Sound quality improvement of a high speed hand dryer

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The latest Dyson Airblade™ hand dryer has been developed specifically with its sound quality in mind. This product is a high speed hand dryer comprised of two high velocity sheets of air which wipe the water from the user's hands leaving them dry in 12 seconds. It has been found that the subjective perception of the noise generated by the hand dryer does not fully correlate with the measured sound power level. As such, the parameters driving the subjective sound quality were investigated.
To assess the sound quality of the hand dryer, a paired comparison test was carried out using binaural recordings of various hand dryer models. The psychoacoustic metrics of loudness and tonality were identified as key parameters and a pleasantness model was derived based on these results. The high tonality observed in early prototypes of the hand dryer contributed to a low sound quality as identified by the pleasantness model. To further understand the influence of these tonal components, detection and annoyance thresholds of tonal noise embedded within a representative broadband noise signal were identified using a staircase method.
This work focussed on the reduction of tonal noises related to the rotational speed of the compressor. Several solutions were proposed and these were subsequently evaluated using the pleasantness model and annoyance threshold. The finalised design incorporates a dissipative silencer and Helmholtz resonators. This paper presents details of the design of these acoustic solutions and their benefits to the subjective acoustic quality.

1 Introduction

Recent studies [1, 2] have investigated the effects of the noise levels of high speed hand dryers on the population. Among the concerns raised in these studies were the loudness of such products and the high frequency content of the noise.

The Dyson Airblade™ hand dryer has been used to support and validate the current study. Firstly a description of this particular hand dryer is presented. The measurement set-up and a description of the acoustic spectrum is also presented.

Secondly, a sound quality assessment of the noise of high speed hand dryers has been carried out by means of a paired comparison test. The results of this test allow the development of a specific metric of pleasantness. This model can then be used to assess the pleasantness of new prototypes during development.

Finally, a description of the tonal components is provided along with the acoustic solutions to reduce them. Specific perceptive tests and metrics have been developed to quantify the improvement of the proposed acoustic solution. The design process highlighted in this document has mainly been informed by the sound quality and more specifically by the tonality.

2 Description of the case study

In this section a presentation of the high speed hand dryer used to support this work is carried out along with the measurement set-up and a succinct description of its acoustic spectrum.

2.1 The Dyson Airblade™ hand dryer

The Dyson Airblade™ hand dryer is a high speed hand dryer [3]. A schematic diagram of such a hand dryer is shown in figure 1. The air is drawn-in through a HEPA filter using a compressor and pushed through small apertures creating two opposing high velocity sheets of air. The two high velocity sheets of air wipe the water from the user's hands, leaving them dry in 12 s. This approach has been proven to be more hygienic than traditional warm air evaporative hand dryers [4].

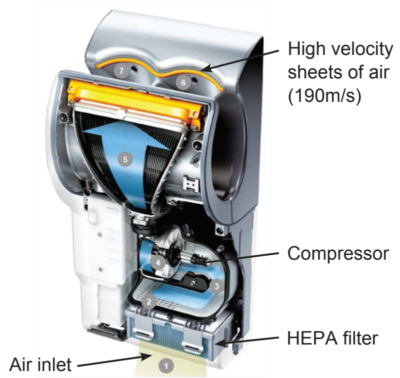

Figure 1: Illustration of a Dyson Airblade™ hand dryer.

2.2 Measurement set-up

The measurement set-up used for this work is shown in figure 2. The measurements were carried out in a semi-anechoic chamber using a binaural recording system (SQuadriga from HEAD acoustics). Although not representative of the acoustics of a typical bathroom, the controlled acoustic environment reduces the number of variables enabling consistency across repeat measurements and fair comparisons. The hand dryers were arranged horizontally with the solid floor representing a wall. The headset was mounted on a dummy head and was placed 500 mm above the floor and 600 mm away from the top of the hand dryer.

Considerable variability was observed when trying to simulate the effect of human hands by placing obstructions in the flow path. To avoid introducing any uncontrollable artefacts, all the measurements were made with no obstructions - "hands-out" operation.

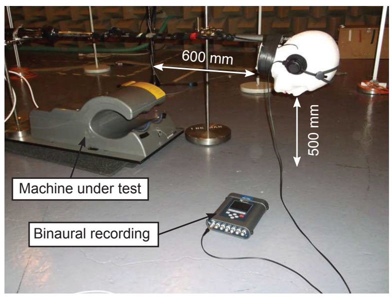

Figure 2: Experimental set-up to measure the noise from high speed hand dryers.

2.3 Acoustic spectrum

The acoustic spectrum of the high speed hand dryer used as a baseline (named AB03) is plotted in blue in figure 3. It can be noted that the spectrum is mainly broadband. The fundamental tone associated with the running speed of the compressor at approximately 85 kRPM (equivalent to ≈ 1.42 kHz) is barely visible in the spectrum whereas, the blade pass frequency tone located at 12.8 kHz (9-bladed compressor) clearly emerges from the broadband.

The high velocity jets are the main contributors to the broadband signal whereas, the tonal components are due to the compressor.

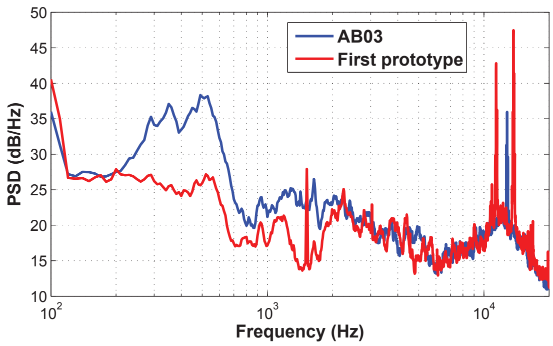

FIGURE 3: Acoustic spectrum of high speed hand dryers comparing baseline machine AB03 (in blue) with a first prototype (in red).

3 Sound quality assessment

In order to assess the sound quality of high speed hand dryers, a listening study was conducted. This test was intended to link the user's perception with psychoacoustic metrics. The resulting model can then be used to assess a first prototype.

3.1 Pleasantness study

A subjective scale was established by means of a paired comparison test. The sounds were presented in pairs and participants had to decide which of the two hand dryer sounds (A or B) they found most pleasant. The sounds were presented automatically without the option for replay, forcing the participant to make a choice based on their first impression.

Sounds from 7 different high speed hand dryers (including one AB03) were used in this test leading to 21 comparisons per participants. The recordings used have been measured according to the set-up described in section 2.2 and the sounds were played back from a laptop using Sennheiser HD600 open back headphones.

Consistency checks were carried out on each participant and on the final pool data. Using the answers from the 34 consistent participants, a subjective scale was constructed. This subjective scale was estimated using a Least Square method, applying the Bradley-Terry's Logistic model, as described in [5]. The ratio-scale results of subjective pleasantness are shown in blue in figure 4, with the machines arranged in order of increasing subjective pleasantness from left to right.

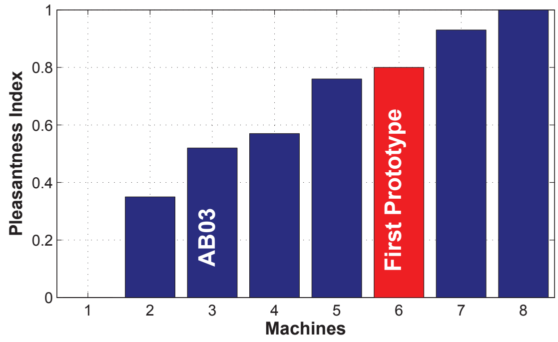

FIGURE 4: Results from the pleasantness study.

3.2 Pleasantness index model

A regression analysis was carried out to define a subjective pleasantness model based on a series of psychoacoustic metrics. This model can then be used to compare the subjective pleasantness of the sound of a new hand dryer without performing another round of listening tests.

The regression was performed using common psychoacoustic metrics (loudness, sharpness, tonality, roughness, fluctuation strength, etc.). The subjective pleasantness was found to correlate best with the total loudness, measured in Sone and the average tonality expressed in tonality unit (Tu). The loudness was calculated according to the ISO standard [6]. The metric of tonality is based on the time-varying Aures and Terhardt model [7], for which a detailed explanation is given in [8]. The value of tonality used corresponds to the average value of the time-varying tonality.

The pleasantness model resulting from this study takes the form of:

$$\text{Pleasantness Index} = \alpha_1 \times \text{Loudness} + \alpha_2 \times \text{Tonality} + \alpha_0 \quad (1)$$

where $\alpha_1 = -0.04$, $\alpha_2 = -2.00$ and $\alpha_3 = 2.72$. The determination factor achieved by this model is 98 %. Moreover, the p-values indicate that both metrics are relevant as they reach less than 5 % significance level. The accuracy of the pleasantness model is illustrated in figure 5.

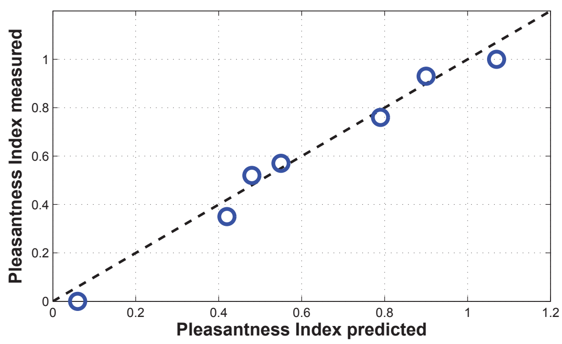

FIGURE 5: Evaluation of the pleasantness index model.

3.3 Evaluation of the first prototype

A first prototype was engineered with the intention of reducing the loudness of the hand dryer by focussing on the main source of broadband noise (i.e. the high velocity jets).

By increasing the aspect ratio of the jets and modifying the angle between the two opposing jets, a significant reduction in loudness was achieved without sacrificing the drying performance of the machine. This reduction in broadband noise can be seen in figure 3.

Furthermore, this prototype was powered by a new compressor operating at a higher running speed (approximately 91 kRPM). A consequence of reducing the broadband noise was the emergence of the fundamental tone associated with the running speed of the motor at 1.52 kHz. This first iteration of the new compressor also exhibits a high blade pass frequency tone at 13.69 kHz (9-bladed compressor) and a resonance located at 11.39 kHz.

The compressor was spring mounted within the machine providing a structural compliance to reduce the transmission of vibrations. Furthermore, a source identification study highlighted the outlet of the motor as carrying most of the tonal components.

The pleasantness index associated to this first prototype was computed according to equation (1). The result, in red in figure 4, shows a clear improvement compared with the baseline hand dryer. This improvement is mainly driven by the reduction in loudness. As further reduction in loudness was expected to have a detrimental effect on the drying performance of the machine, the focus was shifted to improving the tonality. This was accomplished by reducing the fundamental tone and the high-frequency tonal components.

4 Improving the tonal content

After describing the tonality metric, an acoustic solution is proposed to reduce the fundamental tone. The high frequency tones cannot be detected by the tonality algorithm. Therefore, to assess the benefit of the acoustic solutions for these tones, a dedicated metric was developed and evaluated.

4.1 The tonality metric

To assess the reduction in the fundamental tone, the metric of tonality defined in [7, 8] was used. This metric relates to the perception of tonal components within a signal and is measured in tonality unit (Tu). A value of 1 Tu corresponds to the tonality perceived from a pure tone of a magnitude of 60 dB at a frequency of 1 kHz.

A tone can be identified as a peak in the spectrum. Once the peaks are identified, masking effects from the surrounding broadband and other tones which are close in frequency are accounted for. The original algorithm from Aures considers only tones below 5 kHz.

4.2 Reduction of the fundamental tone level

When investigating the acoustic solutions for the fundamental tone, it became apparent that a reactive silencer would be more appropriate. A dissipative silencer (using foam or felt) would have required a prohibitively large volume of sound absorbing material to provide effective attenuation at this frequency. The reactive solution is particularly applicable to the fundamental tone for a number of reasons:

- A large proportion of the motor tone is carried by the outlet duct, making a silencer in this area effective.
- The running speed of the motor results in a fundamental tone sufficiently high in frequency that the reactive silencer is of a practical size.
- The running speed of the compressor is stable and predictable. The motor used in this machine is a constant power motor which is intrinsically less susceptible to variations in running speed due to drifts in supply voltage.

The Helmholtz resonator was chosen as the silencing solution mainly because of packaging reasons.

When designing exhaust silencers, it is important to take the temperature rise induced by the motor into consideration as it will have an effect on the speed of sound and thus the operational frequency of the Helmholtz resonator. The operational frequency of the Helmholtz was therefore designed so that it matched the initial specification of the machine. During the life of the product, as the restriction increases due to loading of the HEPA filter, the flow rate is reduced. Consequently the speed of the motor and the exhaust temperature increase but so does the frequency of the Helmholtz resonator. This extends the useful operation of the Helmholtz over product life.

In order to validate the design of the Helmholtz resonator array, a finite element analysis was performed on the airway surrounding the array. Figure 6 shows contours of sound pressure level in dB at the operational frequency of the Helmholtz resonators (1.52 kHz). The effectiveness of the Helmholtz array can clearly be seen as the sound pressure level decreases further from the compressor. It is worth noting that the sound pressure level in the resonators is very high at the operational frequency of the silencer and by forming the cavities as a separate internal part, noise breakout from the cavities is reduced. A picture of the final Helmholtz array is shown in figure 9.

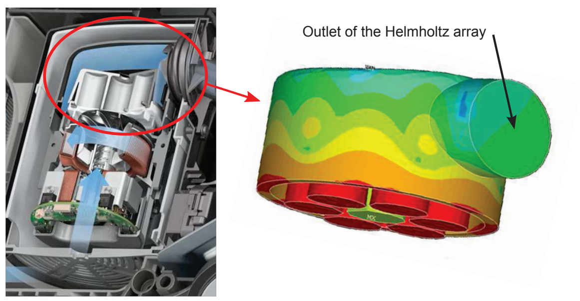

Figure 6: Integration of the Helmholtz array at the outlet of the compressor (left) and sound pressure level at the fundamental tone predicted by finite element analysis (right).

To quantify the effectiveness of the proposed solution on the tonality, development hand dryers were constructed with and without the acoustic control features and compared. The Helmholtz resonator array was developed as an integral component of the motor housing and significantly modifies the flow path. Simply removing this component from the motor housing would alter the machine performance, making comparisons between prototypes with and without the array difficult to interpret. For this reason prototypes were developed with the Helmholtz array housing in place, but the necks of the resonators were either blocked or open depending on the configuration under test. Sound recordings were made following the same procedure as outlined in section 2.2 using the same set-up shown in figure 2.

The acoustic spectrum of the first prototype is compared to the machine with the Helmholtz array. Figure 7 shows a reduction in the fundamental tone level by almost 10 dB. More importantly the tonality metric gives a reduction from 0.036 Tu to 0.011 Tu leading to a further improvement in pleasantness index.

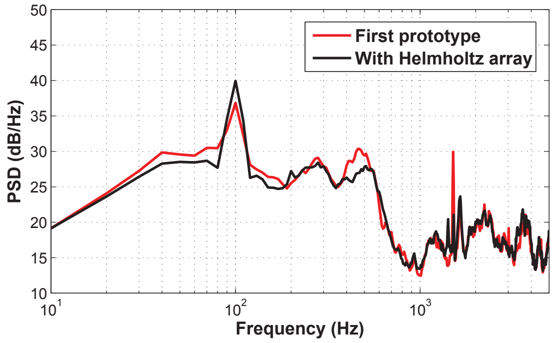

FIGURE 7: Effect of the Helmholtz array on the acoustic spectrum. The spectrum has been limited to 5 kHz to reflect the highest frequency considered by the tonality metric.

4.3 Blade passing frequency tone

As explained in section 4.1, the tonality metric only considers frequencies below 5 kHz. At high frequencies, the noise intensity level increases with frequency as the number of power spectral lines per critical band is higher. Therefore, for a tone at high frequencies to be audible, its level has to be higher than the noise intensity level.

For high speed hand dryer, it is beneficial to be able to quantify the subjective effects of these high frequency tones. Therefore, the tonality algorithm was extended in order to account for high frequency tones. This "in-house" metric has been achieved by lowering the audible limit (which is defined in [7]) by 1 dB/kHz above 3 kHz to enable the detection of high frequency tones. Although this modification was chosen arbitrarily the motivation was to enhance sensitivity of tone detection at high frequency. This new metric will be expressed in HFTu (standing for High Frequency Tonality unit). To understand and interpret this new metric, thresholds of perception and annoyance were determined.

A double staircase method was chosen to estimate the thresholds of perception and annoyance produced by these high frequency tones. In the staircase method, the intensity of the stimulus starts significantly higher or lower than the threshold. If the first presented stimulus intensity is set below the threshold, the experimenter will keep increasing the intensity in fixed step sizes, until the participant changes their response. For instance, to test a threshold of annoyance, the first stimulus starts at a low tonality level which is known to be pleasant. The intensity of the tone is then increased for as long as the participant states not to be annoyed. Once a tonality level which annoys the participant is reached, the intensity of the stimulus is decreased. The test will continue until a certain number of reversals take place. A reversal is defined as a change in the participant response.

In the double staircase method, two staircases are run simultaneously, randomly switching from one to the other, one starting at a very low value of tonality and the other starting at a high value.

The advantage of this method is that the values of tonality presented are adapted according to the participant's responses. The participants were asked whether they could hear a tone or not. If they could hear it, they were then asked if they thought it was annoying or not. The results of the study were therefore not limited by a discrete set of stimuli, but on data that slowly converge towards the threshold of the individual participant.

A total of 40 sound samples were generated by adding up to four tones of random frequency above 5 kHz. The intensity of the tones was also randomised. The length of the signals presented to the participants was 2 s. The stimuli covered a wide range of high frequency tonality from 0 – 0.250 HFTu. 50 participants took part in this test.

The thresholds of perception and annoyance were estimated by fitting a psychometric function to the data gathered as shown in figure 8, using a method detailed in [9]. These psychometric functions have a sigmoid shape and measure the probability of the signal as being perceived or as being annoying. The function reveals the sensitivity of the sensory mechanism underlying the subjective experience. The results show thresholds of 0.04 and 0.09 HFTu for perception and annoyance respectively.

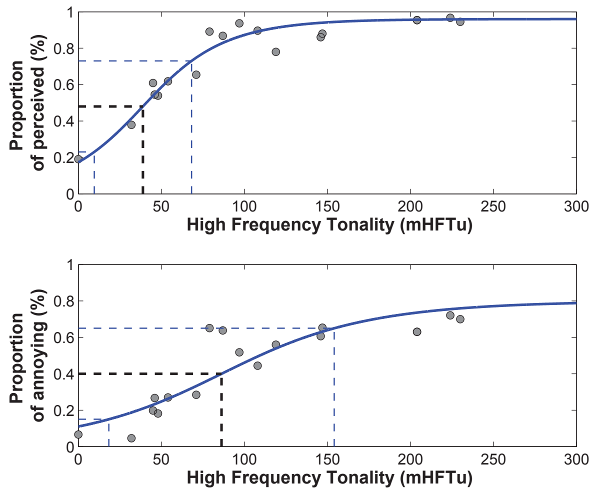

FIGURE 8: Proportion of perceived and annoying stimuli regarding the tonality value.

In figure 8, the perception threshold study gives a very good fit with subjective data. For the annoyance threshold, the fit is not as good, mainly because the annoyance is also driven by the loudness of the stimuli.

For the two high frequency tones identified in section 3.3, dissipative silencers should be effective without having to be physically large. An experimental investigation led to a 3 mm thick felt lining being placed in the motor exhaust cavity. Figure 9 shows a cut away section of the motor bucket in which the Helmholtz resonators and the felt lining can be seen.

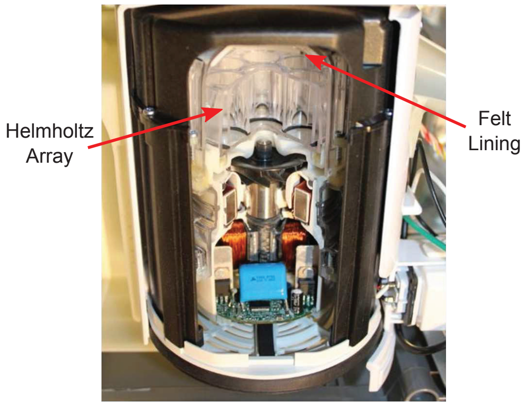

FIGURE 9: Cut away section of the motor casing with the Helmholtz resonator and the felt lining.

The acoustic spectrum of the first prototype (with Helmholtz array) was compared with a similar prototype including the felt lining. Figure 10 shows that the blade passing frequency tone at 13.69 kHz is reduced by 11 dB. The felt does not affect the broadband noise levels at high frequencies. The main contributor to the noise at these frequencies is driven by the high velocity jets. Any reduction of the motor noise at these frequencies is therefore masked by the jet noise. The other tone at 11.39 kHz is also reduced by approximately 15 dB.

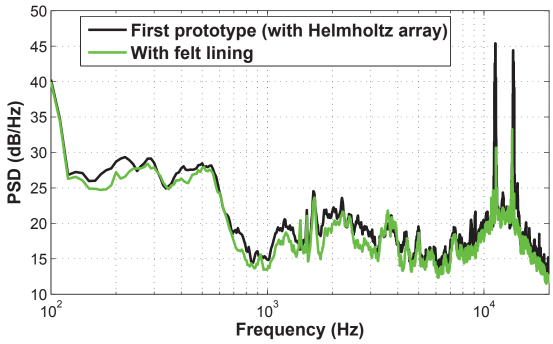

FIGURE 10: Effect of the felt lining on the acoustic spectrum.

Calculating the high frequency tonality shows a reduction from 0.185 to 0.04 HFTu. The high frequency tonality level was therefore successfully reduced below the annoyance threshold and down to the level of the perception threshold.

5 Conclusion

A sound quality study has been conducted at Dyson to assess the perception of high speed hand dryer noise. A pleasantness index was created based on correlation between subjective listening test results and objective psychoacoustic metrics. This model was developed to assess the sound quality during development of a new hand dryer and depends on the total loudness and the average tonality of the sound produced by the machine.

The model was used to evaluate the performance of acoustic solutions intended to enhance the sound quality of high speed hand dryers. An array of Helmholtz resonators was used to reduce the level of the fundamental tone associated with the running speed of the compressor and acoustic felt was used to reduce the high frequency tonal contents.

To account for high frequency tones present in early prototypes an extended tonality algorithm was developed. This high frequency tonality algorithm was used to define a threshold of perception and of annoyance for high frequency tones enabling the performance of the acoustic solutions to be quantified.

This proposed metric should be further developed in the future through a dedicated psycho-acoustic investigation. To further improve the development of high speed hand dryers, several conditions will have to be considered such as the "hands-in" operation and the influence of a bathroom environment.

All improvements mentioned in this document have been implemented in Dyson's latest high speed hand dryer: the Dyson Airblade dB hand dryer.

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