effects also have an economic impact. The annual cost of road traffic noise exposure was estimated as £7-10 billion. This is a combined value as a result of health costs, productivity costs, and amenity (perceived quality / annoyance) costs[4].

Clearly, there is benefit in limiting exposure to environmental noise. Indeed, many new build residential developments are designed to achieve appropriate internal sound levels in line with guidance set out within BS 8233[5]; which in turn are derived from World Health Organization research[6].

In built-up urban areas, however, developable space is often at a premium; resulting in schemes being located close to noisy sources including major roads or railways. It is necessary to rely upon windows being closed to achieve these ideal internal sound levels; resulting in the introduction of high performance acoustically rated windows in combination with some form of attenuated ventilation system to provide background air changes.

2.2 The noise versus overheating challenge

Whilst designing on the basis of windows being closed is acceptable for large parts of the year, this can pose problems. Modern buildings in the UK have been developed to become more thermally efficient in order to limit the energy needed to heat them during colder seasons. An unwanted side effect, however, of this increased thermal performance is the potential for spaces to overheat during periods of warmer weather. The starting point to combat this, for many designers, is to rely upon opening the windows during these warmer periods to allow increased ventilation rates to passively cool the space.

The issue with simply opening a window is the potential also for increased external noise intrusion into the spaces concerned. Occupants are put in the position of having to choose between putting up with too much heat or too much noise.

Alternative solutions aimed at overcoming the noise versus overheating challenge typically range from the provision of full mechanical cooling through to the inclusion of acoustically rated passive ventilators incorporated into the façade. These solutions usually have to be considered at the very onset of design and are difficult to fit retrospectively. Similarly, there is a wealth of existing housing stock that does not include any alternative means of dealing with heat build-up.

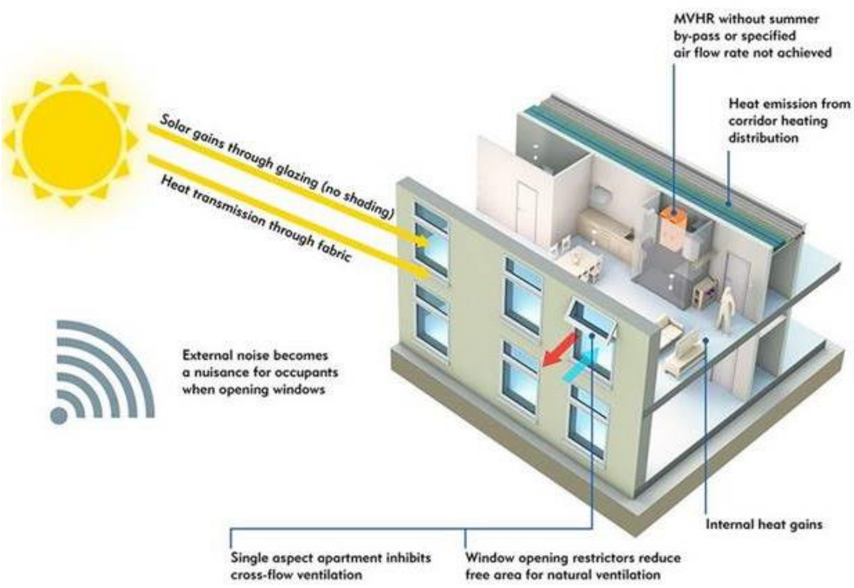

Figure 1 Noise versus overheating challenge in modern residential dwellings

2.3 Change in the construction industry

It is widely acknowledged that the construction industry has traditionally been slow in adopting new techniques and technologies. This is reflected in the Government's drive to stimulate the industry via its Construction Sector Deal[7].

The aim of this initiative is to drive development of the construction industry to build new, smarter homes in a significantly reduced timeframe and cost, whilst simultaneously improving the end quality for occupants, enable lower running costs, and also improving environmental performance.

One only needs to look to the aerospace and automotive industries within the UK to appreciate the degree to which transformation can occur via the adoption of a design and manufacturing ethos that integrates digital technologies, new manufacturing techniques and materials into products and delivery processes alike. In contrast, the basic principle of house building has remained largely unchanged for centuries, with multiple trades being involved in on-site work to deliver a finished product.

2.4 Modern Methods of Construction

The current drive towards Modern Methods of Construction (MMC), and notably in factory-based off-site construction adopting a Design for Manufacturing and Assembly (DfMA) approach, could be key to unlocking transformation in the construction industry. The practical benefits of undertaking as much as possible of the house-building process in a factory environment include:

- *increased speed of delivery, ultimately with reduced costs*
- *finer product tolerances from production line-based processes*
- *reduced waste*
- *less reliance on external uncontrollable factors such as the weather*
- *increased control over health and safety*
- *opening-up of employment opportunities to a wider demographic*

2.5 An outcomes-driven approach

From the perspective of the final delivered product, i.e. accommodation units, the potential benefits could be equally significant. However, these benefits will only be realised by taking a step back to focus on outcomes. The end product is not the accommodation unit itself, but a home which provides an environment in which people can thrive, a home that addresses the balance between the five capitals (human, social, natural, physical and economic) which, together, create a healthier and more sustainable future for individuals and for wider society.

Focussing on the health and wellbeing of the occupants, a home needs to deliver a functional space with plentiful clean air, good light and good acoustics, and a separation of spaces in which to relax, entertain, sleep or concentrate. It needs to provide effective connections with the outside world and wider society whilst also allowing the outside world to be shut out when desired, and not least privacy from close neighbours.

But the multiplicity of demands we place on our homes often leads to conflict. As an example, why do we build windows? To let daylight into our homes and allow our senses to connect to the outdoor environment, and to allow fresh air in to ventilate our indoor living spaces, all of which enhance our sense of wellbeing during daytime. However, the same windows will almost always be the weakest link in many buildings. They allow noise into buildings, even when shut, as well as bringing in polluted air and even more noise when open. Windows also act as sources of heat gain or loss, depending on the balance between internal and external thermal conditions. In the hours of darkness windows have even less technical merit as we seek to minimise the break-in of external light to our sleeping areas, which we generally achieve by closing curtains. However, windows continue to be the weakest link for letting in external noise and air pollutants when opened for cooling and ventilation purposes.

The ‘solution’ to the problem of balancing noise against overheating typically includes providing mechanical ventilation, cooling, or the installation of acoustic cabinets in order to open-up ventilation paths via openings in the external façade. However, neither approach is cheap, and both take up valuable space and require additional on-site installation effort. With MMC the possibility is arising of an integrated approach to designing-in solutions to the basic off-site manufactured components. For example, why not design an acoustically attenuated ventilation path into the façade construction and enhanced blackout technologies integrated within the window itself, which can be manufactured for delivery to site as a fully integrated item? The functionality of the façade-integrated air path could further be extended to include air filtration.

Of course, such solutions may only be applied to the new-build or deep retrofit markets, but with increases in temperature extremes and urban heat island effects there is a need to also address existing building stock. In the case of existing buildings attention will need to focus on the window openings themselves.

For centuries across Southern Europe city dwellers have used window shutters to control daylight and solar gain during the day, and to provide security and shielding from the hustle and bustle of outdoor living at night. Is there something to learn from the past and our continental neighbours as we think about adapting buildings in our own cities to face current and future challenges?

Modern-design shutters exist, but none appear to have been purposely designed to optimise protection against the ingress into buildings of the different external pollutants, weighing up the benefits between partial reductions in noise, light and air pollution, whilst also directly addressing the security and safety issues associated with open windows. The question is: could innovative engineering be applied to such a simple and age-old concept as the humble shutter to address modern-day problems? If this is possible, then the clear attraction of shutters is the relative ease with which they can be retro-fitted on existing buildings as well as being designed into new buildings.

3 DESIGN CONCEPT FOR A NOVEL WINDOW SHUTTER

The feasibility of a novel form of shutter has been investigated as part of an undergraduate research project at Brunel University London. The shutter incorporates acoustic metamaterial into its base specification, with the aim of providing a level of noise reduction whilst also enabling air to pass through.

Given the limited time associated with undergraduate projects, the investigation focussed on the sound attenuation characteristics of the initial proof of concept shutter, with airflow properties being modelled only as a secondary exercise. Whilst promising results were achieved on both acoustic and airflow grounds, the proof of concept nature of the study means that further work will be required to establish its fuller potential. Further work and future development opportunities are discussed later in this paper.

3.1 What are metamaterials?

There has been growing interest in the field of metamaterials over recent decades, as evidenced by the year on year increase in the number of publications on the subject.

The broad definition of a metamaterial is an artificially fabricated material, which is capable of demonstrating phenomena that do not occur naturally in the material from which it is constructed. A typical metamaterial structure is comprised of repeated subwavelength “unit cells”, such that an incident wave experiences the material as a homogeneous medium. Much research has focussed on the inclusion of unit cells with localised resonances that can allow even greater control over incident waves. In summary, it is the structure of a metamaterial that controls waves, not the physical properties of the material itself.

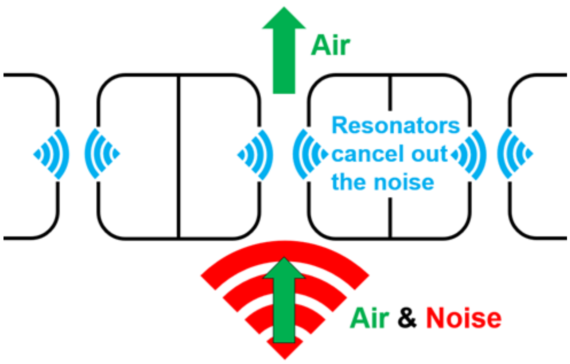

Figure 2 Acoustic metamaterial principles. Ref [8]

Acoustic metamaterials can display several novel phenomena such as lensing and negative refraction. One of the most practically useful applications is to create periodic structures that can allow airflow, whilst displaying stop bands of noise that cannot propagate through the structure (as illustrated in Figure 2).

This combination of properties lends itself well to creating a metamaterial structure in window openings, to receive the benefit of cooling and reduced overheating, whilst reducing exposure to noise from the external environment. The potential application of metamaterial technology to window openings has also been recognised and investigated at a theoretical level by J.Kang et al[9].

3.2 How much noise reduction should be targeted?

As it stands, there are no statutory requirements to provide particular internal sound levels during periods when windows are open (or indeed even when they are shut; although many local authorities control this via planning condition). It is only with the recent introduction of the AVO Guide that practitioners have been provided a means of objectively assessing the suitability of reliance upon openable windows as part of the overheating strategy. The guide sets out to qualify the level of risk associated with accepting increased levels of internal noise during periods when windows are open.

Whilst the ideal sound levels as set out within BS 8233 should be achieved when windows are closed; the AVO guide suggests that occupants may be more accepting of higher noise levels over a short term period when windows are open as it gives them control over their own environment[1].This mirrors the adaptive thermal comfort model set out within CIBSE TM59[10] when assessing overheating risk.

The guide uses a two-tiered approach to assign risk categories, from low to high, against increased levels of noise; with commentary as to the implications of accepting such a noise level. For example, a space regularly exposed to more than 50 dB $L_{Aeq,T}$ inside during the day, is considered a 'high risk'; whereby occupants may be expected to avoid certain activities during periods of noise intrusion, or there is greater potential for sleep disturbance.

Level of risk	Internal ambient noise level		
	$L_{Aeq,T}$ during 07:00-23:00	$L_{Aeq,8hr}$ during 23:00 – 07:00	Individual noise events during 23:00 – 07:00
High	> 50 dB	> 42 dB	Normally exceeds 65 dB $L_{AF,max}$
Increasing risk from low to high	Increasing noise level		
Negligible	≤ 35 dB	≤ 30 dB	Do not normally exceed 45 dB $L_{AF,max}$ more than 10 times a night

Figure 3 Risk associated with increased noise. Adapted from [1]

However, it is important to note that the guide does not advise of which risk category should be considered acceptable. It does, however, suggest that a 'high risk' would constitute a material change in behaviour. Linking this back to Planning Practice Guidance-Noise (PPG)[11], this would be considered to be at the Significant Observed Adverse Effect Level (SOAEL) and should be avoided. Effects described within the 'medium' risk category of the AVO Guide align with the "'Lowest Observed Adverse Effect Level (LOAEL)"; whereby the guidance within PPG is to mitigate and reduce noise to a minimum.

So, when considered within the context of national planning guidance, clearly the minimum aim should be to avoid SOAEL. On the basis that an open window typically provides 10 to 15 dB reduction from outside to inside, this would mean that dwellings exposed to external noise levels of more than 65 dB $L_{Aeq,T}$, or 57 dB $L_{Aeq,T}$ at night, potentially fall within this category.

An external noise level of 65 dB $L_{Aeq,T}$ is not uncommon amongst developments built close to major transportation sources. In fact, the DEFRA noise maps[12] estimate that 3.4 million people in the UK are exposed to these high noise levels during the day. This falls marginally at night; with more than 3 million exposed to external noise of more than 57 dB $L_{Aeq,T}$. The development of an effective noise reducing shutter clearly has the potential to be of benefit to a significant percentage of the population.

Recent metamaterial research[9] suggests that theoretical sound reductions of up to 30 dB are possible across certain frequency bands. Whilst this is a very good level of reduction; even a comparatively small wideband improvement of 5-10 dB, over and above that provided by an open window, could open up the possibility of reducing external noise levels of more than 70, maybe even 75, dB $L_{Aeq,T}$ to beneath SOAEL without the need to introduce more intrusive design measures such as mechanical cooling. The practical implication of this is that SOAEL could be avoided on all but the noisiest sites. There would also, of course, be benefits to applications on less noisy sites to further reduce internal noise.

3.3 Developing the acoustic specification

Initial development of the shutter focused on the potential to reduce noise from road traffic sources; based upon a typical frequency spectrum as given in BS 8233. An analysis was undertaken to determine the bandwidth the shutter would need to reduce in order to be effective, and how much attenuation would be required across each frequency band to maximise the overall level of reduction that could be achieved.

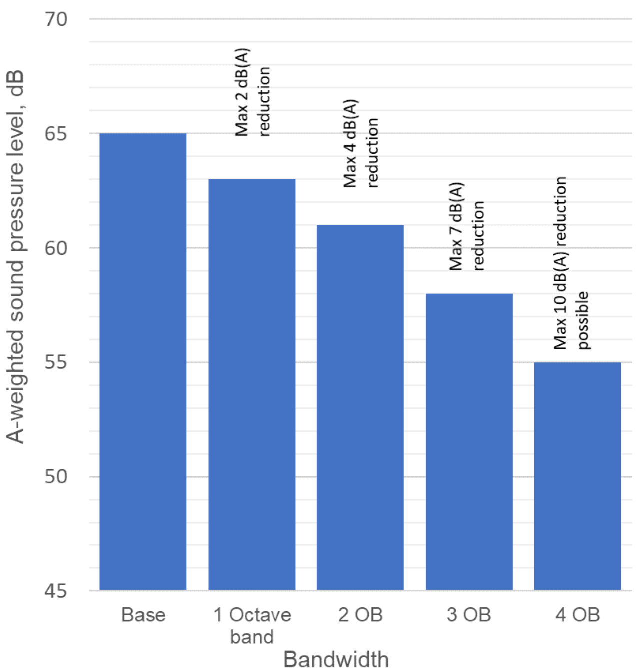

Figure 4 Effect of target bandwidth on A-weighted sound

The analysis confirmed that, if the noise reduction is limited to a single octave band, then the potential for overall reduction is capped at around 2 dB(A); regardless of the level of reduction achieved within that octave band. As expected, increasing the performance of the shutter over a wider bandwidth increases the overall level of noise reduction that can be achieved, as illustrated in Figure 4.

Furthermore, as the target bandwidth of the shutter is increased, the need to target high levels of sound reduction per octave bands decreases. A shutter designed to reduce noise across two octave bands, for example, would require a reduction of 12 dB in each octave band to attain an overall reduction of 4 dB(A). With a three octave bandwidth shutter, the same overall attenuation can be achieved with just 6 dB reduction per band. Of course, it is recognised that this simplistic view assumes that there is no additional sound reduction in the 'non-targeted' octave bands; meaning that greater levels of attenuation may well be achieved in practice.

The analysis also concluded that focussing the attenuation across a frequency range of 500 Hz to 2 kHz yielded the best results. Whilst the reduction of noise at lower frequencies may still be of benefit, the effect on the overall dB(A) reduction is minimal.

Whilst these findings are not necessarily surprising, they are relevant observations for the future development of products utilising acoustic metamaterials which, as previously discussed, have the potential for theoretical sound reductions of up to 30 dB over narrower frequency bands. Of course, there are applications for highly tuned sound attenuators in other aspects of noise control, such as that of plant noise where the elimination of a problem tone would be highly beneficial. However, for the purposes of developing the prototype shutter; it was agreed that a lower noise reduction performance over a wider range of frequencies would be of greater benefit for the end product.

3.4 Design embodiment of the shutter

With the acoustic performance requirements defined, preliminary profiles for the shutter panels were developed and tested using a 2D acoustic simulation.

As previously discussed, the design of the external acoustic shutters is principally based upon the use of acoustic metamaterial structures. Each panel comprises 2 halves that are mirrored in the next adjoining panel. When aligned, each half combines to form the cavities necessary for resonation and subsequent cancellation of incident noise. The use of simulations enabled the design of appropriately sized and positioned cavities in order to maximise noise reduction performance.

Profiles were first drafted as simplistic sketches of cross-sections in order to examine different configurations, shapes, orientations, and sizes of resonant chamber.

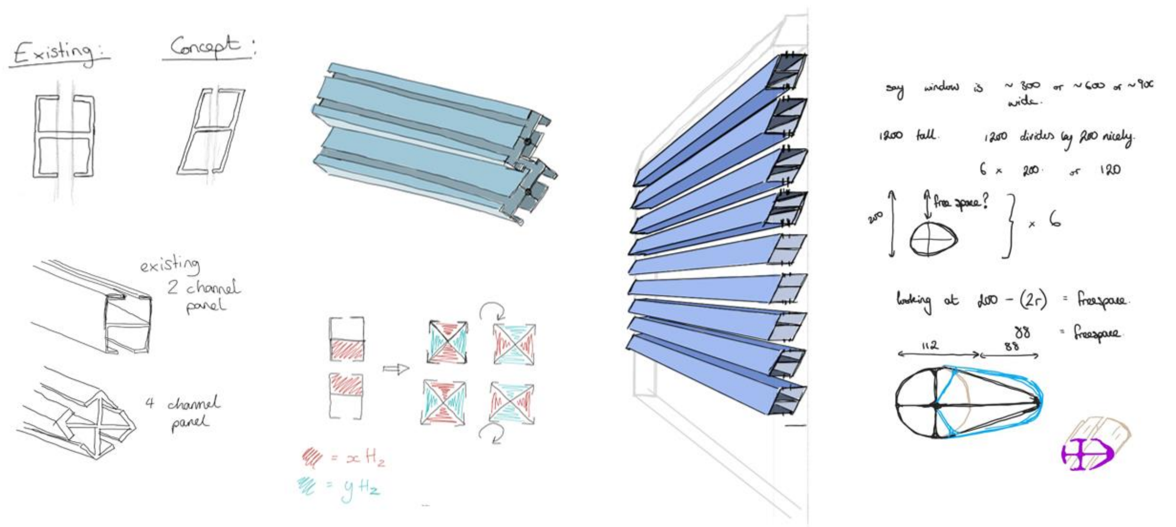

Figure 5 Early sketches of various shutter profiles. Ref [8].

The level of attenuation provided by each profile is dependent on an efficient coupling between similar chambers. The simulations analyse an array of these profiles positioned at different distances and angles to one another; taking into account other design drivers such as the need to permit airflow through the shutter, which favoured certain arrangements.

Results from the early simulations were categorised to identify the profile shapes, dimensions, and arrays that yielded a response across particular frequency bands. The most effective profiles were combined, thorough a series of iterative simulations, to produce a single model that achieved the greatest wideband response possible within the project timeframe. Final simulations of the chosen profile predicted a sound reduction of 5 dB R_w when fully open. This increases as the shutter is closed to a maximum reduction of 13 dB R_w when fully shut.

Following 2D simulation of the final profile, the model was recreated as a full scale prototype ready to be sent for laboratory testing. The test rig was set up to house a sample of 0.56 m^2 area; allowing for four aligned profiles to be tested at varying closing angles for comparison against the respective predictions. Each profile was 3D printed in Acrylonitrile Butadiene Styrene (ABS) plastic with a face to face thickness of 3mm, before being affixed to bearings and an alignment plate, and set within a timber frame.

Upon completion of the prototype, the sample was delivered to the sound transmission suite at Merford Noise Control in Holland where a standardised laboratory test of airborne sound insulation was undertaken.

Figure 6 3D prototype of the final profile. Left: sectional view, Right: Installed within test rig. Ref [8]

3.5 Results

Results from the laboratory testing are provided in the table below for different closing angles of the shutter.

Table 1 Weighted sound reduction index by shutter position

Angle, deg	0°	40°	50°	60°	Shut
R_w, dB	6	7	8	9	11

In terms of the overall sound reduction performance, the laboratory tests align closely with the simulated values; which ranged from 5 - 13 dB R_w depending upon the closure angle. Due to the tuning of the shutter towards the 500 - 2000 Hz range, the ‘R_w’ performance correlates strongly with the reduction on the A-weighted road traffic spectrum.

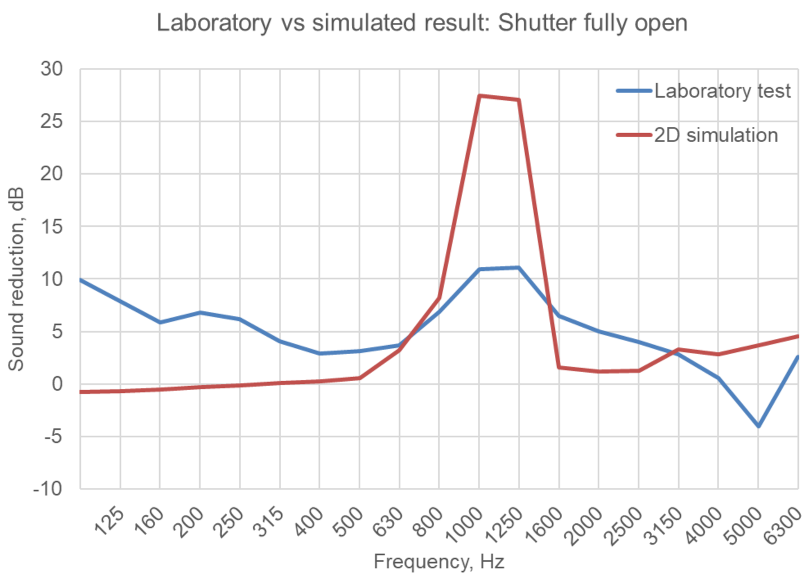

Figure 7 Comparison of laboratory and simulated results. Ref [8]

When comparing spectral levels, it is observed that the measured sound reduction has a flatter response than the calculated reduction. It is likely that this is due to limitations within the initial simulations. Whilst the predicted results accurately predict the frequencies that will be attenuated, the magnitude of attenuation is exaggerated as the model does not account for losses that may occur in practice. Further correlation could have also been achieved if the simulations were undertaken in 3D, rather than 2D, modelling space.

Notwithstanding the difference in magnitude of the various peaks, the measured results are positive. The frequency response of the shutter in the fully open position offers maximum sound attenuation in the 1 kHz and 2 kHz octave bands and so the stated design intent of focussing the attenuating bandwidth on noise from road traffic is being achieved.

3.6 Discussion and future development

The laboratory testing represents a first positive step in demonstrating a ‘proof of concept’ for a tuned acoustic metamaterial shutter. There is, of course, further research and development work to be done.

The first logical step is to undertake additional laboratory testing in combination with a standard window to understand the overall effect of the opening and shutter. Given the undergraduate nature of the project, time was a limiting factor and so this simply could not be completed in the available period. However, this step is vital in realising the potential for the shutter above and beyond a simple ‘open window’s strategy to control overheating.

With more time, there is also opportunity to further optimise the unit cell geometry to provide more efficient cavity couplings for different frequency bands; which would increase the level of attenuation achieved. Alternatively, a number of individually tuned unit cells could be combined across the shutter construction to provide a greater composite performance. There is no reason that this could not be taken further. The tuneable nature of the metamaterial structure, in combination with the flexibility afforded by 3D printing, offers the possibility of developing site-specific shutters that could be tweaked to attenuate noise from individual sources such as train squeal for sites close to railways.

Non-acoustic studies would also need to be completed; in particular effects on airflow and daylight. Whilst airflow performance was not investigated in significant detail, preliminary CFD modelling did highlight an interesting characteristic that the shutter increased the air velocity as it passes through. This jet-like ‘throw’ effect could potentially offset reductions in free area of the open window. With regard to daylight, the shutter could of course be manufactured of a transparent material to reduce shadowing effects.

There is also no reason why shutters need to be considered solely as passive objects, always requiring manual operation. The increasing prevalence of sensing technologies and ‘Internet of Things’ (IoT) based connectivity in homes is opening-up the possibility of integrated intelligence to create a ‘smart’ shutter.

The simultaneous sensing of internal versus external environmental conditions (for example noise, temperature, air quality, light etc), plus room occupancy sensing, could be used to automate the combined operation of windows and shutters.

Using the topic of noise as an example, requirements for closed windows are frequently based on the exceedance of certain external noise levels over prolonged periods. But what if there is no one in a given room to be affected by the noise, or the actual external noise at a given time of day or night is below that which contributes to the trigger level? What if the occupant-generated internal noise within a room is greater than the external noise? In all these instances there is arguably no merit in keeping a window closed. There may be greater merit in opening the window, maybe in combination with actively controlling the relevant performance parameters of the external shutter?

It is also noted here that the active elements of a smart shutter could also be extended to include active noise control[13] to further extend the compromise achieved between acoustic attenuation performance and the ventilation path open area. Other active enhancements could be the inclusion of powered fans to force air through ventilation openings. Being active elements, both would require powering, but this could possibly be achieved via solar PV combined with battery storage, both components being integrated into the shutter design; i.e. the solar gains we are actively trying to limit inside can be utilised to provide power.

Finally, the integration of a relatively simple shutter would not be limited to the new build market. Further developments may open the potential for significant benefits in controlling environmental conditions within existing housing stock as a retrofittable item.

4 SUMMARY

The need to balance overheating risk and exposure to noise, amongst other environmental conditions, has become an increasingly common issue and is now at the forefront of residential building design.

This paper presents an overview of the potential for addressing the noise and overheating challenge through the use of emerging technologies and approaches to construction. Specifically, it focuses upon the initial development of a novel form of passive external shutter that incorporates acoustic metamaterials within its basic design.

Laboratory testing of a preliminary shutter design has demonstrated the potential for such a device to reduce external noise whilst still allowing air and light to permeate the space. With future development, the shutter could be further optimised to provide greater levels of attenuation, or to respond to site-specific environmental noise sources. Smart technology could be incorporated to automate the degree of opening based upon continuous monitoring of the internal and external environments. The technology could also be modified to offer a retrofittable solution within existing housing stock; offering benefits for a significant proportion of the population.

This is just one of the possibilities for acoustic metamaterials. However, within an increasingly complex design environment, emerging technologies, in combination with modern methods of construction, provide an opportunity to rethink the way we design buildings to deliver a better end product; a healthy, enjoyable home that balances the demands of conflicting environmental factors, in which occupants can thrive.

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