Technical note

HVAC noise control using natural materials to improve vehicle interior sound quality

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ABSTRACT

Heating, Ventilation and Air Conditioning (HVAC) unit is a major noise source in a vehicle’s interior space. Reducing this noise will improve the sound quality of the vehicle’s interior space and enhance passengers’ experience. However, current noise control techniques are high-cost and hazardous to environment. Therefore, this paper studies the first ever usage of low-cost, biodegradable natural materials for vehicle’s HVAC noise control. Jute felt and waste cotton were found to have higher sound absorption coefficients than other common sound absorbing natural materials, and were chosen as sound absorbers for noise control treatment of a prototype HVAC unit. Noise sources in the unit were identified and ranked, and the treatment was applied to these. The treatment significantly reduced the noise level (by 4 dBA) and loudness level (by 7 sones) due to the unit at the reference passenger’s ear location, with negligible cost and weight. Sound quality evaluation by 24 participants showed that the treatment significantly reduced the annoyance of the vehicle interior soundscape comprising the HVAC noise. Thus, jute felt and waste cotton are low-cost, light-weight, biodegradable and recyclable natural materials with high potential for HVAC noise control.

1. Introduction

Sound quality of a vehicle interior space is an important aspect of a vehicle and demands special NVH (Noise, Vibration and Harshness) attention. Reducing noise inside a vehicle improves the sound quality of the vehicle interior space, which in turn leads to a higher passenger comfort, better driving experience, and lesser driver distraction. Moreover, reducing noise and improving vehicle interior sound quality enhances a customer’s perception of the vehicle brand; thereby the vehicle attracts more customers and gets a competitive advantage in the market [1,2].

Research and development over the last two decades have led to quieter and better sounding engines. As a result, secondary sound sources located within a vehicle cabin such as heating, ventilation and air-conditioning (HVAC) system, entertainment systems, and audio driver assist systems have become more perceptible to passengers [3]. Among the secondary sources, the HVAC system is the most dominant noise source in a vehicle’s interior space as it operates throughout as long as the vehicle is running. Additionally, the HVAC and blower fan noise reaches the interior space without any sound isolation and can strongly impact passengers’ comfort. In the hot climate of a tropical country like India, a vehicle’s HVAC system operates continuously at higher blower speeds and is one of the most important interior noise sources. Therefore, HVAC noise control is needed to improve the sound quality of the vehicle interior space, and it is gaining growing attention from researchers and manufacturers [3–8].

1.1. Conventional methods for HVAC noise control and sound quality enhancement

The major noise source in the HVAC unit is the aerodynamic blower noise [9–12]. Therefore, the conventional strategy for reducing HVAC noise includes design changes to the blower and its blades [9,10,13,14]. However, the unit examined in this paper was already designed and produced by the manufacturer for optimum performance; hence only noise control strategies at post-production stage are discussed in this paper. Existing post-production noise control techniques include active noise control [4,11,15], and passive noise control using synthetic sound absorbing materials such as micro-perforates [5,6], fiberglass, glass wool and polypropylene [16]. These approaches achieve up to 6–10 dB noise reduction. However, active noise control approaches involve costly equipment, work well only in low frequencies, and are effective only in specific zones of the vehicle interior space. Passive noise control approaches work best at frequencies above \( \approx 500 \text{ Hz} \), and they apply noise reduction throughout the interior space. However, the synthetic sound proofing materials are costly as their manufacturing requires
high-end equipment (for e.g., micro-perforated panels [5,6]) or high-temperature extrusion and synthetic chemical processes (for e.g., fiberglass, glass wool, polypropylene [16]). For the same reasons, these materials have higher carbon footprints, and are neither biodegradable nor recyclable.

1.2. Natural materials for noise control

Due to the discussed disadvantages of synthetic materials, the recent trend in automotive noise control is a shift towards natural materials, also known as natural-fiber materials. Some common sound absorbing natural materials are jute, cotton, flax, kenaf, hemp, coconut coir, bamboo curls, and banana [16–21]. These materials provide good sound absorption, are low-cost, light-weight and biodegradable. Therefore, they have begun to be applied for sound proofing automotive components such as floor carpeting [18] and car boot liners [20].

However, currently there is no research study on the usage and effectiveness of natural material(s) for noise control of a vehicle HVAC system. Testing the effectiveness of natural materials for vehicle HVAC noise control would help in developing low-cost and eco-friendly techniques to enhance vehicle interior sound quality. Furthermore, the existing HVAC noise control case studies ([4–6]) are usually limited in scope as they do not test the effectiveness of the noise control treatment on actual humans. Therefore, there is a need for a systematic case study of a vehicle HVAC noise control using natural materials that tests its effectiveness through human-subject sound quality experiments. Such case studies could guide future NVH engineers across various industries to adopt eco-friendly and human-centered noise control practices.

This paper presents the first ever case study of usage of natural materials, namely, jute felt [22] and waste cotton for noise reduction in a vehicle’s HVAC unit. The other novelty of this paper is that it validates the effectiveness of this noise control treatment through human-subject sound quality evaluation of the HVAC noise and the vehicle interior soundscape comprising the HVAC noise. It also presents a first ever comparison of the sound absorption coefficient of jute felt with other contemporary sound absorbing natural materials. The remaining paper is organized such that Section 2 describes the materials used for noise control. Section 3 describes the test HVAC unit, and its noise evaluation is in Section 4. Section 5 describes the noise source ranking in the unit. Section 6 describes the treatment done on the unit and its noise evaluation. Section 7 describes the sound quality evaluation of the HVAC unit.

2. Details of the natural materials used

Jute is a naturally occurring plant that is readily grown at very low cost in the hot tropical and rainy regions of the eastern parts of India. Jute fiber is a lignin-cellulose fiber composed primarily of cellulose (major component of plant fiber) and lignin (major component of wood fiber). Raw jute fibers have high aspect ratio (length/diameter), high specific modulus, and high tensile strength (see details in [22]). Raw jute fibers are cleaned and spun into a jute yarn. Stacks of jute yarn laid in a definite sequence are pressed under pressure, and the resulting sheets are bonded using natural rubber. The resulting composite is called a “jute felt” (see details in [22]). Jute felt is biodegradable and recyclable, and thus environment-friendly. Jute felt has been extensively tested by Fatima and Mohanty ([22]) and 1% natural rubber treated jute felt is found to have lower flammability than fiberglass, wool and cotton. This jute felt has been shown to have very high normal sound absorption coefficient (see details in [22,23]). Recently, jute felts have been successfully applied to noise control in vacuum cleaners and domestic dryers, [19] and in building semi-anechoic chambers [24].

Experiments were done to compare sound absorption coefficient of a jute felt sample with some of the other existing low-cost sound absorbing natural materials, namely, coconut coir, flax, cotton, wood curls, and rice straw. The experiments were done in Acoustics and Condition Monitoring Laboratory at the Indian Institute of Technology Kharagpur using the two-microphone method in the B&K4206 impedance tube setup as per ISO 10534-2 [25]. The sound absorption coefficient will increase with increase in packing density of these materials. Therefore, for a more valid comparison the samples of these natural materials had similar packing densities within the range of ≈110–155 kg·m⁻³. Table 1 shows the noise reduction coefficient (NRC) values and the densities of these natural materials. Fig. 1 shows the normal specific sound absorption coefficient of these materials. Jute felt was found to have the highest sound absorption coefficient and highest NRC, and was the lightest of the tested materials. Therefore, it was chosen as the primary material for noise control. Waste cotton is more flexible to fit into any shape and it also had good sound absorption, so it was also decided to apply waste cotton, but only in areas such as cavities where jute felt could not be easily applied.

3. Description of the HVAC unit

The HVAC unit used for this case study is a prototype supplied by a manufacturer. It is made of ABS (Acrylonitrile butadiene styrene) plastic and has the following main components – fresh air inlet, recirculation inlet, evaporator, heater, and outlet vents (defrost vent, cabin vent and foot vent). Figs. 2 and 3 show the positioning of the HVAC unit in a car, and the detailed schematic of the HVAC unit respectively. A standard vehicle HVAC unit can operate in either fresh air inlet mode or recirculation inlet mode, so it was also decided to apply waste cotton, but only in areas such as cavities where jute felt could not be easily applied.

![Fig. 1. Sound absorption coefficients of 100 mm thick samples of some common natural materials.](image-url)

<table>
<thead>
<tr>
<th>Sample</th>
<th>NRC</th>
<th>Density (kg·m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jute felt</td>
<td>0.75</td>
<td>108</td>
</tr>
<tr>
<td>Flax</td>
<td>0.70</td>
<td>155</td>
</tr>
<tr>
<td>Waste cotton</td>
<td>0.65</td>
<td>137</td>
</tr>
<tr>
<td>Rice straw</td>
<td>0.65</td>
<td>154</td>
</tr>
<tr>
<td>Wood curls</td>
<td>0.55</td>
<td>110</td>
</tr>
<tr>
<td>Coconut Coir</td>
<td>0.45</td>
<td>108</td>
</tr>
</tbody>
</table>

Table 1 NRC and densities of 100 mm thick samples of some common natural materials.
part of the cooled air is then directly released into the cabin through the cabin vent and towards the windscreen through the defrost vent. The remaining air flow passes through the heat exchanger that consists of a heating coil for heating the incoming air. The heated air is isolated from the cold air flow through the controllable flappers (see Fig. 3(a)). The heated air is released towards the floor of the car through the foot vent. The cabin vent is connected to a duct with two long side vents that release the cold air flow to rear passengers and a central vent at the dashboard to release the cold air flow to the front passengers. The scope of this case study was to test the noise at the location of the front passengers; therefore side ducts were removed from the test HVAC unit. The HVAC unit operates on four different manufacturer-set conditions as summarized in Table 2. These operating conditions were used for all the measurements, and for the sake of convenience these conditions will be referred to as “low speed”, “medium-low speed”, “medium-high speed” and “high speed” conditions from here on.

4. Noise evaluation of the baseline HVAC unit

4.1. Measurement setup

Measurements were done with the prototype HVAC unit at every operating condition. These measurements were referred to as the baseline measurements. The measurements were done in a quiet room at the Acoustics and Condition Monitoring Laboratory of the Mechanical Engineering Department at the Indian Institute of Technology Kharagpur. The overall ambient noise level of the measurement room was 23.7 dBA for all the measurements. Fig. 4 shows a view of the measurement setup.

Three ½” B&K 4189 free field microphones on tripods were used to measure the sound pressure level (SPL) of the sound emitted from every side of the unit. These microphones were placed at positions 2, 3 and 4 of Fig. 4 at 0.01 m from the front, right and left side of the unit at a height of 0.5 m from the ground. Additionally, a microphone was placed at position 1 (see Fig. 4), at a distance of 1.0 m away from the center of the unit and 1.2 m from the ground. This was the reference position provided by the automotive manufacturer as the location of the front passenger’s ear. Later, microphone 1 was replaced with a B&K 4200 D Human Audio Torso Simulator (HATS) to simulate the passenger’s ear more accurately and record binaural sounds which were later used for psychoacoustic analyses and sound quality evaluation.

4.2. Noise evaluation

The binaural sounds measured at position 1 by the HATS were analyzed using PULSE Sound Quality to obtain the SPL and the standard psychoacoustic metrics namely loudness, sharpness, and roughness. Table 3 shows the acoustic and psychoacoustic metrics of the HVAC unit.
noise spectrum at the passenger’s left and right ear position. Fig. 5 shows a typical baseline HVAC noise spectrum (at right ear) at medium-high blower speed.

The manufacturer had set the target SPL at medium-low speed as 65 dBA. However, the average baseline SPL at that speed was 68.4 dBA, which was higher than the accepted level. It was further observed that loudness level of the baseline HVAC unit at medium-high and high speed conditions had crossed 32 sones, which is the threshold for hearing damage during long-term exposure. Thus, there is a need to reduce the noise level and loudness level of the HVAC unit.

5. Noise source identification

As part of the standard noise control strategy, first an experimental modal analysis was performed to check if the set operating conditions were exciting the unit at any of its natural frequencies. This was followed by noise source ranking of the HVAC unit.

5.1. Experimental modal analysis (EMA)

An EMA was performed to find out the natural frequencies of the HVAC unit so as to check if the driving frequencies at the set operating conditions corresponded to any of the natural frequencies of the unit. A random excitation was provided at a 45° angle by a B&K 4824 electromagnetic exciter (Fig. 4, sensor 5) driven by a B&K 2732 power amplifier in the frequency range 0–2 kHz. The excitation force was measured by a B&K 8002 force transducer and the unit’s vibration response was measured by a laser vibrometer Polytec PDV 100 (Fig. 4, sensor 6). The natural frequencies of the HVAC unit were found to be 157.5 Hz, 295 Hz, 320 Hz and 875 Hz. The major noise in the HVAC unit is the aerodynamic noise of the air entering the unit through the

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Blower speed indicator position</th>
<th>Blower motor terminal voltage (V)</th>
<th>Blower motor speed (RPM)</th>
<th>Air outlet speed at cabin vent (m/s)</th>
<th>Air inlet speed at recirculation vent (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low speed</td>
<td>7.0</td>
<td>2442</td>
<td>8.3</td>
<td>3.9</td>
</tr>
<tr>
<td>2</td>
<td>Medium-low speed</td>
<td>9.0</td>
<td>2958</td>
<td>10.4</td>
<td>5.1</td>
</tr>
<tr>
<td>3</td>
<td>Medium-high speed</td>
<td>10.5</td>
<td>3342</td>
<td>11.4</td>
<td>5.5</td>
</tr>
<tr>
<td>4</td>
<td>High speed</td>
<td>12.5</td>
<td>3702</td>
<td>13.2</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Fig. 4. Measurement setup.

![Measurement setup](image)

Table 2
Operating conditions of the HVAC unit.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Blower speed indicator position</th>
<th>Measurement channel</th>
<th>SPL (dB)</th>
<th>SPL (dBA)</th>
<th>Loudness (sones)</th>
<th>Sharpness (acums)</th>
<th>Roughness (asper)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low speed</td>
<td>Left ear</td>
<td>66.3</td>
<td>63.2</td>
<td>19.3</td>
<td>1.43</td>
<td>1.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right ear</td>
<td>67.2</td>
<td>63.9</td>
<td>20.1</td>
<td>1.43</td>
<td>1.42</td>
</tr>
<tr>
<td>2</td>
<td>Medium-low speed</td>
<td>Left ear</td>
<td>71</td>
<td>68</td>
<td>25.7</td>
<td>1.49</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right ear</td>
<td>71.9</td>
<td>68.8</td>
<td>26.9</td>
<td>1.48</td>
<td>1.53</td>
</tr>
<tr>
<td>3</td>
<td>Medium-high speed</td>
<td>Left ear</td>
<td>73.8</td>
<td>71.1</td>
<td>30.8</td>
<td>1.52</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right ear</td>
<td>74.3</td>
<td>71.5</td>
<td>32</td>
<td>1.52</td>
<td>1.39</td>
</tr>
<tr>
<td>4</td>
<td>High speed</td>
<td>Left ear</td>
<td>76.1</td>
<td>73.5</td>
<td>35.9</td>
<td>1.56</td>
<td>1.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right ear</td>
<td>76.7</td>
<td>74.1</td>
<td>37.4</td>
<td>1.56</td>
<td>1.46</td>
</tr>
</tbody>
</table>

Fig. 5. A typical baseline HVAC noise spectrum at medium-high blower speed.
from the blower motor RPM, \( N_b \) as: 
\[
fb = \frac{N_b}{60}
\]
The blade pass frequency is \( fbpf = 43 \times \frac{N_b}{60} \) (here number of blades = 43).

### Table 4
Driving frequencies and natural frequencies of the HVAC unit.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Condition</th>
<th>Blower motor speed (RPM)</th>
<th>Measured natural frequency (Hz)</th>
<th>Blower motor frequency (Hz)</th>
<th>Blade pass frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low speed</td>
<td>2442</td>
<td>157.5</td>
<td>40.7</td>
<td>1750.1</td>
</tr>
<tr>
<td>2</td>
<td>Medium-low speed</td>
<td>2958</td>
<td>295.0</td>
<td>49.3</td>
<td>2119.9</td>
</tr>
<tr>
<td>3</td>
<td>Medium-high speed</td>
<td>3342</td>
<td>320.0</td>
<td>55.7</td>
<td>2395.1</td>
</tr>
<tr>
<td>4</td>
<td>High speed</td>
<td>3762</td>
<td>875.0</td>
<td>61.7</td>
<td>2653.1</td>
</tr>
</tbody>
</table>

The dominant noise sources in the HVAC unit were identified using sound intensity measurements. A B&K 2260 two microphone sound intensity probe with 12 mm spacing was used to measure the sound intensity all around the unit, by roving the hand-held probe (see Fig. 6) at a perpendicular distance of 0.01 m from the different surfaces of the unit. Table 5 shows the noise source ranking of the HVAC unit based on the 30-s-mean sound intensity level radiating from the different noisy sources. The radiated noise was the highest from the recirculation inlet. From the principles of noise control, the noise must be reduced at the most noisy source, here the recirculation inlet, to significantly bring down the SPL. Thus, the recirculation inlet must be treated. Other noisy sources were the defrost vent and the cavity near it. Thus, it was decided to use sound absorbing materials at these locations.

### 5.2. Noise source ranking

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### 6. Noise evaluation of the treated HVAC unit

As discussed in Section 2, jute felt and waste cotton were chosen as materials for noise control. A number of treatments were tried and tested and the treatment that maximized the noise reduction while minimizing the cost and weight was finalized and is described below:

### 6.1. Proposed noise control treatment

The final treatment applied to the baseline HVAC unit primarily consisted of lining recirculation inlet and other air flow paths with jute felt, and stuffing the cavities with waste cotton. The detailed treatment is described in Table 6, Figs. 7 and 8.

### 6.2. Evaluation of the treated HVAC unit

The resultant HVAC noise was measured and analyzed using the same setup as used for baseline measurements (see Fig. 4). Table 7 shows the acoustic and psychoacoustic metrics of the HVAC noise spectrum at the passenger’s ear position after applying the treatment. Fig. 9 shows the typical HVAC noise spectrum (at right ear) at medium-high blower speed after applying the treatment. Compared to the baseline, the treatment resulted in a reduction of SPL by 4 dBA (3.7 dB) at the passenger’s ear position (a minimum SPL reduction of 3.6 dBA per blower speed). Further, the treatment significantly reduced the HVAC’s loudness level by 7 sones (24% reduction). However, there was no significant change in sharpness and roughness. In Section 4.2, it was found that the loudness of the original HVAC system had crossed the threshold for hearing damage during long-term exposure (32 sones) at medium-high and high speeds. This problem was solved by applying the proposed treatment, as it resulted in the loudness levels of the HVAC unit to be less than 30 sones at every blower speed. Thus, the treated HVAC unit was deemed safer for long term sound exposure.

An anemometer was used to measure the outlet air speed at the cabin vent after applying the treatment. There was no change in the outlet air speed at every operating condition. The proposed treatment costed approximately $0.5 and weighed approximately 0.15 kg (≈3% of the total weight of the baseline HVAC unit). Based on the objective data, the proposed treatment was deemed effective as it reduced the noise and loudness level significantly with negligible cost and weight, and without compromising the air flow performance of the original HVAC unit.

### 7. Experiments for sound quality evaluation of the HVAC unit

Finally, this case study tested the effectiveness of the applied treatment on actual humans through a human-subject evaluation of the “annoyance” of the baseline and the treated HVAC sounds. The experiment details are given below:

#### 7.1. Participants

Data was collected from 24 adult participants, 9 females and 15 males, with a mean age of 32 years (SD = 8.47 years). The participants included 18 institute staff and students and 6 people from outside the academia.

#### 7.2. Sound samples

Two sets of experiments were conducted. In the first set of experiments, participants had to evaluate 5 s sound samples of the HVAC noise recorded binaurally at the manufacturer specified reference position of a passenger’s ear (see Fig. 4, position 1). Total 8 sounds were used for evaluation corresponding to the sounds of the baseline and the treated HVAC unit running at the four different operating speeds.

However, testing the HVAC sounds without any background soundscape is not sufficient, because in a real car the HVAC unit runs in conjunction with other noise sources such as engine noise, road-tire interaction noise, etc. Noises due to the mentioned sources reach vehicle interior space after attenuation by the vehicle body acting as noise barrier. Therefore, the second set of experiments were conducted. Here, sound was recorded using binaural headphones placed in the ears of a front passenger inside a closed BMW 3 series 320i car, running at the speed of 35 kph (≈9.72 ms⁻¹) in the Institute campus with HVAC shut off. A 5 s segment of this recording (53.5 dBA (58 dB)) (see Fig. 10) was used as the background soundscape. Eight sounds samples were prepared by adding each HVAC sound to this background soundscape by superimposing their respective wavefronts in MATLAB.

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**Fig. 6.** Sound intensity measurement for noise source ranking.
7.3. Experimental design

This experiment aimed to test if a passenger/person would prefer HVAC sounds after the treatment over the baseline sounds and by how much. Therefore, a paired comparison listening evaluation was deemed more relevant and was used as the method for data collection. Moreover, in a pilot evaluation, the paired comparison method was found easier to use by non-expert assessors whereas, the usual method of data collection, namely, semantic differential scales, was found difficult to use and inappropriate for the task at hand. Table 8 lists the sound pairs used for comparison. Within each participant every sound pair was repeated twice in the reverse order to check reliability and eliminate the order effect. A repeated measures design was chosen for this experiment. Thus, every participant listened to all 8 sound pairs in a pre-determined sequence randomized by 8 × 8 Latin Square method. This ensured there was no bias due to sequence effect.

7.4. Sound quality measures

Research shows that effect of HVAC noise exposure or in general any environmental noise exposure on humans is usually expressed through the semantics of “annoyance” and/or “pleasantness” [3,7,8,26,27]. A pilot study was conducted asking people to rate HVAC sounds on these attributes. It was found that people found HVAC sounds synonymous to a machine noise and related “annoyance” but not “pleasantness” as its attribute. Hence, in the presented experiment, participants were asked to judge the “annoyance” due to the sounds from the HVAC unit.

7.5. Evaluation environment

Experiments were conducted in an enclosed quiet room (background ≈ 24 dBA) within the Acoustics Laboratory at IIT Kharagpur. The sounds used for the experiments had been recorded binaurally at the front passenger ear location with reference to the HVAC unit.
position. Thus, it was assumed that each listener for these experiments was a front passenger. Accordingly, every participant sat on a chair and listened to the sounds through a binaural headphone.

7.6. Procedure

The sounds appeared in pairs on a computer screen (see Fig. 11). Participants listened to the 8 sound pairs one by one via the binaural headphone. For each pair, they selected the sound they found as “less annoying”. A free-play paired comparison method [28] was used, i.e., participants could listen to the sounds in each pair as many times as necessary.

Table 7
Acoustic and psychoacoustic metrics of HVAC noise spectrum after treatment.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Operating condition</th>
<th>Measurement channel</th>
<th>SPL (dB)</th>
<th>SPL (dBA)</th>
<th>Loudness (sones)</th>
<th>Sharpness (acums)</th>
<th>Roughness (asper)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low speed</td>
<td>Left ear</td>
<td>62.8</td>
<td>59.4</td>
<td>13.7</td>
<td>1.42</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right ear</td>
<td>63.3</td>
<td>59.8</td>
<td>14.1</td>
<td>1.41</td>
<td>1.55</td>
</tr>
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<td>2</td>
<td>Medium-low speed</td>
<td>Left ear</td>
<td>67.4</td>
<td>64.4</td>
<td>19.6</td>
<td>1.47</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right ear</td>
<td>68.0</td>
<td>64.7</td>
<td>19.9</td>
<td>1.47</td>
<td>1.59</td>
</tr>
<tr>
<td>3</td>
<td>Medium-high speed</td>
<td>Left ear</td>
<td>70.0</td>
<td>67.3</td>
<td>23.7</td>
<td>1.51</td>
<td>1.41</td>
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<td>Right ear</td>
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<td>24.3</td>
<td>1.52</td>
<td>1.52</td>
</tr>
<tr>
<td>4</td>
<td>High speed</td>
<td>Left ear</td>
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<td>69.8</td>
<td>28.4</td>
<td>1.54</td>
<td>1.56</td>
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<tr>
<td></td>
<td></td>
<td>Right ear</td>
<td>73.0</td>
<td>70.1</td>
<td>29.0</td>
<td>1.56</td>
<td>1.46</td>
</tr>
</tbody>
</table>

Fig. 9. A typical HVAC noise spectrum after treatment at medium-high blower speed.

Fig. 10. Spectrum of the car interior soundscape used for sound quality experiments.

Table 8
Sound pairs used for paired comparison.

<table>
<thead>
<tr>
<th>HVAC operating condition</th>
<th>HVAC sounds being compared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1</td>
<td>Low speed</td>
</tr>
<tr>
<td>Pair 2</td>
<td>Medium-low speed</td>
</tr>
<tr>
<td>Pair 3</td>
<td>Medium-high speed</td>
</tr>
<tr>
<td>Pair 4</td>
<td>High speed</td>
</tr>
<tr>
<td>Pair 5</td>
<td>Low speed</td>
</tr>
<tr>
<td>Pair 6</td>
<td>Medium-low speed</td>
</tr>
<tr>
<td>Pair 7</td>
<td>Medium-high speed</td>
</tr>
<tr>
<td>Pair 8</td>
<td>High speed</td>
</tr>
</tbody>
</table>

Pair 1 Low speed Baseline Vs Treatment
Pair 2 Medium-low speed Baseline Vs Treatment
Pair 3 Medium-high speed Baseline Vs Treatment
Pair 4 High speed Baseline Vs Treatment
Pair 5 Low speed Treatment Vs Baseline
Pair 6 Medium-low speed Treatment Vs Baseline
Pair 7 Medium-high speed Treatment Vs Baseline
Pair 8 High speed Treatment Vs Baseline
they wanted and in any order. This is because free play is more accurate and user-friendly than the conventional fixed play (where participants can listen to sounds only once in fixed order) [28]. Participants also had an option to select “no significant difference”, if they found both sounds in a pair similarly annoying. This ensured that the paired comparison was not a forced choice task, and only a significant difference in annoyance was recorded. The full procedure was repeated for the two sets of HVAC sound samples (without/ with car interior background soundscape) at a gap of two months.

7.7. Analysis

In paired comparison method, the quantitative scores for every sound sample is calculated using the Bradley-Terry model [29,30]. The sound scores are represented by the following terminologies:

- **Pair probabilities** ($P_{ij}$): It is the probability of listeners to pick sound i over sound j.

\[
P_{ij} = \frac{\text{No. of times sound } i \text{ is preferred over sound } j}{\text{No. of times sound } i \text{ is compared with sound } j}
\]

- **Normalized merit scores** ($M_i$): The normalized merit score for a sound is calculated using Eq. (2) where, $N$ is the number of sounds being compared [28]. The sum of merit scores of all sounds is zero. The sounds with negative merit scores are rejected and sounds with positive merit scores are selected.

\[
M_i = \frac{1}{N} \sum_{ij} \ln \left( \frac{P_{ij}}{P_{ji}} \right)
\]

In the Bradley-Terry model, the hypothesis that “one sound is significantly better than the other” can be tested at a 95% confidence interval by calculating the critical difference ($\Delta_{95}$) as follows [30]:

\[
\Delta_{95} = 1.64 \left( \frac{NT^{\frac{1}{2}}}{2} \right) + 0.5
\]

where $T$ is the total number of comparisons made, which is, the total number of listeners multiplied by the number of times a sound pair appears within each listener evaluation. The test of significant difference is done as follows [30]:

\[
\begin{align*}
&\text{If } N_i - N_j > \Delta_{95} \Rightarrow \text{“Sound } i \text{ is significantly better than sound } j\text{”} \\
&\text{If } N_i - N_j \leq \Delta_{95} \Rightarrow \text{“No significant difference between sound } i \text{ and sound } j\text{”}
\end{align*}
\]

7.8. Results of sound quality evaluation

Tables 9 and 10, Figs. 12 and 13 show the percentage pair

<table>
<thead>
<tr>
<th>Table 9</th>
<th>Percentage probability of preferring treated HVAC sounds over baseline HVAC sounds.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition</td>
<td>Comparisons made with baseline</td>
</tr>
<tr>
<td>Low speed</td>
<td>48</td>
</tr>
<tr>
<td>Medium-low speed</td>
<td>48</td>
</tr>
<tr>
<td>Medium-high speed</td>
<td>48</td>
</tr>
<tr>
<td>High speed</td>
<td>48</td>
</tr>
<tr>
<td>Total</td>
<td>192</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 10</th>
<th>Percentage probability of preferring treated HVAC sounds over baseline HVAC sounds in the presence of car interior soundscape.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition</td>
<td>Comparisons made with baseline</td>
</tr>
<tr>
<td>Low speed</td>
<td>48</td>
</tr>
<tr>
<td>Medium-low speed</td>
<td>48</td>
</tr>
<tr>
<td>Medium-high speed</td>
<td>48</td>
</tr>
<tr>
<td>High speed</td>
<td>48</td>
</tr>
<tr>
<td>Total</td>
<td>192</td>
</tr>
</tbody>
</table>
probabilities for preferring treated HVAC sounds over the baseline HVAC sounds, and the merit scores for the baseline and treated HVAC sounds for every operating condition and overall. Tables 9 and 10 also show the result of test of significant difference between baseline and the treated HVAC sounds. It is found that a very high percentage of the listeners (80.2%) preferred the HVAC sounds after the treatment over the baseline HVAC sounds, with as well as without the presence of the car interior soundscape. Moreover, the listeners’ preferences of the treated HVAC sounds over baseline sounds are statistically significant for every operating condition and overall. Thus, the applied treatment improved the sound quality of a vehicle interior space by causing a significant reduction in the annoyance of the HVAC sound, and also in the annoyance of the overall vehicle interior soundscape (comprising that HVAC sound). This is also supported by the merit scores data where the treated HVAC sounds score positive and the baseline sounds score negative for every operating condition and overall.

8. General discussions and future recommendations

This case study demonstrates the potential of jute felt and waste cotton as light-weight, low-cost, biodegradable and recyclable natural materials for vehicle HVAC noise control. Jute felt and waste cotton were tested to have higher sound absorption coefficients than many of the existing low-cost sound absorbing natural materials. The major noise source of the HVAC unit was the aerodynamic flow that was noisiest at the recirculation inlet. Therefore, a proposed natural material-based noise control technique involves lining jute felts along the recirculation inlet vent, outlet vents, and other locations in the path of the air flow. Moreover, cavities unassociated with air flow path should be sealed with waste cotton.

This natural material-based treatment was able to reduce HVAC noise level at the passenger ear location by an average of 4 dBA at all blower speeds. This reduction can be called significant as the minimum noise level reduction perceptible by a human ear is 2 dB, and every 3 dBA noise reduction is said to double the permissible human noise exposure duration. In the human-subject sound quality experiments, 80.2% people preferred a typical car interior soundscape with the treated HVAC sounds over the soundscape with the baseline HVAC sounds. Both, the treated HVAC sounds and the car interior soundscape comprising these treated sounds had statistically significant lower annoyance (95% confidence interval) at all blower speeds. From these results, it can be concluded that the treatment has a potential to improve sound quality of a vehicle interior space. This is further supported by psychoacoustic analyses showing a loudness level reduction of 7 dB.
sones, and previous studies find direct correlation between loudness level and annoyance/pleasantness of an HVAC unit [3,7,8].

The current study was conducted on a ductless HVAC prototype isolated from the rest of the vehicle. The measurements of noise level and psychoacoustic metrics would change when the HVAC unit is installed inside the car, but the general trend of noise reduction and perception of sound quality should remain the same.

9. Conclusions

The paper presents a case study of first ever usage of natural materials for a vehicle’s HVAC noise control. Jute felt and waste cotton are shown to have higher sound absorption coefficients than other contemporary sound absorbing natural materials, and are chosen for noise control treatment. The major noise source of the HVAC unit is the aerodynamic flow that is noisiest at the recirculation inlet. Thus, proposed noise control treatment involves reducing the aerodynamic noise by lining recirculation inlet vent, outlet vents and other air flow paths with sound absorbing jute felt and sealing unwanted cavities with waste cotton. This treatment is very effective as it significantly reduces the SPL (by 4 dBA) and loudness level (by 7 sones), with only negligible weight (3% of total unit’s weight) and cost ($0.50), and without reducing the HVAC air flow. Moreover, the treatment results in a significantly lesser annoyance and better perceived sound quality of the vehicle interior space. Thus, jute felt and waste cotton are low-cost, light-weight, biodegradable and recyclable natural materials with high potential for HVAC noise control.

Acknowledgements

We would like to thank the students and staff at the Mechanical Engineering Department, IIT Kharagpur for participating in our sound quality experiments. We also thank Mr. Manish Kumar Singh for his suggestions on the experimental design of the sound quality experiment.

References


