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Noise reduction of a vacuum-assisted toilet

Michael T. Rose[a]
B. Dagan Pielstick[b]
Zach T. Jones[c]
Scott D. Sommerfeldt[d]
Kent L. Gee[e]
Scott L. Thomson[f]
N232 ESC
Brigham Young University
Provo UT 84602

ABSTRACT

Flushing of an aircraft vacuum-assisted toilet generates high noise levels that can be disturbing to both users and those seated near lavatories. This paper describes the results of an investigation into reducing the aeroacoustically-generated noise. Three stages of noise can be correlated with distinct flush valve conditions during a flush cycle: an initial noise level peak associated with the flush valve opening, an intermediate noise level plateau associated with the valve being fully opened, and a final noise level peak associated with the flush valve closing. It was hypothesized that increasing the distance between the flush valve and the bowl and increasing the bend radius of the attachment at the bowl exit reduces overall noise levels. These modifications resulted in a ~14 dB reduction in the radiated noise during the valve opening and closing in addition to a ~5 dB noise reduction during the open valve condition. The paper also discusses intermediate results that show the effects of varying tube length and bend radius on the radiated sound levels, which gives insight into the noise generation mechanisms.

1 INTRODUCTION

A vacuum-assisted toilet utilizes a pressure difference, rather than gravity, to transport waste from the toilet to a septic tank. The main motivation for vacuum-assisted toilets is to reduce the water required per flush. Conventional gravity toilets use 5.68 liters (1.5 gallons) of water per flush while vacuum-assisted toilets use only 0.12 liters (1/2 cup) of water per flush.[1] This is ideal because

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[a] rose.michael@byu.edu
[b] dagan.pielstick@gmail.com
[c] ztj1@sbcglobal.net
[d] scott_sommerfeldt@byu.edu
[e] kentgee@byu.edu
[f] thomson@byu.edu

it reduces weight and, by extension, fuel costs for transport vehicles such as airplanes, cruise ships, and trains. This cost savings comes at the expense of the high noise levels generated with vacuum-assisted toilets.

Vacuum-assisted toilets are the subject of current and previous noise control efforts. Some toilets have lids designed to provide some transmission loss.[2] Some toilets have a bypass valve that provides a secondary source of air so that when waste clears the bowl, the primary flush valve does not have to stay open to transport the waste all the way to the tank.[3] A third noise control strategy is an in-line expansion chamber with the tube between the toilet and the tank to act as a muffler.[4] A fourth is to recycle grey water and rinse the toilet with much more than 0.12 liters (1/2 cup) of water so that the grey water acts as an absorption agent for the noise.[5]

Current noise levels for vacuum-assisted toilets are time dependent. Three stages of the flush cycle correspond to distinct radiated sound levels as shown in Fig. 1 by the A-weighted overall sound pressure level. A spectrogram of the noise levels is shown in Fig. 2. The first stage of the flush cycle is the valve opening event. As the valve introduces the vacuum pressure to the toilet, the peak noise level corresponds to the highest level of the whole flush. The noise is broadband, containing energy from about 300 Hz to 3 kHz. The second stage occurs while the valve is completely open, which we refer to as the "steady vacuum" stage. During this stage, the noise levels plateau about 7 dB lower than the opening peak. The noise is broadband and contains energy from about 300 Hz to about 8 kHz. Evidence of tonal noise is apparent by the horizontal banding in the spectrogram. The third stage occurs as the valve closes and is manifest by another peak in the noise level. In our experimental apparatus, we are not able to fully maintain a constant vacuum pressure difference through the entire flush cycle, so the closing peak noise level in Figs. 1 and 2 is lower than what it would be in practice.

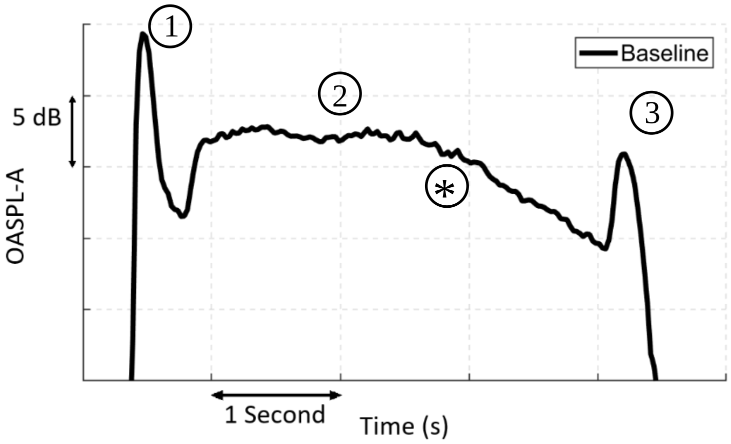

Fig. 1: The A-weighted overall sound pressure level of a vacuum-assisted toilet averaged over 5 flushes. Number 1 marks the initial peak due to the valve opening event. Number 2 marks the steady vacuum phase while the valve is completely open. Number 3 marks the closing peak due to the valve closing event. The * marks the time in the flush cycle our test apparatus no longer maintains constant vacuum pressure.

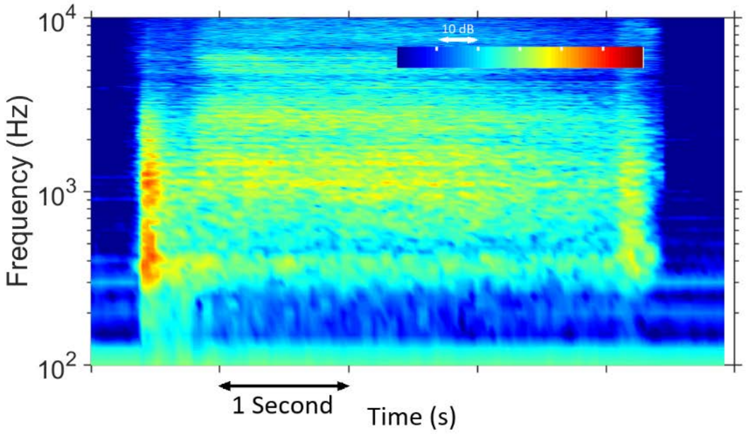

Fig. 2: Spectrogram of a baseline flush.

Our hypothesis is that the radiated aeroacoustic noise from a vacuum toilet can be reduced by increasing the bend radius of tubes near the bowl and by increasing the length of tube between the valve and bowl. This hypothesis was inspired by OSHA's recommendation to place all bends and valves at least 10 pipe diameters away from each other.[6] Previous investigations have shown that damping the structural vibrations of the bowl result in about 20 dB vibration reduction but only about a 3 dB noise reduction for part one of the flush cycle.[7] The methods section describes the setup of the vacuum-assisted toilet, the tube materials and shapes, and the data collection and analysis methods used for this investigation. The results section presents the radiated noise of an initial prototype, an investigation reducing the bend radius and tube length from that of the initial prototype, and the acoustic equivalence of using different tube materials. We conclude that increasing the bend radius and tube length between the bowl and valve reduces the radiated noise of a vacuum-assisted toilet. The valve opening event noise level is reduced by 14 dB while the steady vacuum phase noise level is reduced by 5 dB. The bend radius for the modified tube need not be larger than 9.5 cm and the tube length need not be longer than 0.77 m between the bowl and valve to achieve similar noise reductions that were obtained with a 16.5 cm bend radius and 1.7 m tube length.

2 METHODS

2.1 Experimental Setup

Vacuum-assisted flushes were investigated in the Brigham Young University (BYU) hemi-anechoic chamber. A commercial vacuum-assisted toilet and a septic tank system evacuated to -67727.8 Pa gauge (-20 inHg) for each flush were used. A 1.27 cm (0.5 in) prepolarized GRAS 40AE free-field microphone was placed 1 m above the front edge of the bowl pointing downwards toward the toilet. Figure 3 shows this in schematic form.

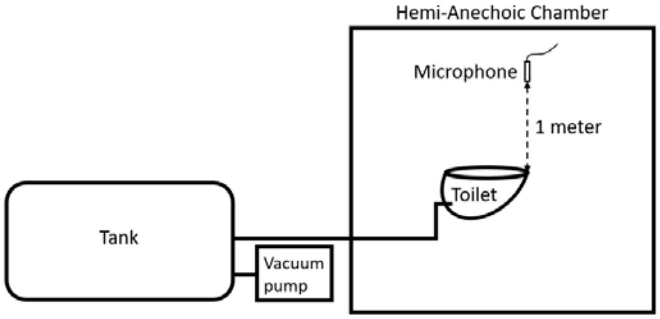

Fig. 3: Schematic of experimental setup.

Three tube materials were used throughout this investigation. First, the tube that comes with the vacuum-assisted toilet is a hard, smooth plastic with 4.45 cm (1.75 in) inner diameter. Second, a flexible plastic tube with 5 stiffening corrugations per 2.54 cm (1.0 in) and with a 5.08 cm (2.0 in) inner diameter was used. Third, an ABS 3D-printed tube with 5.08 cm (2.0 in) inner diameter was used. Figure 4 shows a photo of these tube materials.

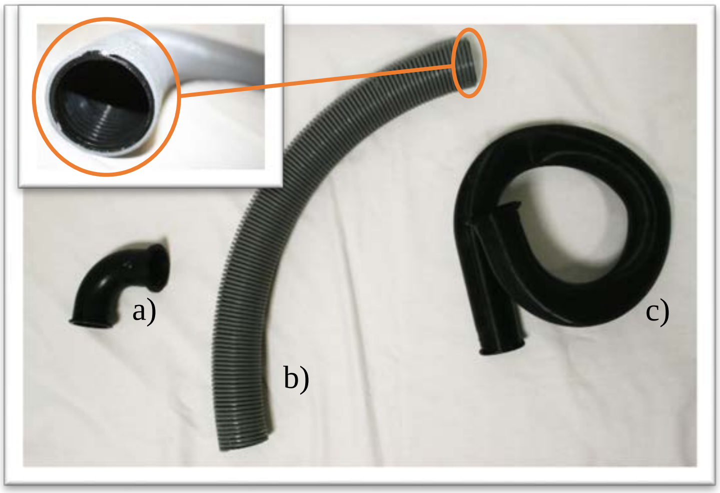

Fig. 4: Photo of tube materials used. a) 90-degree elbow included with vacuum toilet, b) corrugated flexible tube, c) 3D printed tube

2.2 Tube Geometries

Five general tube geometries have been investigated. First, the baseline geometry which uses the first material tube, as shown in Fig. 4 a), that has hard plastic shaped into a tube, bent at a 90-degree angle with a bend radius of 4.5 cm which is used to connect the bowl to the valve. Second, the flexible tube shown in Fig. 4 b) was wrapped twice around the base of the toilet to connect the bowl to the valve. Third, the flexible tube forming a straight connection between the bowl and valve with no bends as shown in Fig. 5. Fourth, the flexible tube in a spiral-esque shape that makes one revolution with variable bend radius and pitches 2.5 inches upward connecting the bowl to the valve with a fixed tube length as shown in Fig. 6. Fifth, a combination of changing the bend radius with the tube length such that the valve attaches to the end of the spiral. The combination of the smallest bend radius and tube length was 3D printed.

Fig. 5: Photo of the straight-tube configuration.

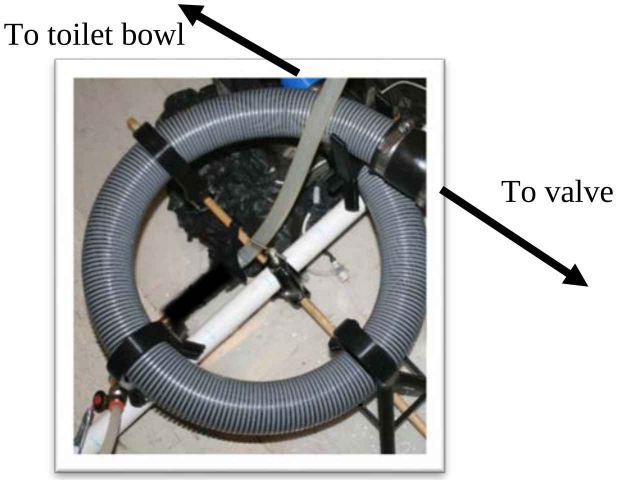

Fig. 6: Photo of the varying bend radius investigation.

2.3 Analysis Techniques

Two types of analyses are shown. First is an A-weighted running instantaneous overall sound pressure level from the microphone located above the bowl. Second is a spectrogram from 100 Hz to 10 kHz, to provide a detailed description of the radiated noise.

3 RESULTS

3.1 Initial Prototype

A proof of concept investigation was done to test if increasing the bend radius and tube length between the bowl and valve reduces the radiated noise. A flexible tube was wrapped twice around the base of the toilet and connected to the bowl and valve. Figure 7 shows the OASPL-A for both the baseline and prototype configurations. The initial prototype tube reduced the initial peak by 14 dB, the steady vacuum region by 4 dB and the closing peak by 4 dB. The prototype tube reduced the noise over a broad range of frequencies, 300 Hz to 10 kHz, throughout the whole flush cycle as shown by comparing Fig. 8 to Fig. 9.

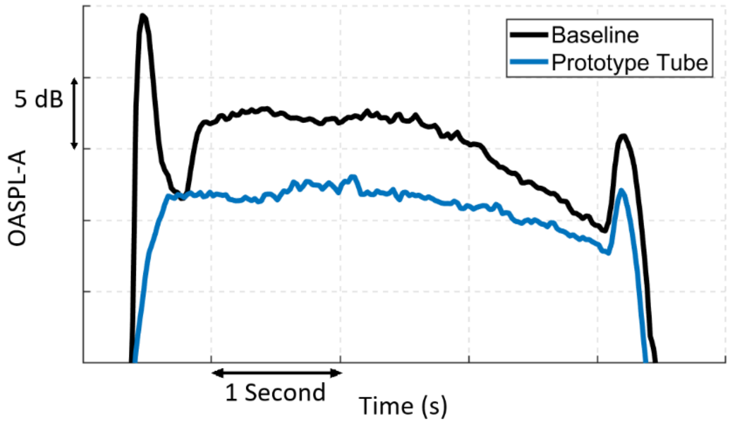

Fig. 7: Running A-weighted overall sound pressure level for a baseline flush and initial prototype flush. Each are averaged over five flushes.

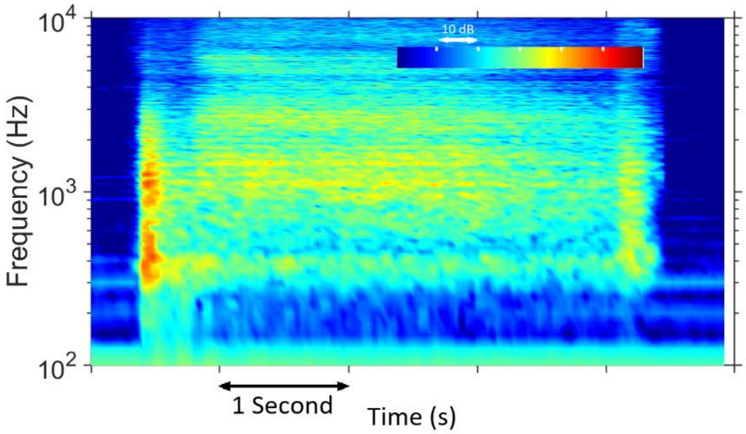

Fig. 8: Spectrogram of the baseline flush.

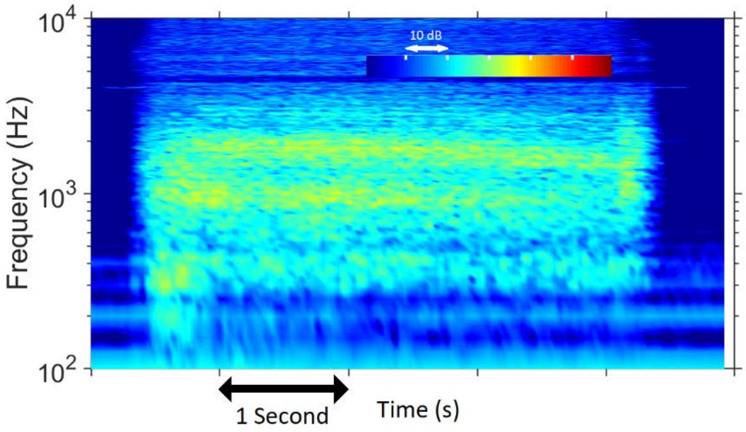

Fig. 9: Spectrogram of the prototype tube flush.

3.2 Reduced Bend Radius with Constant Tube Length

The prototype tube of 1.7 meters was coiled into a spiral of one revolution starting at a 16.5 cm bend radius and successively coiled tighter to 15, 13.5, 12.5, 11.5, 10.5, and 9.5 cm. The tightest bend radius this tube could make was 9.5 cm. Figure 10 shows the OASPL-A averaged over five flushes for each configuration. Minimal OASPL-A variation occurred from bend radius to bend radius. The initial peak has a range of OASPL-A levels varying by 4 dB but the maximum level is within 1 dB of the steady vacuum levels. The steady vacuum level varies by ~1 dB, and the closing peak varies by slightly more than 1 dB.

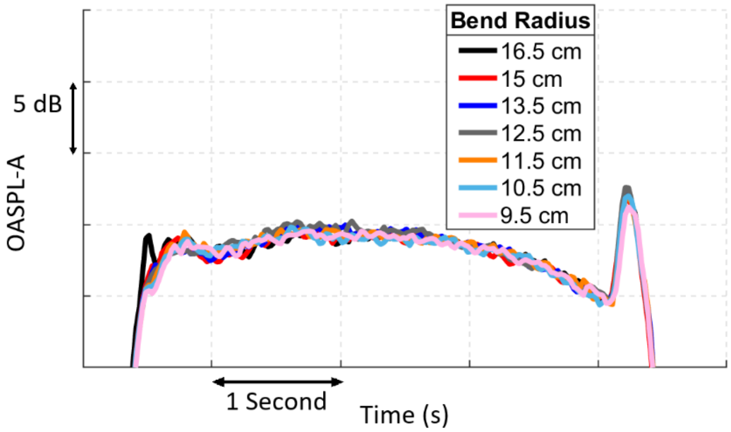

Fig. 10: Running A-weighted overall sound pressure level for the varying bend radius investigation. The bend radius is varied from 16.5 cm to 9.5 cm while the tube length is kept constant.

3.3 Reduced Tube Length with Constant Bend Radius

We wanted to see how short the tube could be starting at 1.7 m before the noise reduction was significantly different. The 1.7 m tube was attached to the bowl and valve such that it had no bends and was completely straight. The tube was shortened successively from 1.7 to 1.3, 1.22, 1.10, and 1.04 m. Figure 11 shows the OASPL-A during each of these configurations averaged over five flushes each. The initial peak has a range of OASPL-A levels varying by 5 dB. The steady vacuum levels vary by 2 dB, and the closing peak varies by 4 dB.

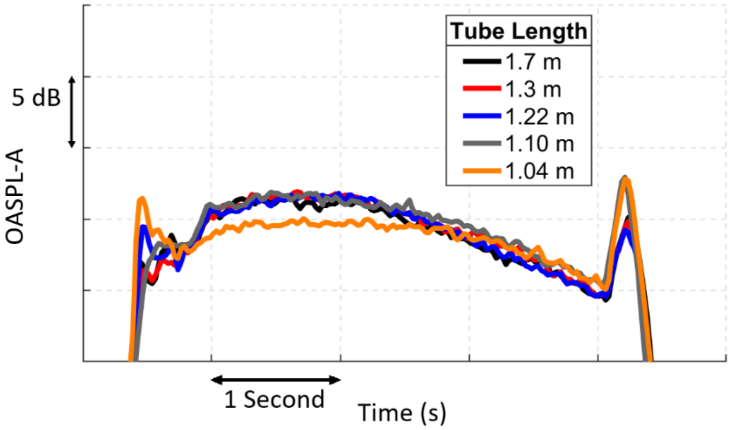

Fig. 11: Running A-weighted overall sound pressure level for investigation that varies the tube length from 1.7 m to 1.04 m but not the bend radius.

3.4 Reduced Bend Radius with Reduced Tube Length

The previous bend radius results were done with a 1.7 m tube. By removing the excess tubing after each contraction of the bend radius, the length of the tube also decreased. The combination of bend radii and tube length are reported in the legend of Fig. 12. The figure shows the OASPL-A during each of these configurations averaged over five flushes each. The initial peak varied by less than 1 dB. The steady vacuum varied by 1 dB, and the closing peak varied by 3 dB.

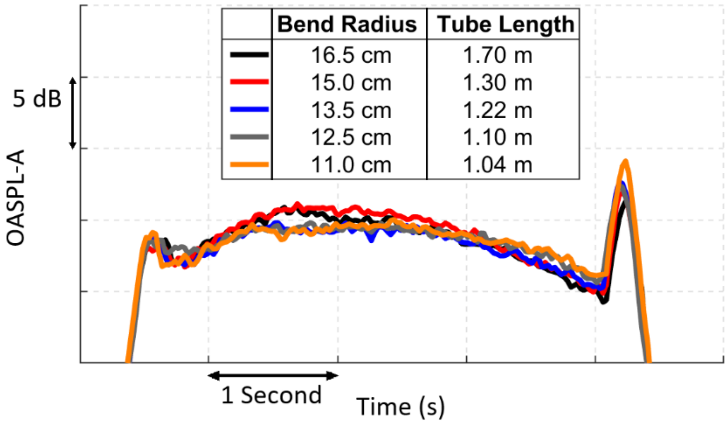

Fig. 12: Running A-weighted overall sound pressure level for changing the bend radius with the tube length.

3.5 3D Printed Version

Some concern may be whether the flexible tube and its stiffening corrugations may affect the radiated noise. A spiral tube matching the geometry of the flexible tube was 3D printed and installed on the vacuum-assisted toilet. Figure 13 shows that the agreement of the OASPL-A measured with a flexible tube and a 3D printed tube is within 1 dB throughout the flush cycle, each averaged over five flushes. Figure 14 and 15 show spectrograms of the flexible and 3D printed flushes. The flexible tube has more energy in the 2-3 kHz range while the 3D printed version has more energy in the frequency range above 3 kHz than the flexible tube. This shows that the choice of material may be important for sound quality.

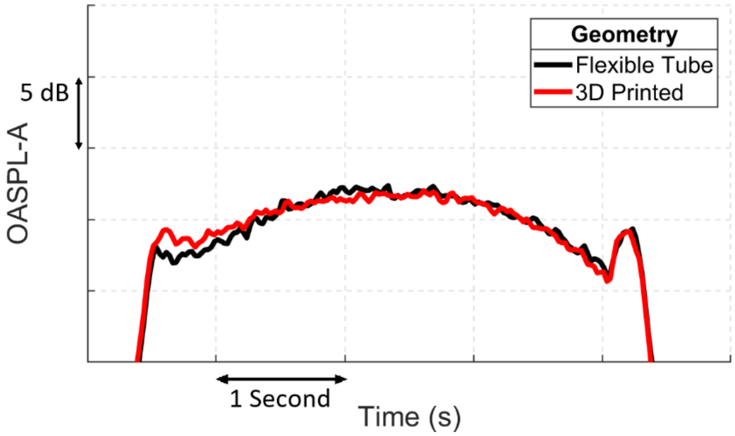

Fig. 13: Comparison of the flexible tube geometry with 9.5 cm bend radius to the 3D printed version. Levels are nearly the same.

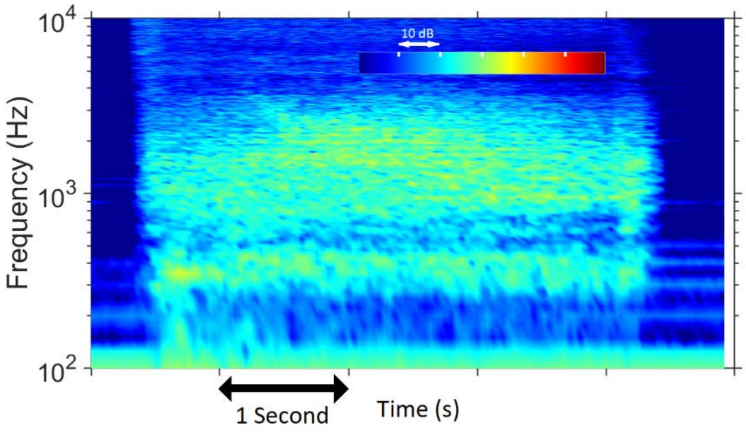

Fig. 14: Spectrogram of the 9.5 cm bend radius flexible tube flush noise.

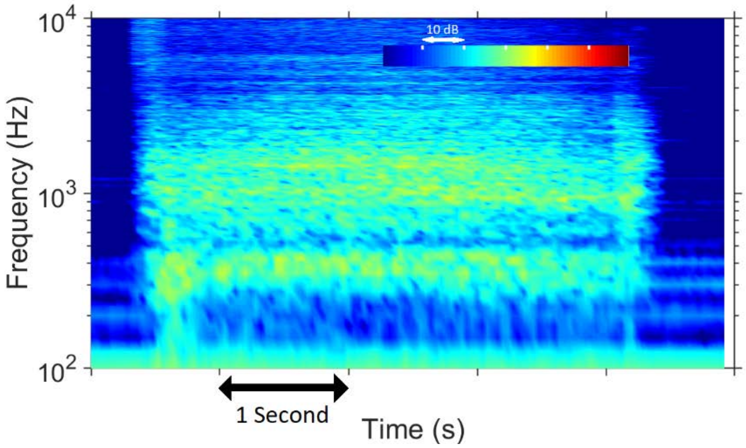

Fig. 15: Spectrogram of the 3D printed 9.5 cm bend radius tube flush noise.

Other form factors than the spiral can be printed and tested with similar bend radii and tube length as the 9.5 cm bend radius and 0.77 m tube length spiral tube. There may not be sufficient space for a full spiral behind the toilet in most practical applications, but a tube designed to fit into the space allotted could give similar noise reductions so long as it has comparable bend radii and tube length used here.

4 CONCLUSIONS

The radiated noise from a vacuum-assisted toilet was investigated. A previous investigation showed that structural damping yields minimal radiated noise level reductions while another investigation suggests distancing bends and valves by 10 pipe diameters reduces flow-induced noise. We introduced a longer tube with a larger bend radius which reduced the radiated noise of a vacuum-assisted toilet. After investigation, a bend radius of 9.5 cm and greater has a similar noise reduction effect as the initial 16.5 cm bend radius. Likewise, a tube length of 0.77 m has a similar noise reduction effect as the initial 1.7 m tube length. This investigation was done with a flexible tube with stiffening corrugations. Using a tube with a smooth inside did not affect the overall levels but did change the spectral content which is linked to sound quality. These advances may help provide an improved experience for transport vehicle lavatory users. Ongoing and future investigations may reduce the overall footprint of the modified tubing while using it in concert with other noise control strategies.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

1. M. Pondelick, “Vacuum toilet assembly.” U.S. Patent 7,690,053 B2, issued April 6, 2010.

2. G. Moore, “Toilet apparatus.” U.S. Patent 6,401,270 B1, issued April 15, 1998.

3. R. Boodaghians, K. Huang, C. Goschel, C. Ortolan, V. Antonczyk, T. Birbeck, “Two-stage flush and grey water flush systems and devices.” International Patent WO/2013/172953, issued November 21, 2013.

4. C. Seibt, M. Mueller, “Noise reduction unit for vacuum suction drains.” U.S. Patent 9,365,368 B2, issued June 14, 2016.

5. H. Frank, C. Sparr, “Apparatus for low noise flushing a vacuum toilet, especially in an aircraft.” U.S. Patent 5,317,763 A, issued June 7, 1994.

6. Occupational Safety & Health Administration (OSHA) (2013). OSHA Technical Manual (Section III: Chapter 5.II.J.2) Retrieved from https://www.osha.gov/dts/osta/otm/new noise/index.html

7. M. Rose, J. Kilts, D. Pielstick, S. Sommerfeldt, K. Gee, S. Thomson, “Vibration damping of a vacuum-assisted toilet.” Proc. Mtgs. Acoust. 32, submitted (2018).