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Noise Control of Vacuum-Assisted Toilets

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Master of Science

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ABSTRACT

Noise Control of Vacuum-Assisted Toilets

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Vacuum-assisted toilets make use of a large pressure difference between the ambient pressure and a vacuum tank to transport waste from the toilet bowl to the septic tank. This process requires 98% less water per flush making it an attractive product for transport vehicles such as airplanes, cruise ships, and trains. Unfortunately, the water savings come at the cost of high noise levels. This thesis investigates the acoustic characteristics of a vacuum-assisted toilet flush and several methods to reduce the radiated noise. Some methods include changing rinse parameters such as rinse pressure, rinse length, and rinse timing, adding structural damping of the bowl to reduce re-radiation, inserting a tube between the bowl and valve that utilizes a larger bend radius and longer tube length than what is currently installed, and modifying the valve. The most effective solution without requiring more water per flush was to insert a tube. The initial peak level was reduced by 16 dB and the steady-vacuum noise was reduced by 5 dB. Evidence of evanescent decay and reduced flow velocity as possible mechanisms for the noise reduction are presented and discussed. Rinse variations show a strong impact of the rinse-tube interaction on the noise reduction. In addition to these techniques, a modified flush plate opening and closing velocity profile is suggested which optimizes the sound generated by the opening and closing of the valve. Finally, a promising dual-valve solution that may take extra coordination of vacuum-assisted toilet manufacturers and airplane/cruise ship/train manufacturers is presented. By placing a secondary valve near the septic tank, the main noise from the valve is significantly reduced.

Keywords: vacuum-assisted toilet, noise control, bend, radius of curvature, tube length, constrained layer damping, evanescent decay

ACKNOWLEDGMENTS

I am grateful firstly to the academic support of my committee: Dr. Scott Sommerfeldt, Dr. Kent Gee, and Dr. Scott Thomson who first of all made it possible for me to attempt a master's degree by recommending me to the admissions committee even though I had some things working against me. Secondly for all the hours they spent meeting with me, advising me and reviewing my work. I am also grateful to the Department of Physics and Astronomy. Several people made a significant impact on my experience at BYU, specifically: machinist, Jeremy Petersen, and his students for their skill and continued help in the design and creation of parts of the test setup; Nan Ellen Ah You who tirelessly made graduate events such as graduate gobble and luncheons an environment to socialize, network, and become a better citizen of the physics department. Thank you to my wife, Kaia Rose, for her love and support, allowing me to spend an extra two years in school which is not a small sacrifice. I thank the undergraduates who helped get a lot of the work done including: Josh Kilts, Joe Masson, Brandon Burkhardt, Dagan Pielstick, Zach Jones, and Mark Anderson.

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Chapter 1

Introduction

1.1 Introduction

A vacuum-assisted toilet is an engineering feat that has several impressive capabilities. It utilizes a pressure difference which can be as great as 2/3 of an atmosphere, rather than gravity, to transport waste from the toilet to a septic tank. A single gate valve with a thin metal plate with a square-edged cutout placed about 25 cm downstream of the bowl supports the pressure difference. Flow due to the large pressure difference can move faster than 150 m/s. This much suction beneficially reduces the amount of water required per flush. Vacuum-assisted toilets typically only require half a cup of water for lavatory service which is 98% less water than conventional gravity toilets.[1] Water reduction is desirable because it reduces weight and, by extension, fuel costs for transportation vehicles such as airplanes, cruise ships, and trains. Cost savings, however, come at the expense of higher noise levels.

Airlines and other transport vehicle industries can have a competitive advantage by providing a more comfortable lavatory experience by reducing the flush related noise. Overall sound levels inside the lavatory are similar to those produced by a typical motorcycle. This can be uncomfortable and can scare unaware passengers. Due to much work to reduce the engine noise on airplanes, vacuum-assisted toilets are beginning to be heard inside the main cabin. For this reason, passengers may become self-conscious when attempting to flush.

Two types of sound are considered to contribute to this noise problem, namely: aerodynamic sound and flow-induced vibration that reradiates into the lavatory from the bowl.

The aerodynamic sound is thought to come most significantly from flow separation and shearing forces over the valve as it opens and closes and from tube bends whose radius of curvature is too small leading to flow separation over the bend. In addition to aerodynamic noise, the flow collides with the tubes (most especially the bends) causing structural vibrations which can propagate to the bowl and then radiate from the bowl, contributing to the noise of the vacuum-assisted flush.

1.2 Prior Work

Several past studies have focused on noise control for vacuum-assisted toilets. In 1987, Olin *et al*[2] invented a bypass valve and lid system for reducing the noise on vacuum toilets. A bypass valve provides a secondary source of air which enables the primary flush valve to close the acoustic transmission path to the user. A lid further closes off the transmission path of toilet noise to the user. In 1988, Oldfelt and Stahl[3] patented the idea to rinse while the valve was opening. Adding water (mass) to the bowl when the valve opens reduces the noise the valve makes while opening. In 1989, Ask *et al*[4] patented the idea to recycle grey water from sink rinse water and other sources as the toilet rinse water supply allowing for either more water per flush or less overall water use. Hufenbach *et al*[5] in 2008 made an acoustical analysis of a vacuum-assisted toilet, and showed that decreasing the vacuum pressure, modifying the valve and outlet area, and using a lid are some ways to reduce radiated noise. In 2013, Boodaghians *et al*[6] patented the idea to utilize a two-stage flush such that waste would be transferred to a transient tank attached to the bowl via a weak vacuum from where the waste can be accelerated with the strong vacuum down to the septic tank.

Flow-induced vibrations can lead to radiated noise.[7] Constrained layer damping (CLD) has been shown to reduce structural vibrations.[8] Therefore, it may be possible to reduce the radiated noise by applying constrained layer damping materials to a vacuum-assisted toilet. An investigation of CLD as part of this thesis work was carried out and is published[9] in the Proceedings of Meetings on Acoustics (POMA).

Other previous work suggests a need to reduce flow velocity to limit noise production. Davies and Williams[10] shows that there is a power law relationship between the flow velocity and the aeroacoustically generated sound pressure. They also show that sound radiation from turbulence inside a tube exceeds that of turbulence in free space. Hufenbach *et al*[5] shows that with reduced vacuum level (and thus flow velocity), overall sound pressure level of the flush can be reduced.

Several previous works suggest increasing the tube length between sound sources and the receiver location to affect noise reduction. The Occupational Safety and Health Administration (OSHA)[11] recommends placing all bends and valves at least 10 pipe diameters away from each other. Hoff[12] showed significant attenuation per meter for sound propagating in the upstream direction. According to Davies and Williams[10], low frequency small-scale turbulence radiates into modes that decay exponentially with distance, i.e. evanescent decay. References that present a mathematical development of evanescence in tubes are in Refs. 13-15.

Previous works also suggest reducing noise by increasing the radius of curvature of tube bends. Experiments done by Hufenbach *et al*[5] suggest modifying the bowl outlet geometry such that the bend radius is as large as it can be. Aissaoui *et al*[16] performed a numerical optimization of an HVAC system in an automobile that considered geometric modifications to the tubes connecting the blowers to the outlets. Qiu and Liu[17] achieved noise reduction for jet engine bypass flow noise by numerically optimizing the tube geometry near the outlet. Vizzini *et al*[18] compared noise generated by flow through a straight tube to that generated by flow through a tube with a 90-degree curve and found that the configuration with the 90-degree curve was louder.

Another component of the toilet system is the valve. It acts as a varying orifice in a tube that influences the flow field and the aerodynamic noise. Ward-Smith[19] shows various types of flow fields for large and small orifices. The variability of the valve geometry and opening and closing speed are more parameters that can affect the noise that a vacuum-assisted flush produces. This work investigates those effects.

1.3 Thesis Overview

This thesis presents the effect on radiated noise from a vacuum-assisted toilet by various noise control strategies. Chapter 2 introduces the vacuum-assisted toilet and how it functions and how it behaves acoustically. Then, an investigation into how the rinse affects the sound is presented. Chapter 3 stems from a published paper[9] by the author in the Proceedings of Meetings on Acoustics (POMA) that shows the effect of applying constrained layer damping materials to the bowl. Chapter 4 is a paper in the process of being submitted to the Noise Control Engineering Journal that presents the effect of increasing the bend radius of the tube near the bowl and increasing the tube length between the valve and bowl. Chapter 5 is a series of experiments that measure evidence of the noise control mechanisms behind the successes in Chapter 4. Chapter 6 explores the possibility of modifying the valve velocity profile and location for better reduction of the initial and final noise peaks of the flush cycle. Chapter 7 recaps the key takeaways from the thesis and provides guidance for future work that can be done on controlling the noise of vacuum-assisted toilets.

Chapter 2

Vacuum-Assisted Toilet Acoustic Characterization and Rinse Effects

2.1 Noise Characterization

We investigated noise associated with a vacuum-assisted flush in the Brigham Young University (BYU) variable acoustics chamber in a hemi-anechoic configuration. We connected a commercial vacuum-assisted toilet to a septic tank and evacuated the air in the tank down to a gauge pressure of -68 kPa (-20 inHg or -2/3 atm) for each flush. A 1.27 cm (0.5 in) free-field microphone was placed one meter above the front edge of the bowl pointing downwards toward the toilet. Figure 2.1 shows this in schematic form. Each flush cycle was repeated five times from which their running overall A-weighted sound pressure levels (OASPL-A) were averaged resulting in a single running OASPL-A. An individual flush did not vary more than 1-2 dB from another flush of the same configuration as shown by Fig. 2.2.

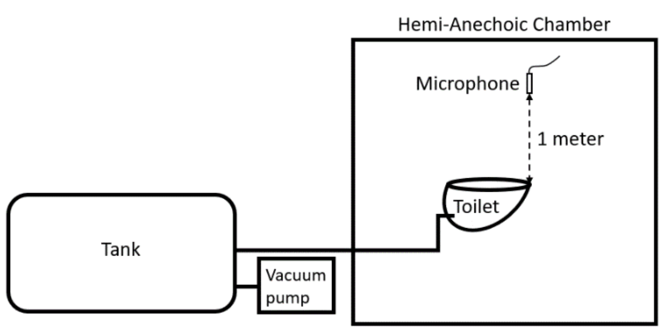

Figure 2.1: Schematic of experimental setup.

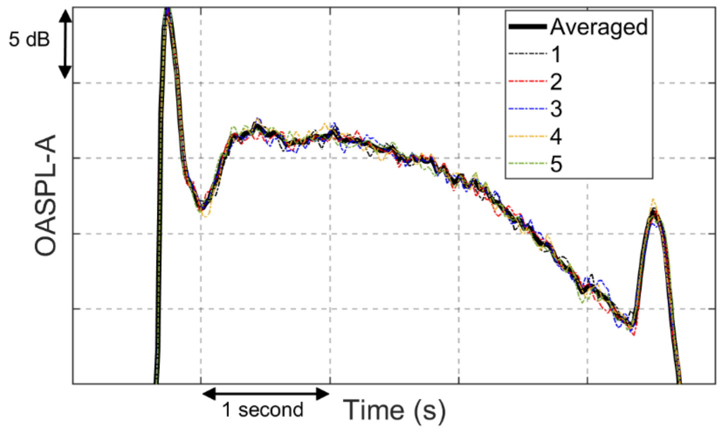

Figure 2.2: Five individual flushes with their average overlaid. Flushes of the same configuration tend not vary by more than 1-2 dB flush to flush.

The noise from a vacuum-assisted flush can be characterized by three events associated with the status of the valve which is illustrated in Fig. 2.3. The first and loudest sound is while the valve is opening which only lasts for a fraction of a second. While the valve is opening, it is partially obstructing the flow in the pipe causing large shearing forces and flow separation which generates lots of noise. The second is while the valve is completely open. The noise while the valve is open is characterized by a high and relatively steady noise level over roughly 3 seconds. This noise is dominated by the turbulence of the flow that has accelerated to very fast speeds. The third is while the valve is closing. Again, the valve partially obstructs the flow which causes large shear forces and flow separation. The radiated noise level spikes again but not as high as the initial peak when the valve opened. Our vacuum system does not have the capacity to maintain suction during the entire ~4 seconds of the flush cycle. Figure 2.3 shows what the running OASPL-A might be if our system could maintain suction during the entire flush cycle. Figure 2.4a) shows a spectrogram of the sound pressure level (SPL) by frequency over the time of the flush cycle. The entire flush is broadband from 300 Hz to 2 kHz. Figure 2.4b) shows a spectrogram of the acceleration level by frequency measured on the surface of the toilet bowl during a flush. The acceleration on the bowl concentrates in the 300 – 500 Hz frequency band which is also a strong band in the radiated noise as shown by the white rectangle in both spectrograms of Figure 2.4a) and b). It was hypothesized that the radiated noise could be in part reduced by damping the structural vibrations of the bowl in this frequency band.

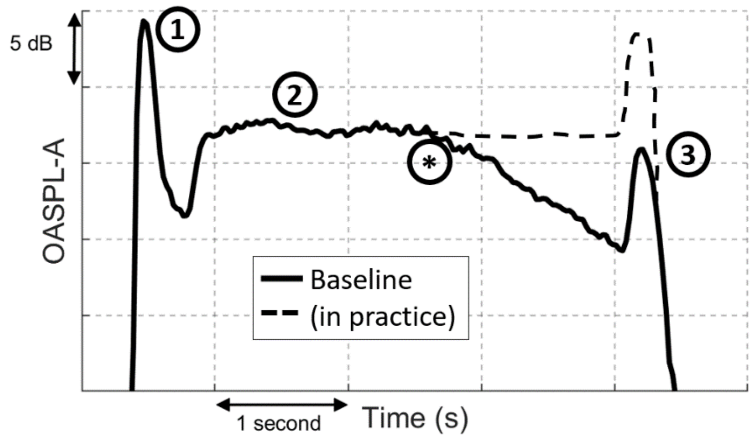

Figure 2.3: Running OASPL-A for the baseline tube geometry. The number 1 indicates the valve opening sound level, 2 indicates the steady vacuum phase, the star indicates the time during the flush that vacuum suction is no longer sufficient to replicate a normal flush, and 3 indicates the valve closing sound level.

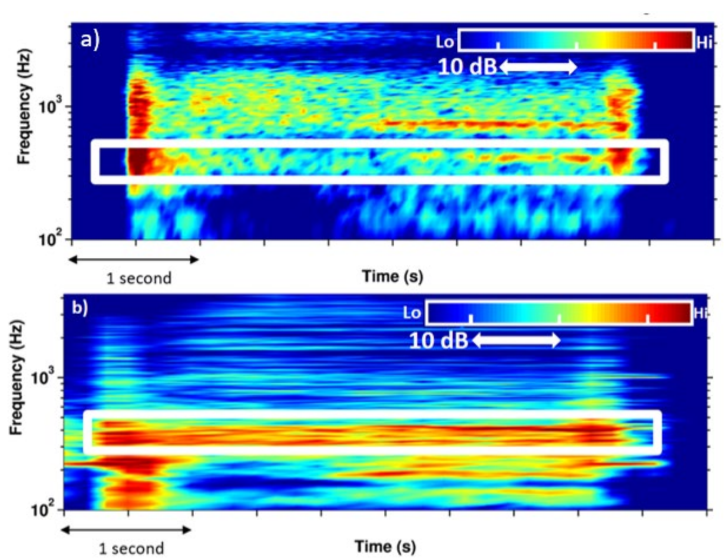

Figure 2.4: Spectrogram of a vacuum-assisted toilet a) measured by a microphone and b) measured by an accelerometer. The white box encloses the frequency range that correlates structural vibrations on the bowl to acoustic radiation.

2.2 Rinse of a Vacuum-Assisted Toilet

This section includes investigations of the rinse pressure, length, and timing in addition to valve to tank distance. Water injection into high speed air jets has been investigated by

Krothapalli *et al*[20] to successfully reduce the aeroacoustically generated noise by 2-6 dB. We likewise inject water into the high speed flow to control the radiated sound level.

2.3 Methodology

A vacuum-assisted toilet may typically rinse half a cup of water near the top of the bowl during the beginning of the flush cycle. The total volume of water used per rinse can be changed by varying the pressure applied to the rinse water and the time period the rinse injects water. A controller functioning with the commercial toilet determines the time the rinse begins and the period over which the water can be injected. The baseline rinse begins at 1.8 seconds after the flush has been triggered, rinses for 0.8 seconds at 40 psi after which no more water is injected into the bowl.

The valve to tank distance (assuming the valve is close to the bowl) was also investigated. This was not used to develop any type of noise control solution but rather to inform us of the tube length effects in our system. This parameter became interesting because there were some significant differences in the results measured during a demonstration on-site of the sponsor compared to results measured at BYU. Specifically, the steady vacuum overall levels were lower at the demonstration site. It is likely that the difference in sound levels was because an extremely long tube was used between the valve and tank at the sponsor's facility compared to the 5 meters used at BYU.

2.4 Results

2.4.1 Dry Flush

Flushing the toilet without rinsing results in very loud sound radiation from the toilet. Figure 2.5 shows the running OASPL-A of a dry flush which is characterized by its especially loud initial peak that is not knocked down but maintains a high sound level even after the valve has completely opened. The vacuum system cannot maintain suction throughout the flush cycle and thus the sound pressure level decreases with time as the suction weakens.

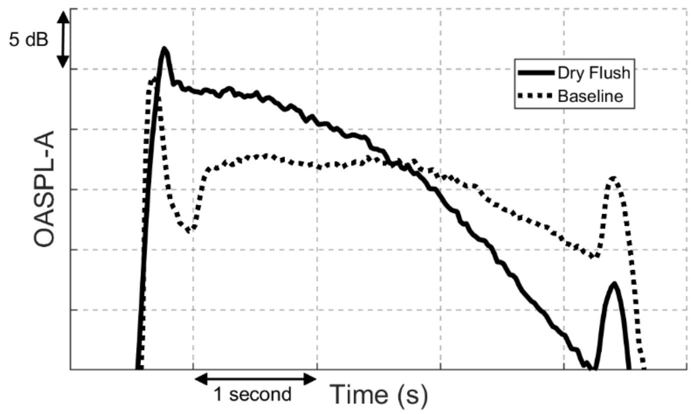

Figure 2.5: Running OASPL-A of a dry flush compared to the baseline flush. The vacuum system cannot maintain suction throughout a dry flush and so the noise level also is not maintained as it would on a commercial toilet in practice.

2.4.2 Rinse Length

It was noticed initially that the moment the rinse is injected, steady-vacuum levels drop to 5 dB below a steady state level, but return 5 dB up as soon as the rinse stops being injected. It was hypothesized that by rinsing longer, the steady-vacuum noise levels can be controlled. The rinse length was increased from +0 to +2.8 seconds relative to the period over which the rinse is currently injected. From Fig. 2.6, it can be seen that indeed, increasing the rinse length controls the steady-vacuum noise levels to the time the rinse stops. To control the entire steady-vacuum phase, a rinse length with +2.8 seconds relative to the current rinse length must be used. Rinsing during the steady-vacuum phase reduces noise levels by 5 dB.

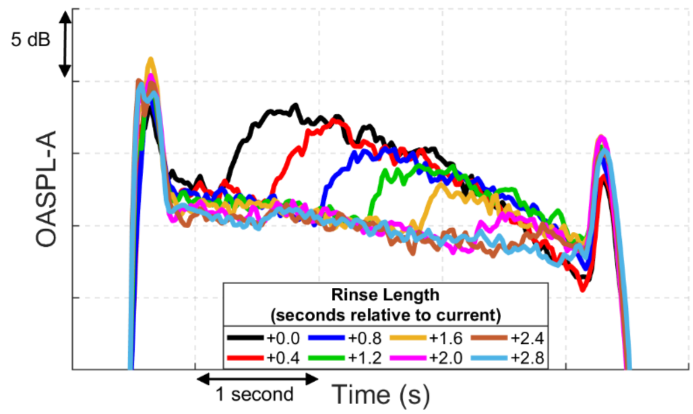

Figure 2.6: Varying rinse length from +0 to +2.8 seconds relative to the current rinse length. The rinse timing was set to +0.3 seconds while the rinse pressure was set to -20 psi both relative to the baseline rinse settings.

2.4.3 Rinse Pressure

The rinse pressure was modified between -35 psi to +32 psi relative to the current rinse pressure. The rinse length was set at +2.8 seconds relative to the current rinse length as suggested by Section 2.4.2. Figure 2.7 shows that the opening peak and closing peak are mostly unaffected by the rinse pressure variation while the steady vacuum noise levels are drastically modified. At -35 psi relative to the current rinse pressure, the noise is similar to as if there were no rinse at all, similar to Fig. 2.5. The rinse volume for -35 psi is actually only 6% under the current rinse volume but because the rinse is spread over the whole flush cycle, there seems to be relatively no water during the whole flush. At -30.6 psi relative to the current rinse pressure, the steady vacuum noise levels are approximately 5 dB lower than the standard rinse which is found in Fig. 2.3. The total volume of water required for flushing at -30.6 psi for +2.8 seconds turns out to increase the rinse volume by 27% (a small value compared to the larger rinse pressures). Then, increasing the rinse pressure progressively to +0 or +8.5 psi relative to the current rinse pressure one may argue either way that there is or is not any significant difference in the levels. One would certainly not need to increase past +8.5 psi as shown by the +32 psi not resulting in any more noise reduction than +8.5 psi. At +8.5 psi, the water volume required per flush is 419% of the current rinse volume while +0 is 367%.

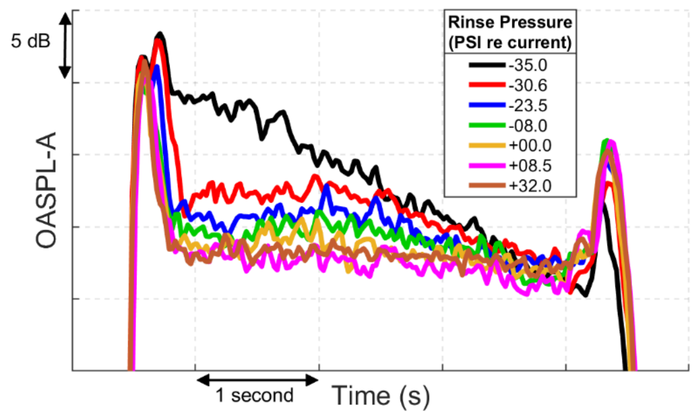

Figure 2.7: Varying rinse pressure from +32 psi to -35 psi relative to the current rinse pressure. The rinse length for this configuration is +2.8 seconds relative to the current rinse pressure. The rinse timing was set to +0.3 seconds relative to the current rinse timing.

2.4.4 Rinse Timing

For this investigation, the rinse timing was varied between -0.3 and +0.7 seconds relative to the current rinse start time. Figure 2.8 shows the variation in the initial noise peaks with a minimum at +0.1 seconds and higher peak noise levels for earlier and later than +0.1 seconds. By delaying the rinse start time by +0.1 seconds, the initial peak is reduced 3 dB. Also, delaying the rinse time moves the 5 dB reduction during the rinse to a point later in time. Changing the rinse timing is the probably the easiest control strategy to implement because it does not come with push back because it does not increase the water requirement. It simply is reprogramming the already existing controller.

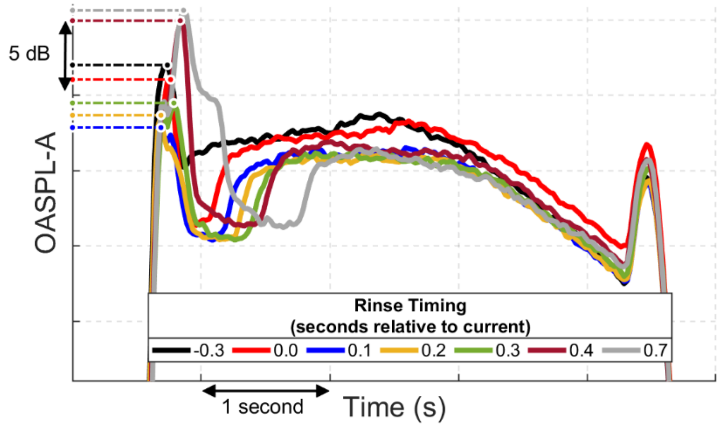

Figure 2.8: Varying rinse timing from -0.3 to +0.7 seconds relative to the current rinse timing. The rinse length rinse pressure were set to the current rinse length and pressure.

2.4.5 Valve to Tank Distance

Investigating the valve to tank distance was motivated by the difference in noise performance of the vacuum toilet flush at BYU versus a flush at the sponsor's facility. The main difference was that the steady-vacuum phase was lower at the sponsor's facility and essentially unaffected by a longer rinse. The likely cause of the performance difference was the toilet to tank tube length. At BYU, the toilet to tank tube length is about 5 meters. At the sponsor's facility, the tube went a considerable distance, eventually going out to another room before it reached the vacuum tank.

The tube length was significantly increased at BYU by coupling several long sections of tube together down and back through the hallway outside the variable acoustics chamber. Sections measuring a total of 12.7 meters, 18 meters, 21.7 meters, and 24.7 meters were attached to the setup and their associated sound levels were measured, as shown in Fig. 2.9. The steady-vacuum noise level decreased as tube length increased following the hypothesis that the tube length was the likely cause of the reduced steady-vacuum noise levels. The steady-vacuum noise level tends to be proportional in some way to the pressure gradient inside the tube. By increasing the distance between the vacuum source and pressure source, the pressure gradient is decreased. Interestingly, the valve opening and closing peaks were unaffected. This is not surprising since the valve to bowl distance did not change.

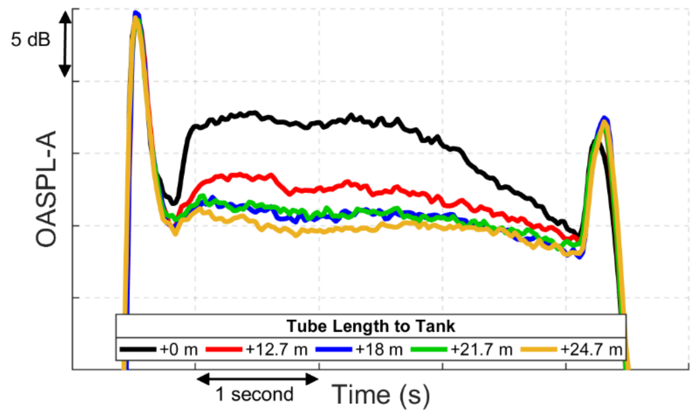

Figure 2.9: Running OASPL-A for varied toilet to tank tube lengths (+0 to +24.7 meters). The tube length affects the steady-vacuum levels but not the valve opening and closing peaks.

Chapter 3

Structural Vibration Damping

3.1 Introduction

3.1.1 Background

We investigated noise associated with a vacuum-assisted flush in the Brigham Young University (BYU) variable acoustics chamber in a hemi-anechoic configuration. We connected a commercial vacuum-assisted toilet to a septic tank and evacuated the air in the tank down to a gauge pressure of -68 kPa (-20 inHg or -2/3 atm) for each flush. A 1.27 cm (0.5 in) free-field microphone was placed one meter above the front edge of the bowl pointing downwards toward the toilet. Figure 3.1 shows this in schematic form. Each flush cycle was repeated five times from which their running overall A-weighted sound pressure levels (OASPL-A) were averaged resulting in a single running OASPL-A. An individual flush did not vary more than 1-2 dB from another flush of the same configuration as shown by Fig. 3.2.

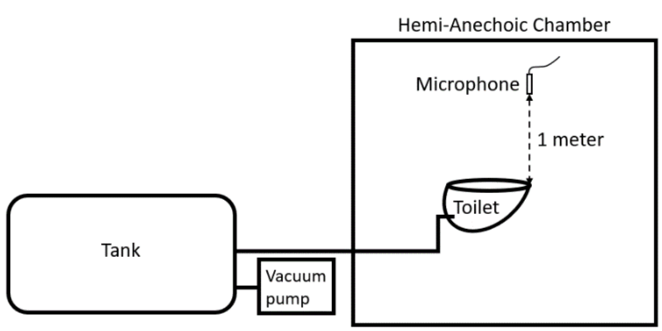

Figure 3.1: Schematic of experimental setup.

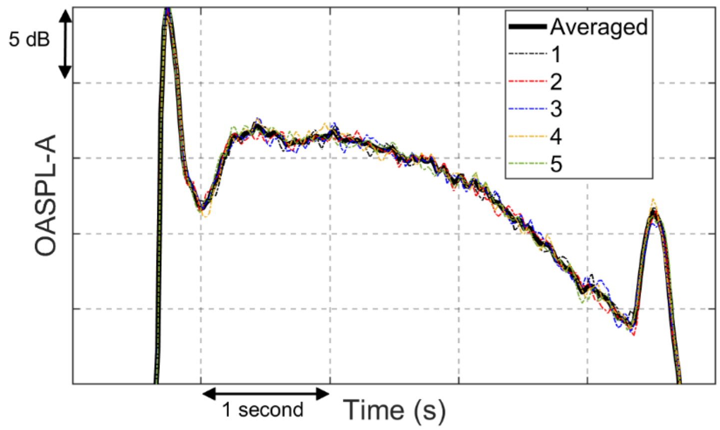

Figure 3.2: Five individual flushes with their average overlaid. Flushes of the same configuration tend not vary by more than 1-2 dB flush to flush.

A valve on the toilet separates a pressure difference between the cabin and the waste storage tanks. This pressure difference accelerates the flush contents causing them to collide with the tubes (most especially the bends) and the valve as it opens and closes. Structural vibrations can propagate from these collisions in the tubes to the bowl, vibrating the bowl which can radiate acoustically, contributing to the noise of the vacuum-assisted flush.

The noise from a vacuum-assisted flush can be characterized by three events associated with the status of the valve which is illustrated in Fig. 3.3. The first and loudest sound is while the valve is opening which only lasts for a fraction of a second. While the valve is opening, it is partially obstructing the flow in the pipe causing large shearing forces and flow separation which generates lots of noise. The second is while the valve is completely open. The noise while the valve is open is characterized by a high and relatively steady noise level over roughly 3 seconds. This noise is dominated by the turbulence of the flow that has accelerated to very fast speeds. The third is while the valve is closing. Again, the valve partially obstructs the flow which causes large shear forces and flow separation. The radiated noise level spikes again but not as high as the initial peak when the valve opened. Our vacuum system does not have the capacity to maintain suction during the entire ~4 seconds of the flush cycle. Figure 3.3 shows what the running OASPL-A might be if our system could maintain suction during the entire flush cycle. Figure 3.4a) shows a spectrogram of the sound pressure level (SPL) by frequency over the time of the flush cycle. The entire flush is broadband from 300 Hz to 2 kHz. Figure 3.4b) shows a spectrogram of the acceleration level by frequency measured on the surface of the toilet bowl during a flush. The acceleration on the bowl concentrates in the 300 – 500 Hz frequency band which is also a strong band in the radiated noise as shown by the white rectangle in both spectrograms of Fig. 3.4a) and b). It was hypothesized that the radiated noise could be in part reduced by damping the structural vibrations of the bowl in this frequency band.

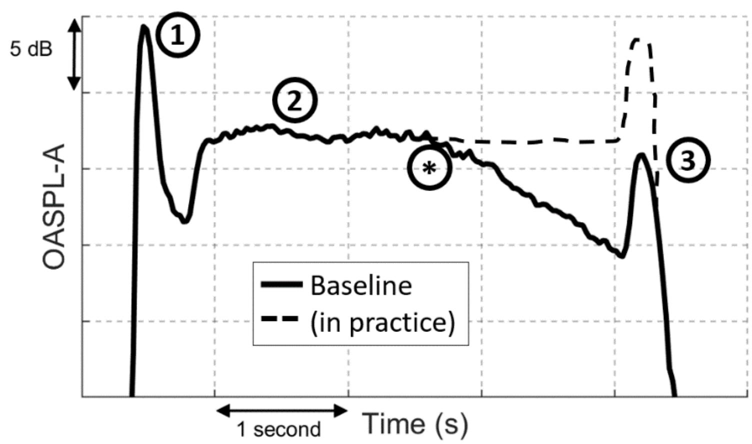

Figure 3.3: Running OASPL-A for the baseline tube geometry. The number 1 indicates the valve opening sound level, 2 indicates the steady vacuum phase, the star indicates the time during the flush that vacuum suction is no longer sufficient to replicate a normal flush, and 3 indicates the valve closing sound level.

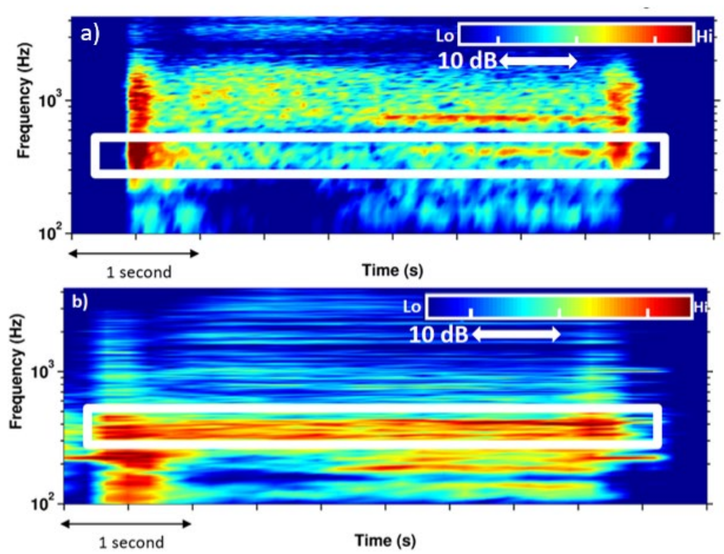

Figure 3.4: Spectrogram of a vacuum-assisted toilet a) measured by a microphone and b) measured by an accelerometer. The white box encloses the frequency range that correlates structural vibrations on the bowl to acoustic radiation.

3.1.2 Structural Damping

Structural vibrations can lead to radiated noise.[7] Constrained layer damping (CLD) has been shown to reduce structural vibrations.[8] Constrained layer damping is the dissipation of mechanical energy into thermo-viscous losses by the application of a viscoelastic material onto a vibrating surface.[21,22] As the vibrating surface deflects, it creates a shearing action in the viscoelastic material. An outer layer of stiff metal is applied to the viscoelastic resulting in the viscoelastic being sandwiched between the vibrating surface and the stiff metal. The stiff outer layer acts as a second surface that will create shear in the viscoelastic material as the vibrating surface displaces, increasing the energy dissipation of the viscoelastic. Some advantages of CLD are its low weight and low volume. CLD avoids making the toilet heavy by adding only minimal treatment to maintain the weight advantages of a vacuum-assisted toilet. Partial coverage of the vibrating surface can yield results similar to full coverage without significant penalty to energy dissipation if the damping layer is applied to the locations of maximum shear.[7] These locations tend to be collocated with places of high velocity or acceleration A scanning laser Doppler vibrometer was used to find the locations of highest velocity.

3.2 Scanning Laser Doppler Vibrometer

3.2.1 Experimental Setup

Locations on the bowl with the highest velocity response were found. The bowl was driven with band limited white noise from a shaker near the bottom of the bowl as shown in Fig. 3.5. Various other driving locations near the valve were tested resulting in similar responses. The bowl's response was measured with a 3-dimensional scanning laser Doppler vibrometer. A scanning laser doppler vibrometer is advantageous because it is a non-contact method to scan the entire surface of the bowl without adding mass. Visualizations were made of the operational vibration shapes at discrete frequencies. Figure 3.6 shows the laser vibrometer scanning the bowl (red lines added). Figure 3.7 shows the grid density that was scanned on the surface of the bowl.

Figure 3.5: A photo of a shaker attached to the bottom of the bowl. This is where the bowl was excited for scanning laser Doppler vibrometer measurements.

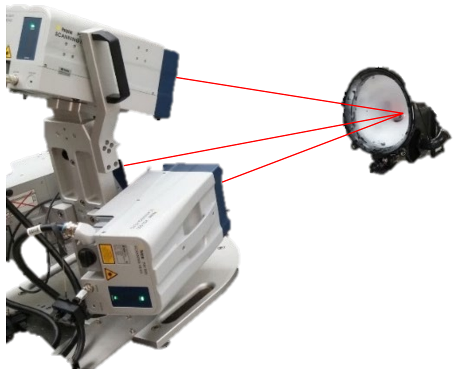

Figure 3.6: A picture of the 3D scanning vibrometer ready to scan the inside of the bowl.

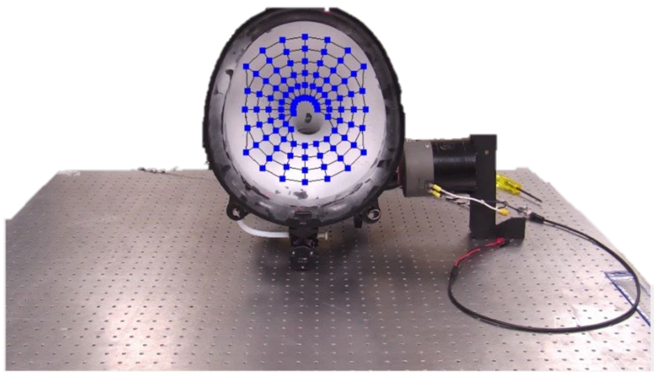

Figure 3.7: A photo of an example grid where the blue points represent measurement points. Most locations near the rim of the bowl have at least one laser obstructed by the rinse ring making those locations impossible to measure.

3.2.2 SLDV Results

Operational velocities were measured on the surface of the vacuum-assisted toilet bowl. Figure 3.8 shows the velocity response spectrum between 10 – 2000 Hz. Each curve is the velocity magnitude in either the x, y, or z direction averaged over the entire grid of the SLDV measurement. The frequency band between 300 and 500 Hz shows a band of rather high velocity levels in the x, y, and z directions. There were some high quality factor peaks below 300 Hz but they do not correspond to high sound pressure levels in the acoustic measurements and therefore no further discussion is included for vibrations below 300 Hz. A representative velocity response pattern in the 300 – 500 Hz frequency band is shown in Fig. 3.9. The operational velocity shapes throughout this band appear very similar to the one shown in Fig. 3.9. This response pattern shows that the area near the rim of the bowl has the highest velocity response, especially near the front right and left sides. This suggests that placing damping materials in these locations would be the most effective of all locations on the bowl. It may be of note that the operational shape shown in Fig. 3.9 is not symmetric. This is likely because the bowl is attached to a valve assembly that is not symmetric. It is heavily weighted to one side which may cause the bowl to rest against the left side differently than the right side. Since damping treatments would not withstand repeated exposure on the top side of the bowl, CLD was attached to the underside of the bowl near the left and right sides of the rim.

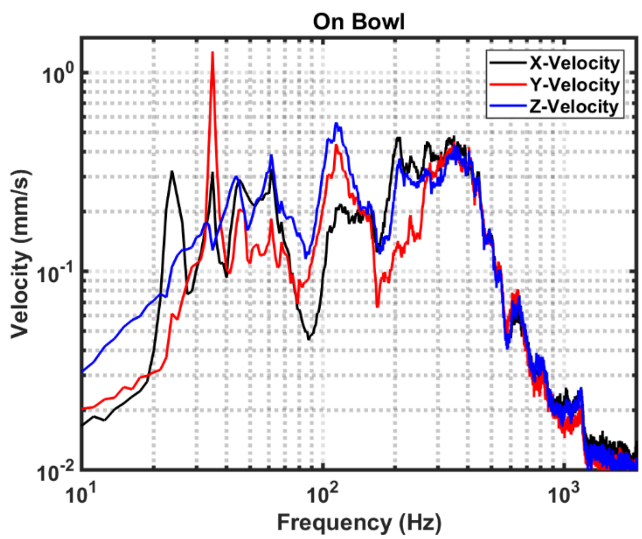

Figure 3.8: Spectra of the x, y, and z components of the velocity magnitude. Since many points were measured, these curves represent the averaged magnitude.

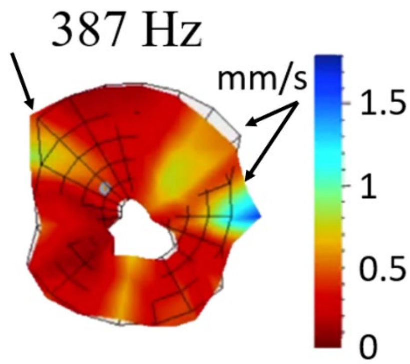

Figure 3.9: Visualization of the velocity operational shape at 387 Hz of the bowl. Scanning points near the forward right and left portions of the rim of the bowl (indicated by the black arrows) measured the highest velocity amplitude.

3.3 Flush Cycle

3.3.1 Experimental Setup

A vacuum-assisted toilet system was installed in the BYU hemi-anechoic chamber (and hallway) to measure the acceleration and radiated noise levels of an actual vacuum-assisted flush. Two vacuum tanks that are typically used on commercial airplanes were outside the chamber and evacuated by a high powered vacuum pump. An actual vacuum-assisted toilet was mounted to an iron block and placed in a hemi-anechoic chamber. Vacuum tubes attached the toilet to the tanks.

Two types of constrained layer damping materials in addition to Velcro were used. Pyrotek Decidamp CLD and 3M 4014 CLD were each applied to the bowl near the rim on the front left and right sides, one type at a time, as shown in Fig. 3.10. After removing the CLD, the loops of a Velcro strip were attached to the rim of the bowl and the hooks of the Velcro strip were attached to the inside of the toilet chassis where they would contact the loops as shown in Fig. 3.11. Velcro is not typically thought of as a constrained layer damping material. While it does act as a constrained layer damping material in this case, the Velcro varies from the CLD in this experiment because it stiffens the attachment of the bowl to the chassis of the toilet as opposed to a thin layer of metal on the backside of the viscoelastic without any extra connection to the chassis.

An accelerometer was used for measurements made during actual flush cycles instead of the 3D SLDV due to measurement difficulty. Measuring the bowl's response with the 3D Polytec SLDV while the bowl is right side up means needing to mount the SLDV on the ceiling pointing down. The hemi-anechoic chamber was not set up to mount a 3D SLDV on the ceiling. Measurement locations with the accelerometer corresponded with the locations scanned by the 3D SLDV earlier.

Figure 3.10: A photo of the Pyrotek constrained layer damping material applied to the bowl.

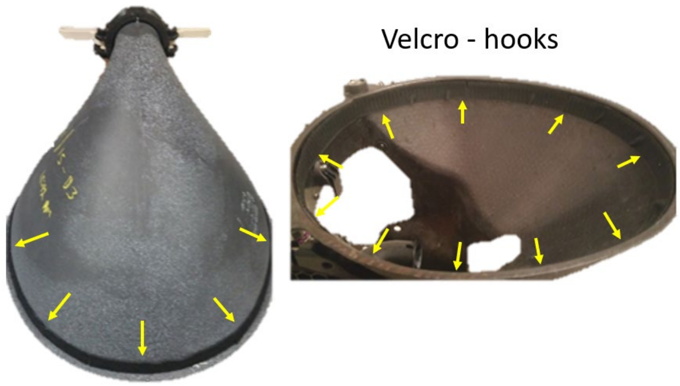

Figure 3.11: Two photos of the bowl. The first shows the loops side of the Velcro attached to the outside of the bowl. The second shows the hooks side of the Velcro attached to the inside of the chassis where the bowl makes contact.

3.3.2 Flush Cycle Structural Results

A baseline (no CLD treatment) grid on the bowl was recorded followed by the three different types of constraining materials. Figure 3.12 shows a comparison of accelerometer measurements for no damping treatment and Velcro treatment looking at the 390 Hz bin. The acceleration measured near the right rim of the bowl with no damping treatment was in the red part of the color spectrum while with Velcro, the acceleration level was in the cyan part of the color spectrum. This corresponds to a 20 dB reduction in acceleration at that location at 390 Hz. Figure 3.13 shows a spectrogram for the recording at the right rim location. The reduction is over the 100 – 10,000 Hz band shown. If the noise were dominated by structural vibrations that radiate sound, then there should be a corresponding 20 dB reduction in the radiated noise.

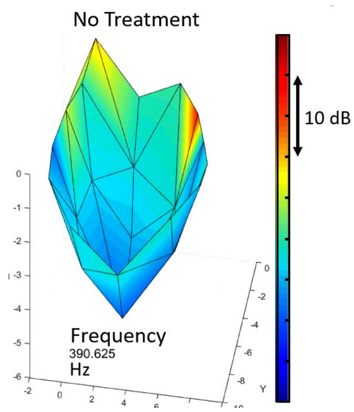

Figure 3.12: Visualization of the measured acceleration on the bowl surface during a dry flush with and without Velcro treatment at 390 Hz. A 20 dB reduction can be seen in the upper right and left sides of the bowl.

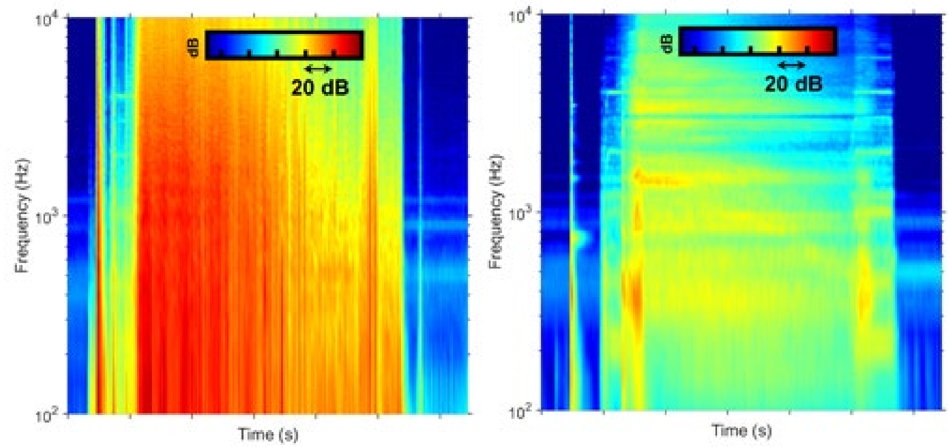

Figure 3.13: Two spectrograms of the acceleration measured near the top right of the bowl. The left spectrogram has no damping treatment while the right spectrogram has Velcro attached.

3.3.3 Flush Cycle Acoustic Results

Figure 3.14 shows the A-weighted running overall sound pressure level measured with a microphone one meter above the toilet comparing levels without CLD and with 3M 4014, Pyrotek CLD, and Velcro. The most reduction in the noise was achieved with the Velcro only during the valve opening event. Since this was only 3 dB and not similar to the 20 dB (or close to it) that was achieved structurally, it is determined that for radiated noise reduction purposes, structural vibrations are not the most significant contributor to the overall noise of vacuum-assisted toilets.

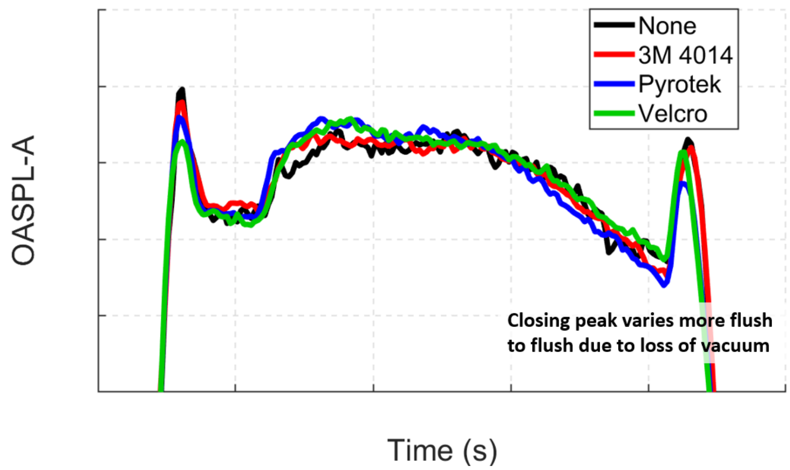

Figure 3.14: A plot showing the running overall sound pressure level A-weighted one meter above the toilet when the toilet was flushed under 4 conditions: 1. No damping treatment, 2. 3M 4014 CLD applied, 3. Pyrotek CLD applied, and 4. Velcro applied. Each curve represents an average of 5 flushes. The Velcro reduces the opening peak the most with a 3 dB reduction.

3.4 Conclusions

The frequency response between 10 and 2000 Hz of a vacuum-assisted toilet was measured with a 3D SLDV. Operational shapes associated with the frequency band from 300 to 500 Hz were used to inform the optimal placement of damping layers. While Velcro was able to reduce peak mechanical vibrations by 20 dB, the effect only translated into a 3 dB reduction in the radiated acoustic noise for the opening valve event. This suggests that structural vibrations (though present) are not a significant contributor to the noise from a vacuum-assisted toilet.

Chapter 4

Tube Insert: Radius of Curvature and Tube Length

4.1 Introduction

4.1.1 Background and History

Several past studies have focused on noise control for vacuum-assisted toilets. In 1987, Olin *et al*[2] invented a bypass valve and lid system for reducing the noise on vacuum toilets. A bypass valve provides a secondary source of air which enables the primary flush valve to close the acoustic transmission path to the user. A lid further closes off the transmission path of toilet noise to the user. In 1988, Oldfelt and Stahl[3] patented the idea to rinse while the valve was opening. Adding water (mass) to the bowl when the valve opens reduces the noise the valve makes while opening. In 1989, Ask *et al*[4] patented the idea to recycle grey water from sink rinse water and other sources as the toilet rinse water supply allowing for either more water per flush or less overall water use. Hufenbach *et al*[5] in 2008 made an acoustical analysis of a vacuum-assisted toilet, and showed that decreasing the vacuum pressure, modifying the valve and outlet area, and using a lid are some ways to reduce radiated noise. In 2013, Boodaghians *et al*[6] patented the idea to utilize a two-stage flush such that waste would be transferred to a transient tank attached to the bowl via a weak vacuum from where the waste can be accelerated with the strong vacuum down to the septic tank.

Other previous work suggests a need to reduce flow velocity to limit noise production. For this application, reducing flow velocity can present a danger of limiting toilet performance. Davies and Williams[10] shows that there is a power law relationship between the flow velocity to the sixth power and the propagating sound for large- and small scale turbulence in the plane-wave mode of a tube. Consequently, a small decrease in flow velocity can correspond to a large decrease in sound radiated. The relationship of in-tube radiation exceeds that of turbulence in free space by a factor of M^{-2}, where M is the Mach number, implying even more pronounced noise production for flow through tubes. However, high-frequency-small-scale turbulence can excite higher order modes which do not have the M^{-2} boost when nearly all modes are excited. Hufenbach *et al*[5] shows that with a 2/3 reduction in vacuum pressure for their system overall sound pressure level of the flush can be reduced by 6 dB. Their work shows a nonlinear relationship between vacuum pressure and sound pressure level in their Fig. 5.

4.1.2 Motivation for This Work's Noise Reduction Techniques

Several previous works suggest increasing the tube length between sound sources and the receiver location to affect noise reduction. The Occupational Safety and Health Administration (OSHA)[11] recommends placing all bends and valves at least 10 pipe diameters away from each other. Hoff[12] showed a 2-3 dB per meter attenuation in the 1-3 kHz frequency range for sound propagating in the upstream direction of a 90 meters per second gas flow. An attenuation over distance suggests that increasing tube length between aerodynamic noise sources in the tube and bowl can significantly reduce noise given a sufficient tube length. According to Davies and Williams[10] low frequency small-scale turbulence radiates into modes that decay exponentially with distance. Providing sufficient tube distance for small-scale low frequency turbulence to decay should therefore motivate increasing the tube length between the bowl and valve.

Additional references that present a mathematical development of evanescence in tubes can be found in Refs. 13-15.

Previous works also suggest reducing noise by increasing the bend radius of tube bends. Experiments done by Hufenbach *et al*[5] suggest modifying the bowl outlet geometry such that the bend radius is as large as it can be. An 8 dB noise reduction occurs in a tube with an infinite bend radius, i.e. a straight tube, on a vacuum-assisted toilet. Aissaoui *et al*[16] achieved a 4 dB noise reduction by performing a numerical optimization of an HVAC system in an automobile that considered geometric modifications to the tubes connecting the blowers to the outlets. Qiu and Liu[17] achieved a 2.5 dB noise reduction for jet engine bypass flow noise by numerically optimizing the tube geometry near the outlet. Vizzini *et al*[18] compared flow at 96 m/s through a straight tube with that through a tube with a 90-degree curve having a 7.5 cm bend radius. In the frequency range of interest of this work, the straight pipe radiated 2-5 dB less than the tube with the 90-degree bend.

The work reported here investigates the reduction in the radiated noise from a vacuum-assisted toilet that can be achieved by increasing the bend radius of tubes near the bowl and by increasing the length of tube between the valve and bowl. Since there are spatial constraints that limit the tube length and bend radius for any practical system, this investigation systematically varies the tube length and bend radius to find what the smallest combination that will achieve the most noise attenuation.

4.1.3 Chapter Layout

The layout of this chapter is as follows: Section 2 describes the setup of the vacuum-assisted toilet, the tube materials and shapes, and the data collection and analysis techniques used for this investigation. Section 3 presents data regarding the radiated noise of an initial prototype designated as the double spiral tube insert involving a long tube wrapped twice underneath the bowl, an investigation on the effect of reducing the bend radius and tube length from that of the double spiral tube insert, the acoustic equivalence of using different tube materials, and two tube inserts that use the bend radius and tube length constraints defined from the aforementioned investigation. In Section 4, conclusions are made that by increasing the bend radius and tube length between the bowl and valve, the radiated noise of a vacuum-assisted toilet can be reduced and that there is a critical bend radius and tube length required to maintain noise control performance relative to a tube with a large bend radius and long tube length.

4.2 Methods

4.2.1 Baseline Setup

We investigated noise associated with a vacuum-assisted flush in the Brigham Young University (BYU) variable acoustics chamber in a hemi-anechoic configuration. We connected a commercial vacuum-assisted toilet to a septic tank and evacuated the air in the tank down to a gauge pressure of -68 kPa (-20 inHg or -2/3 atm) for each flush. A 1.27 cm (0.5 in) free-field microphone was placed one meter above the front edge of the bowl pointing downwards toward the toilet. Figure 4.1 shows this in schematic form. Each flush cycle was repeated five times from which their running overall A-weighted sound pressure levels (OASPL-A) were averaged resulting in a single running OASPL-A. An individual flush did not vary more than 1-2 dB from another flush of the same configuration as shown by Fig. 4.2.

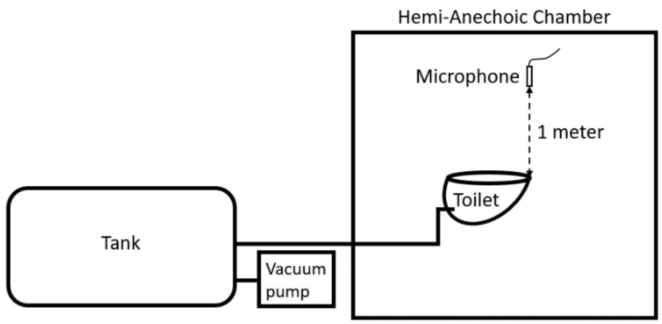

Figure 4.1: Schematic of experimental setup.

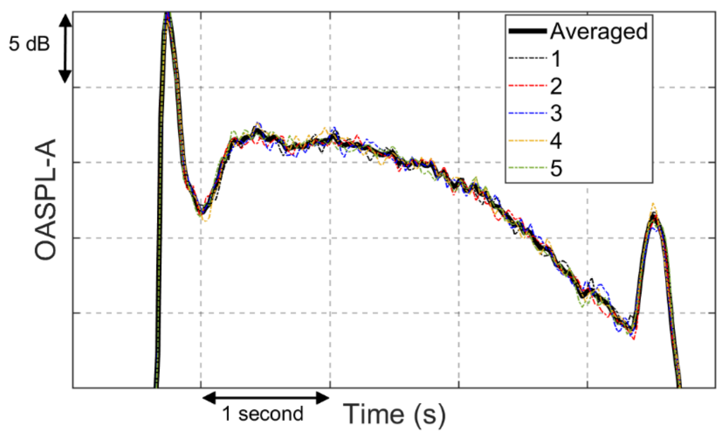

Figure 4.2: Five individual flushes with their average overlaid. Flushes of the same configuration tend not vary by more than 1-2 dB flush to flush.

A valve on the toilet separates a pressure difference between the cabin and the waste storage tanks. This pressure difference accelerates the flush contents causing them to collide with the tubes (most especially the bends) and the valve as it opens and closes. Structural vibrations can propagate from these collisions in the tubes to the bowl, vibrating the bowl which can radiate acoustically, contributing to the noise of the vacuum-assisted flush.

The noise from a vacuum-assisted flush can be characterized by three events associated with the status of the valve which is illustrated in Fig. 4.3. In our experimental apparatus, a constant vacuum pressure difference through the entire flush cycle was not possible, so the closing peak noise level is lower than what it would be in practice. The first and loudest sound is while the valve is opening which only lasts for a fraction of a second. While the valve is opening, it is partially obstructing the flow in the pipe causing large shearing forces and flow separation which generates lots of noise. The second characteristic is while the valve is completely open. While the valve is open, the noise is characterized by a high and relatively steady noise level over roughly 3 seconds. This noise is dominated by the turbulence of the flow that has accelerated to very fast speeds. The third is while the valve is closing. Again, the valve partially obstructs the flow which causes large shear forces and flow separation. The radiated noise level spikes again but not as high as the initial peak when the valve opened. Our vacuum system does not have the capacity to maintain suction during the entire ~4 seconds of the flush cycle. Figure 4.3 shows what the running OASPL-A might be if our system could maintain suction during the entire flush cycle. A spectrogram of the noise levels is shown in Fig. 4.4. It should be noted that at least three tones (~100 Hz, ~200 Hz, and ~300 Hz) appear in the spectrogram which are associated with the vacuum pump operating noise and is not associated with the vacuum-assisted flush noise. Figure 4.4 shows that the initial noise contains significant energy from about 300 Hz to 3 kHz with some insignificant frequency banding. The steady-vacuum noise contains significant energy from about 300 Hz to about 8 kHz with evidence of tonal noise apparent by the horizontal banding in the spectrogram.

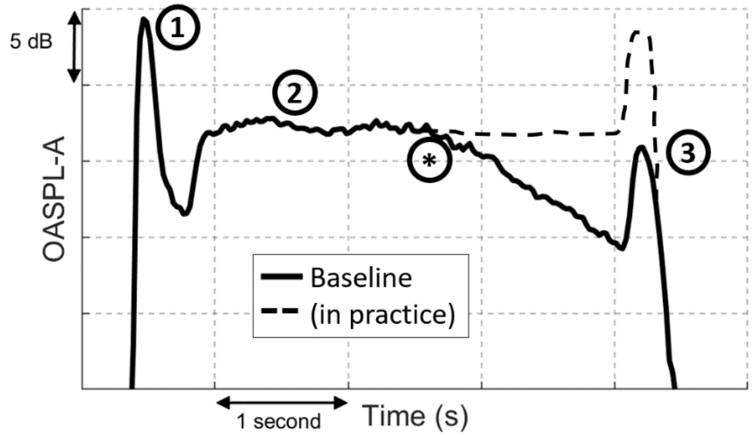

Figure 4.3: Running OASPL-A for the baseline tube geometry. The number 1 indicates the valve opening sound level, 2 indicates the steady vacuum phase, the star indicates the time during the flush that vacuum suction is no longer sufficient to replicate a normal flush, and 3 indicates the valve closing sound level.

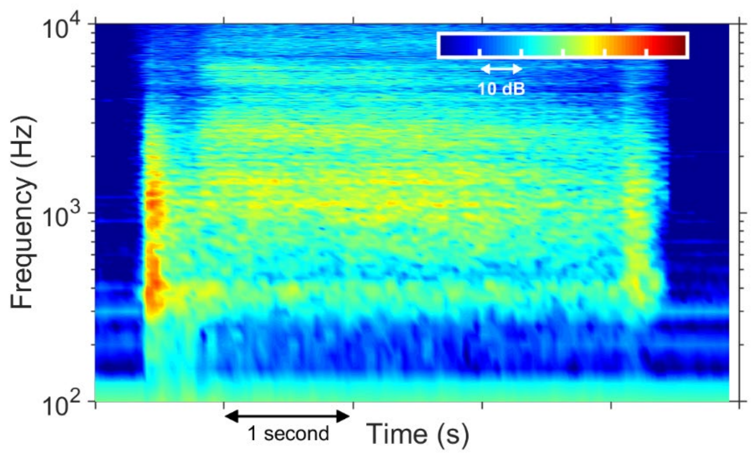

Figure 4.4: Spectrogram of baseline flush. Three dominant tones are perceptible from the vacuum pump at about 100, 200, and 300 Hz that do not correspond to flush noise.

4.2.2 Tube Materials and Geometries

Three tube materials were used throughout this investigation: First, a 4.45 cm (1.75 in) inner diameter tube made of hard plastic with a smooth inside used currently in vacuum-assisted toilets, shown in Fig 4.5a; second, a 5.08 cm (2.0 in) inner diameter tube made of flexible plastic with 5 stiffening corrugations per 2.54 cm (1.0 in), shown in Fig. 4.5b; third, a 5.08 cm (2.0 in) inner diameter tube 3D printed of ABS, shown in Fig. 4.5c.

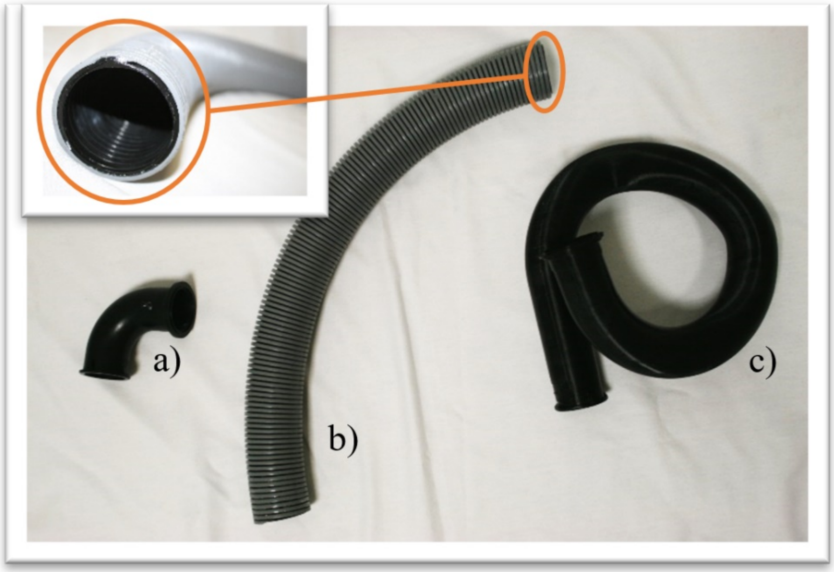

Figure 4.5: Photo of tube materials used. a) 90-degree elbow included with vacuum toilet, b) corrugated flexible tube, c) 3D printed tube

We investigated four tube geometries for connecting the bowl to the valve: First, the tube currently installed on vacuum-assisted toilets with a 90-degree bend and radius of curvature of 4.5 cm, shown in Fig. 4.6. The radius of curvature is measured from the centerline of the tube to the center of the circle that the centerline arc would make if allowed to continue for 360 degrees. Second, a flexible tube wrapped twice around the base of a toilet, shown in Fig. 4.7. Third, a flexible tube forming a straight connection between the bowl and valve with no bends, shown in Fig. 4.8. Fourth, a flexible tube in a spiral-esque shape with a pitch of 2.5 inches per revolution that makes one revolution with variable bend radius, shown in Fig. 4.9. The combination of the smallest bend radius and tube length without significant loss in performance was 3D printed to evaluate the effect of a smooth versus corrugated tube.

Figure 4.6: Notional diagram of baseline tube geometry in relation to the toilet

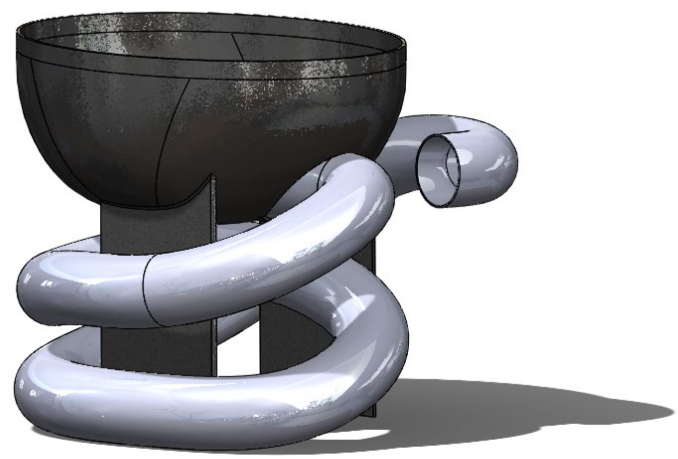

Figure 4.7: Notional diagram of double spiral tube insert in relation to the toilet

Figure 4.8: Photo of straight-tube configuration

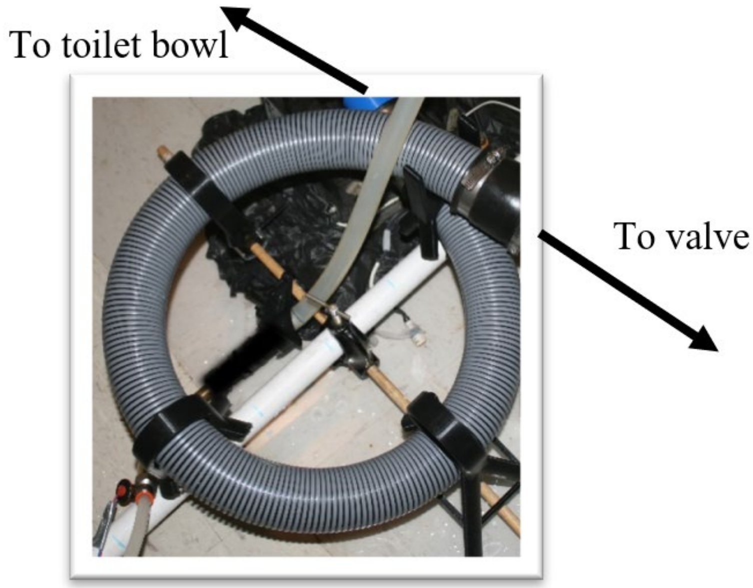

Figure 4.9: Photo of varying bend radius investigation.

4.3 Results and Discussion

4.3.1 Double Spiral Tube Insert

To verify whether increasing the bend radius and tube length between the bowl and valve reduces the radiated noise, a 1.7 m flexible tube was inserted which connected the bowl to the valve and wrapped twice around the base of the toilet with an approximate 16.5 cm bend radius, similar to the drawing in Fig. 4.7. The double spiral tube insert reduced the initial peak by 14 dB, the steady-vacuum level by 4 dB on average and the closing peak by 4 dB as shown in Fig. 4.10. The double spiral tube insert tube reduced the noise significantly over the broad frequency range of 300 Hz to 10 kHz throughout the whole flush cycle as shown by comparing Fig. 4.4 to Fig. 4.11. Since the double spiral tube insert does not fit inside the footprint of the toilet, an investigation of the effect the tube length and bend radius has on the noise was carried out. Finding a shorter tube length and smaller bend radius that does not significantly increase the noise control performance of the double spiral tube insert is advantageous.

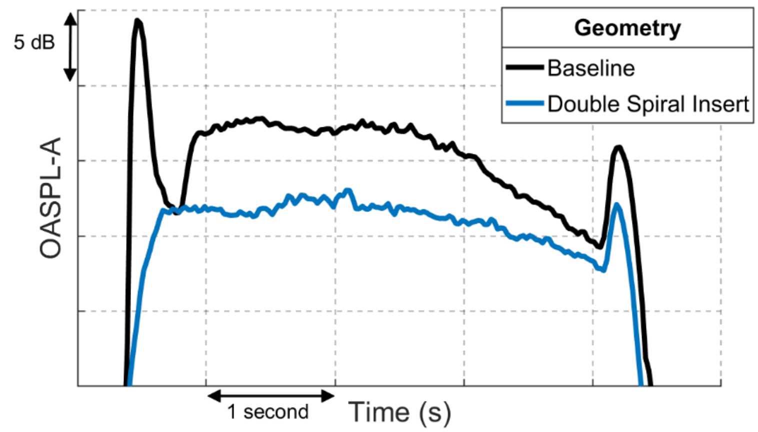

Figure 4.10: Running OASPL-A for baseline tube flush and double spiral tube insert flush, each averaged over five flushes

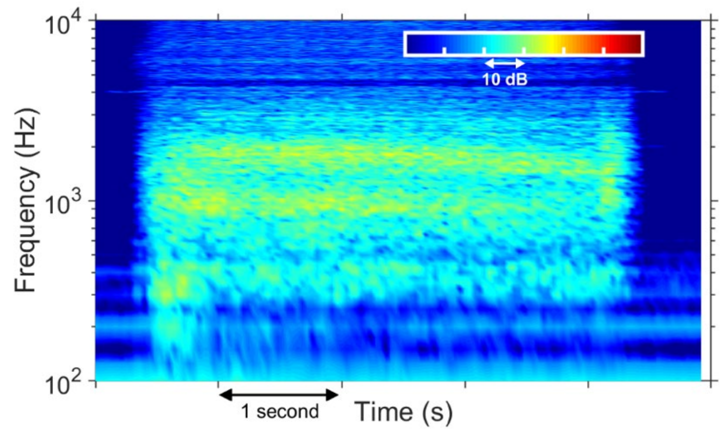

Figure 4.11: Spectrogram of double spiral tube insert flush

4.3.2 Reduced Bend Radius with Constant Length Tube

In a configuration similar to Fig. 4.9, the bend radius was decreased without modifying the tube length. A flexible tube was coiled into a spiral with one revolution behind the toilet. The valve was also moved behind the toilet and spiral. This was done for experimental convenience, moving the valve in this manner is not required to make this noise control technique possible. Starting at 16.5 cm, the bend radius was progressively reduced to 15, 13.5, 12.5, 11.5, 10.5, and 9.5 cm. As the bend radius was decreased more of the flexible tube continued tangentially after the spiral. The flexible tube could not be forced tighter than a circle with a bend radius of 9.5 cm which set a lower limit for this investigation. Fig. 4.12 shows the OASPL-A for each configuration. Surprisingly, the initial peak, steady-vacuum sound level, and closing peak are all nearly identical across all bend radii with the exception of the 16.5 cm bend radius opening peak having an early 4 dB pop. Bend radius may not be as significant a contributor as hypothesized.

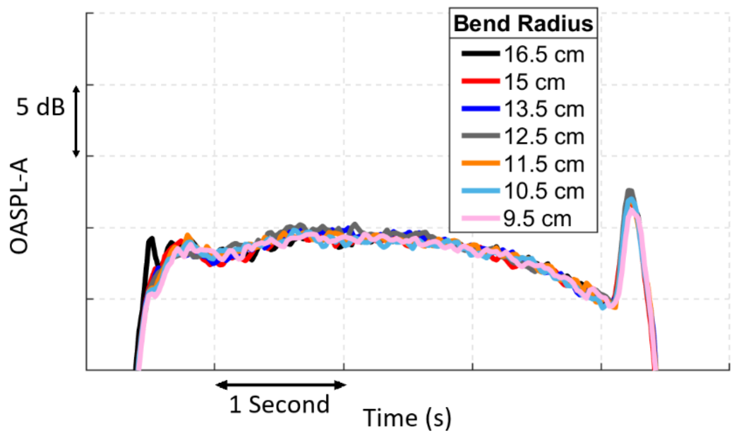

Figure 4.12: Running OASPL-A for the varying bend radius investigation. The bend radius is varied from 16.5 cm to 9.5 cm while the tube length is kept constant at 1.7 meters.

4.3.3 Reduced Tube Length with Constant Bend Radius

In a configuration similar to Fig. 4.8, only the tube length was decreased. The flexible 1.7 m tube was attached to the bowl and connected to the valve behind the toilet, keeping the tube completely straight. The tube was progressively shortened from 1.85 m down to 1.45, 1.05, 0.75, 0.55, 0.40, 0.30, and 0.15 m. Fig. 4.13 shows the OASPL-A for each configuration. The opening peak and steady-vacuum noise level are lower with longer tube lengths. From 0.15 m to 1.85 m, there is a 10 dB reduction in the initial peak and steady-vacuum noise level. There is a 5 dB noise reduction from 0.15 to 0.30 m for the initial peak and 2-3 dB for the steady-vacuum. From 0.75 to 1.05 m there is a 4 dB reduction in the initial peak and 1-2 dB in the steady-vacuum noise level. Similar trends follow where small changes in tube length for a short tube change the noise more than large changes in tube length for a long tube.

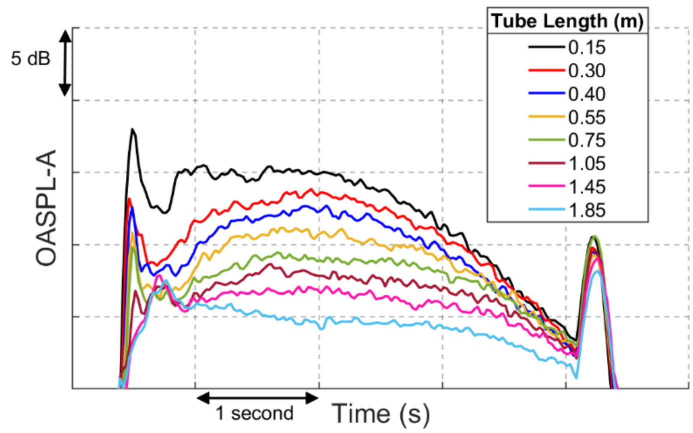

Figure 4.13: Running OASPL-A for the varying tube length investigation. The tube length was varied from 1.85 m to 0.15 m with a completely straight tube between the bowl and valve.

4.3.4 Reduced Bend Radius with Reduced Tube Length

In the final configuration, both bend radius and tube length were decreased simultaneously by removing excess tubing after each contraction of the bend radius. Figure 4.14 shows the OASPL-A curves, while the combinations of bend radii and tube length are reported in the legend. The initial peak varied by less than 1 dB. The steady-vacuum levels varied by about 1 dB for tube lengths 1.04 m and greater, while the tube with 0.77 m length increased by about 2 dB. The closing peak varied by 3 dB, except for the 0.77 m tube which was 2 dB lower than the next lowest configuration. There seems to be a tradeoff between the steady-vacuum level and the closing peak level with this tube size, i.e. a 2 dB increase during the steady-vacuum phase for 2 dB decrease in the closing peak level compared to the 1.7 m length and 16.5 cm bend radius tube. Larger tubes show no significant variation in the initial peak and steady-vacuum phase from the largest tube, while there is a 3 dB spread in the closing peak level. We chose the 9.5 cm bend radius and 0.77 m tube as our smallest version that preserves a significant amount of the reduction performance.

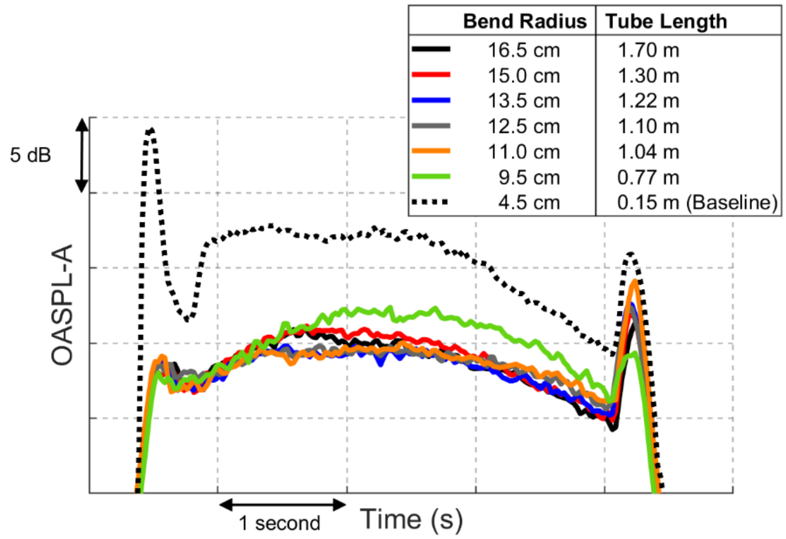

Figure 4.14: Running OASPL-A for the changing bend radius and tube length investigation

4.3.5 3D Printed Version

Based on the results of the experiments with bend radius and tube length, a spiral tube matching the geometry of the flexible tube was 3D printed and installed on the vacuum-assisted toilet. Figure 4.15 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. Figure 4.16 and Fig. 4.17 show spectrograms of the flushes with a flexible tube and 3D printed tube. The flexible tube has more energy in the 2-3 kHz and 10-20 kHz range while the 3D printed version has more energy in the frequency range from 3-10 kHz than the flexible tube. Consequently, the choice of material may be important for sound quality.

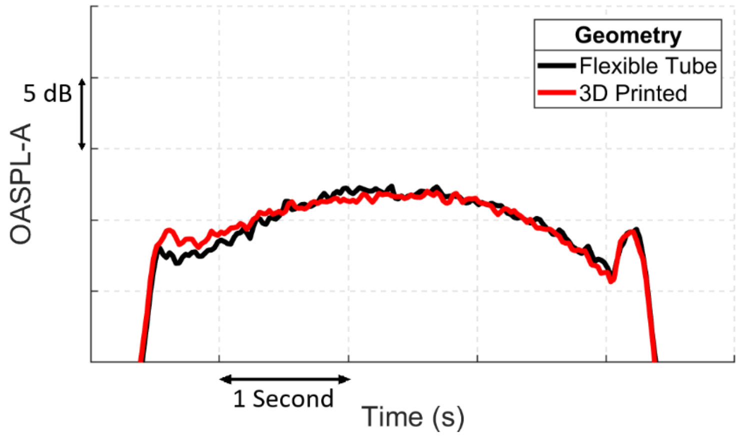

Figure 4.15: Comparison of the flexible tube geometry with 9.5 cm bend radius to the 3D printed version. Levels are nearly the same.

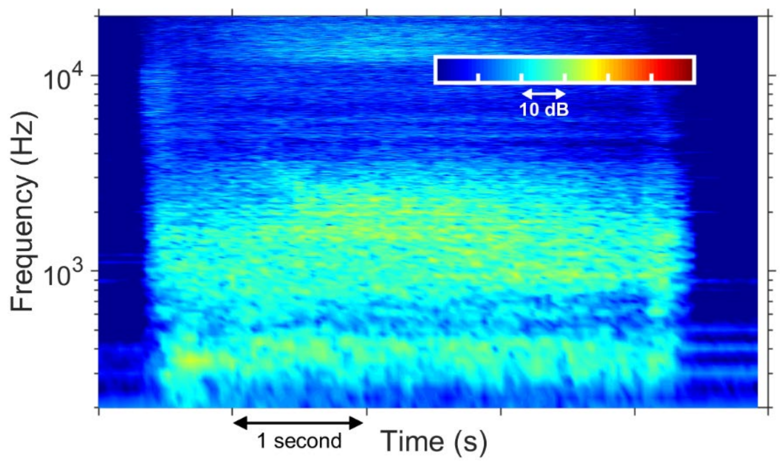

Figure 4.16: Spectrogram of 9.5 cm bend radius flexible tube flush noise

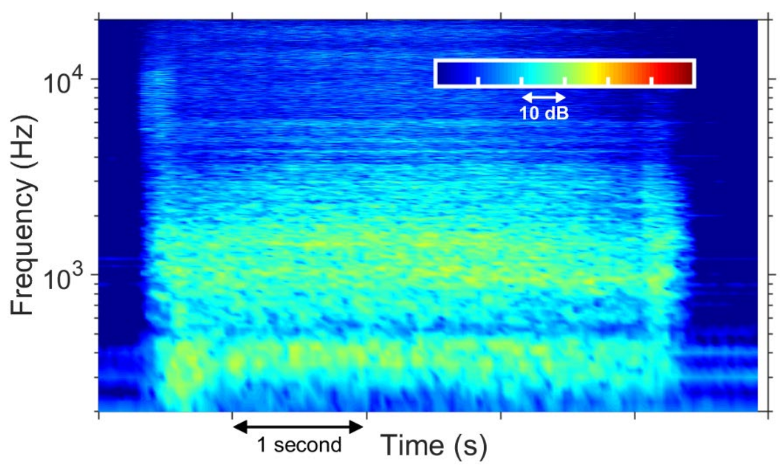

Figure 4.17: Spectrogram of 3D printed 9.5 cm bend radius tube flush noise

There may not be enough 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. Other form factors besides the previously selected spiral can be printed and tested with similar bend radii and tube lengths. From Section 4.3.2, it was found that the bend radius need not be greater than 9.5 cm to preserve noise control performance. From Section 4.3.3, it was found that the tradeoff between noise control performance and tube length becomes less advantageous with longer tube length, 0.7 meters being the elbow in the tradeoff curve. From Section 4.3.4, it was found that when looping the tube, the shortest tube length with the tightest bend radius when noise reduction performance begins to be affected is 0.7 m tube length and 9.5 cm bend radius. This length and bend radius become the design constraints for designing the smallest tube possible without significantly affecting noise control performance. From Section 4.3.5, it was found that a smooth or corrugated tube makes little overall sound level difference but may impact the sound quality.

4.3.6 Wrapped & Back-Only Inserts

A replacement for the 90-degree tube was designed to fit underneath the bowl without modifying any other toilet component. With the above constraints, we designed a replacement insert which wraps around the left or right half of the base which effectively increases both the tube length and bend radius between the bowl and valve as shown in Fig. 4.18. Another insert was designed to fit completely behind the back of the toilet while still following the above constraints, as shown in Fig. 4.19. Figure 4.20 shows the running overall sound pressure level resulting from the baseline, double spiral, wrapped, and back-only tubes. Importantly, the initial peak level of the wrapped tube is the same as the double spiral tube insert while the back-only insert is 1.5 dB lower. The wrapped and back-only inserts produced a steady-vacuum level within 1.5 dB of the levels produced with the double spiral tube insert. The closing peak levels of the wrapped and back-only inserts are within 2 dB of the levels with the double spiral tube insert. In Fig. 4.20, the sound of the valve opening is still present with the wrapped and back-only inserts although 14-16 dB quieter than the baseline. However, with the double spiral tube insert, the sound of the valve opening is not present but seems to only have the steady-vacuum noise. What is meant by “the sound of the valve opening” is the characteristic rising OASPL-A followed by a drop in level and then the steady-vacuum level is reached. The spectrograms of the baseline, back-only, and wrapped tubes show a broadband pulse at the beginning of the flush cycle as shown in Fig. 4.4, Fig. 4.21, and Fig. 4.22 respectively while the double spiral tube insert does not in Fig. 4.11. Instead, the double spiral begins with a gradual increase in OASPL-A up to the steady-vacuum phase noise level.

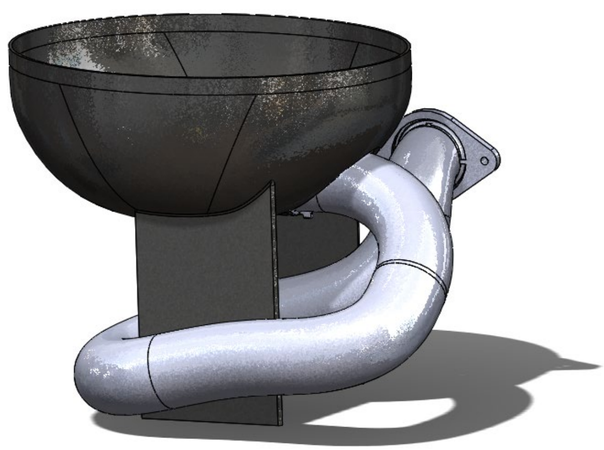

Figure 4.18: Notional diagram of how the wrapped tube interfaces with the toilet

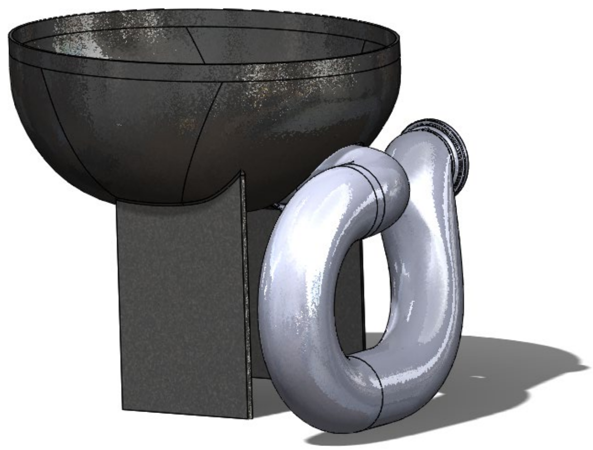

Figure 4.19: Notional diagram of how an insert may fit behind the toilet i.e. back-only insert

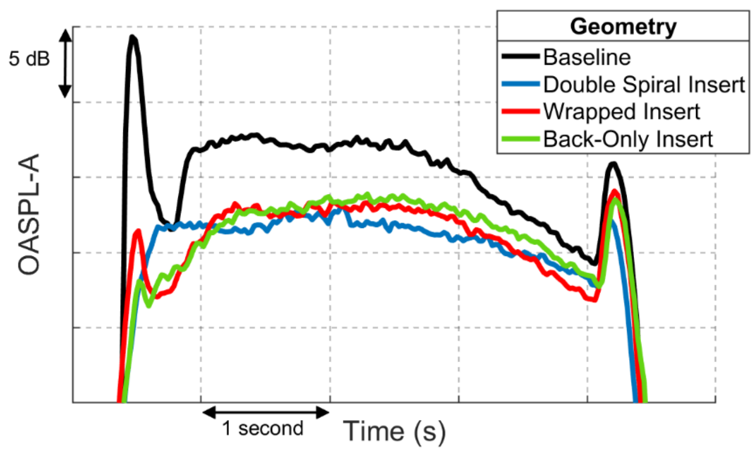

Figure 4.20: Running OASPL-A comparing the baseline setup to the double spiral tube insert, wrapped insert, and the back-only insert. Table 1 tabulates the noise control performance of each tube for the initial peak, steady-vacuum phase, and closing peak.

Table 1: Nominal noise control performance of the double spiral, wrapped, and back-only insert for the initial peak, steady-vacuum noise level, and closing peak.

	Initial Peak (dB re Baseline)	Steady-vacuum (dB re Baseline)	Closing Peak (dB re Baseline)
Double Spiral	Not apparent	-4.3	-3.7
Wrapped	-14	-3.7	-1.8
Back-Only	-17	-3.5	-2.3

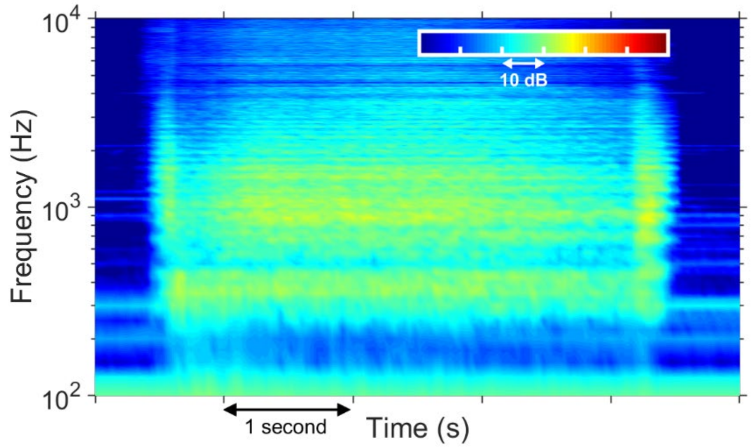

Figure 4.21: Spectrogram of the wrapped tube flush noise

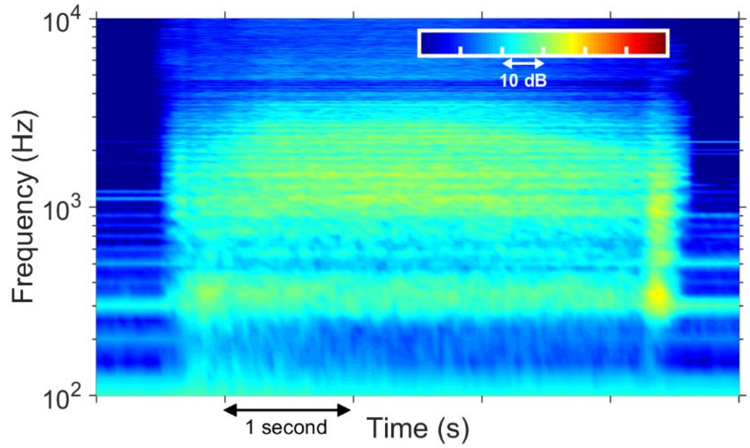

Figure 4.22: Spectrogram of the back-only insert flush noise

4.4 Conclusions

Chapter 4 investigates the effect on radiated sound of tube bend radius and tube length on a vacuum-assisted toilet for tubes that connect the bowl to the valve. Like OSHA, Hoff, and Davies and Williams suggest, this investigation of radiated noise from a vacuum-assisted toilet indicates that increasing tube length reduces the radiated noise. The bend radius did not show to be a significant contributor to the radiated noise. Replacing the baseline tube with a 1.7 m (33 pipe diameters) tube with a bend radius of 16.5 cm wrapped two times underneath the toilet reduces the radiated noise of a vacuum-assisted toilet by 14 dB during the valve opening and 4 dB during the "steady-vacuum" phase. After an investigation of placing a spiral tube behind the toilet, a similar noise reduction was achieved with a tube length of 0.77 m (15 pipe diameters) and bend radius of 9.5 cm. Using a tube with either a smooth or corrugated inside surface did not affect the overall levels but did have some impact on the spectral content which is linked to sound quality. We designed a tube to fit underneath the toilet bowl or fit completely behind the bowl in a compact manner while applying these tube length and bend radius constraints. Noise reduction performance was maintained with both smaller configurations. These advances may help provide an improved experience for transport vehicle lavatory users and passengers by providing the capability to retrofit already installed vacuum-assisted toilets. Ongoing and future investigations may use this tube design in concert with other noise control strategies.

Chapter 5

Noise Control Mechanisms

5.1 Introduction

A geometric modification of the tube that connects the bowl to the valve, as explained in Chapter 4, was shown to be effective at reducing the noise radiating from a vacuum assisted toilet. It was hypothesized that the mechanisms for reducing the radiated noise are evanescent decay of sound generated from the valve, decreased flow velocity and turbulence.

5.2 Evanescent Decay

5.2.1 Previous Work

Several previous works suggest increasing the tube length between sound sources and the receiver location affects noise reduction due to evanescent decay. Hoff[12] showed a 2-3 dB per meter attenuation in the 1-3 kHz frequency range for sound propagating in the upstream direction of a 90 meters per second gas flow. This suggests increasing tube length between aerodynamic noise sources in the tube and bowl can significantly reduce noise. According to Davies and Williams[10] low frequency small-scale turbulence radiates into modes that decay exponentially with distance. This suggests noise from small-scale low frequency turbulence can be reduced with sufficient tube distance from the source location to the bowl. Additional references that present a mathematical development of evanescence in tubes can be found in Refs.13-15. Evanescence is stronger for higher order modes which are generated by discontinuities[23,24] like the flush plate as it opens.

The first cut-on frequency for a straight 2” inner diameter with no mean flow is when the wavenumber,

$$k_{m,\mu} = \sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{\alpha_{m,\mu}}{a}\right)^2}, \quad \text{Eq. 1}$$

becomes imaginary when $\frac{\omega}{c} < \frac{\alpha_{m,\mu}}{a}$, where m and μ are the modal numbers and $\alpha_{m,u}$ are the zeros of the first derivative of the Bessel function of the first kind of order m, and a is the tube radius. This puts the first cut-on frequency for this tube without mean flow at 3.96 kHz. If mean flow[25] is included,

$$k_{m,\mu} = \left(-\frac{\omega}{c}M \pm \sqrt{\left(\frac{\omega}{c}\right)^2 - \beta^2\left(\frac{\alpha_{m,\mu}}{a}\right)^2}\right)/\beta^2, \quad \text{Eq. 2}$$

which has an imaginary part when $\frac{\omega}{c} < \beta\frac{\alpha_{m,\mu}}{a}$, where $\beta = \sqrt{1-M^2}$. This expression corrects the first cut-on frequency to be 3.56 kHz. It also means there is a real part no matter what frequency. With a real part for all frequencies and modes, it is likely that more sound will radiate. Since the bulk of the noise is below 3 kHz, it is very likely that evanescent decay is occurring in the tube downstream of the bowl.

5.2.2 Methodology

To measure evidence of evanescent decay, pressure transducers were flush mounted into the 3D spiral tube as shown in Fig. 5.1. The static pressure change of the tube when the flush begins is so large that PCB Piezotronics 112A23 pressure probes were used which have a dynamic range up to 190 dB and a noise floor of 110 dB. Measurement locations were designed for every 20 degrees (about 3 cm centerline distance) along the tube. Figure 5.2 shows a photo that helps illustrate how the spiral tube interfaces with the toilet and how the valve is placed relative to the toilet. Evanescent decay can manifest itself as an exponential decay in pressure or linear decay in decibels per meter from the valve upstream towards the bowl. To determine if evanescent decay is a mechanism for the noise reduction of the inserted tube, sound pressure levels across the tube were measured. Individual time slices were compared across the whole tube length (e.g. the time the valve opens or a certain time during the steady-vacuum phase).

Figure 5.1: Photo of the 3D printed spiral tube with flush mounts built in.

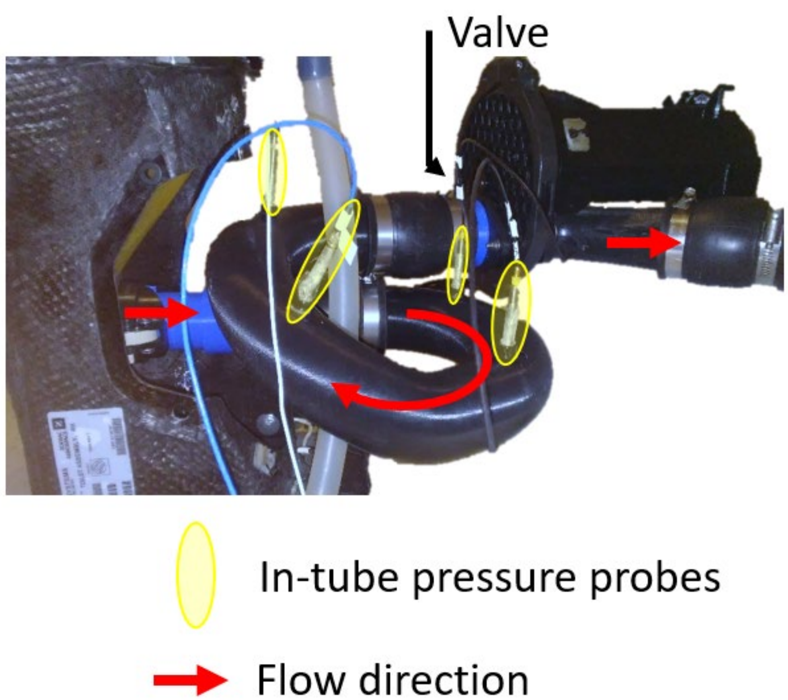

Figure 5.2: Photo of a 3D printed spiral with pressure transducers flush mounted every 90 degrees.

5.2.3 Results

The measured OASPL-A along the tube as the valve opened are shown in Fig. 5.3. This method does not track a single mode's evanescence but rather the sum of all modes and their partial evanescent decay. Near the valve, the highest noise levels are measured. Measurements farther upstream (closer to the bowl) have noise levels lower than those downstream with spatial decay rate of 9.75 dB per meter. This decay may be a significant contributor to the effectiveness of the tube insert at reducing the opening peak levels.

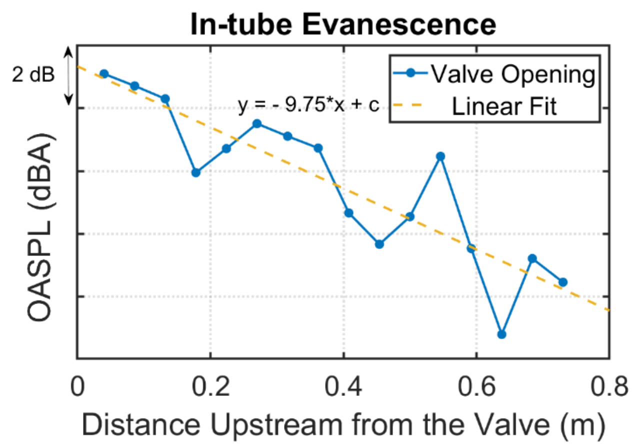

Figure 5.3: OASPL-A while the valve is opening measured along the tube length. A 9.75 dB/m can be fitted from the data

The measured OASPL-A along the tube during the steady-vacuum phase are shown in Fig. 5.4. A linear fit suggests a 1.2 dB/m reduction but the standard deviation from measurement location to measurement location in the tube is larger than the slope of the fit. Both the variation and the low decay rate suggest that there is much less evanescent decay during the steady-vacuum phase than for the valve opening event. This is consistent with the radiated levels in Fig. 4.10 where the opening peak was reduced by 13-16 dB with an insert while the steady-vacuum noise levels were reduced about 5 dB.

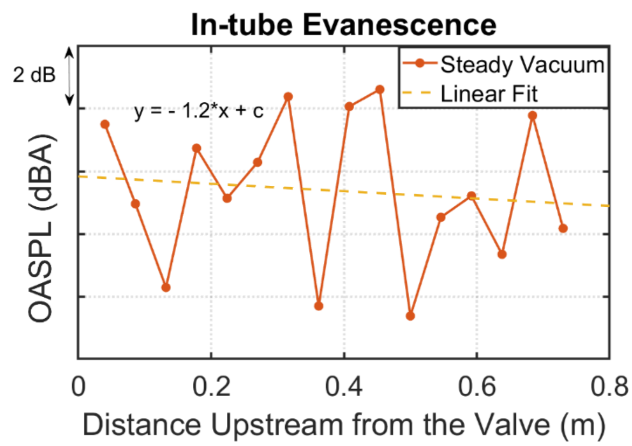

Figure 5.4: OASPL-A while the valve is completely open measured along the tube length. While a 1.2 dB/m reduction can be fitted from the data, the standard deviation from location to location does not allow for much confidence in the fit.

5.3 Reducing Flow Velocity

Other previous work suggests a need to reduce flow velocity to limit noise production. Davies and Williams[10] show that there is a power law relationship between the flow velocity to the sixth power and the propagating sound for large- and small scale turbulence in the plane-wave mode of a tube. Consequently, a small decrease in flow velocity can correspond to a large decrease in sound radiated. The relationship of in-tube radiation exceeds that of turbulence in free space by a factor of M^{-2}, where M is the Mach number, implying even more pronounced noise production for flow through tubes. However, high-frequency, small-scale turbulence can excite higher order modes which do not have the M^{-2} boost when nearly all modes are excited. Hufenbach *et al*[5] shows that with a 2/3 reduction in vacuum pressure that the overall sound pressure level of the flush can be reduced by 6 dB.

5.3.1 Methodology

The flow velocity is an important quantity to measure for describing the noise generation mechanisms for a vacuum-assisted toilet. A high-speed camera at 100,000 frames per second recorded flow through clear cylindrical tubes just downstream of the valve. This is shown in Fig.

5.5. The flow velocity was measured by tracking the vaporized clouds of rinse water from the left to the right side of the aperture as shown in Fig. 5.6. Many difficulties arose in measuring the vapor velocity, one of which was the sheet of water that creeps along the surface of the tube which interrupts the line of sight to the centerline flow. To minimize the effect of the sheet along the tube surface, the rinse was delayed until after the valve was completely open such that the fastest moving vapor could make it to the recording aperture before any surface sheet develops over the aperture. Knowing the distance from the left to right side of the aperture and how many frames the transit took, a velocity can be calculated. This painstaking process was done for both the baseline geometry and the wrapped insert tube. There is mean flow velocity in addition to velocities of particles moving much faster and slower than the mean flow, thus for every vacuum level and tube geometry, many parts of the flow needed to be tracked. In addition, the hope was that there would be visible flow patterns that would indicate a qualitative flow difference that describes why the tube insert was successful e.g. uniform flow downstream that was otherwise separated or recirculating with the baseline tube.

Figure 5.5: Photo of the clear tube for flow velocity measurements

The flow velocity for the baseline, Fig. 4.6, and wrapped insert, Fig. 4.18 configurations for the various vacuum levels was calculated and is presented in this section. In addition, flow velocity versus radiated sound pressures is also compared. Finally, vacuum level to sound pressure level is compared.

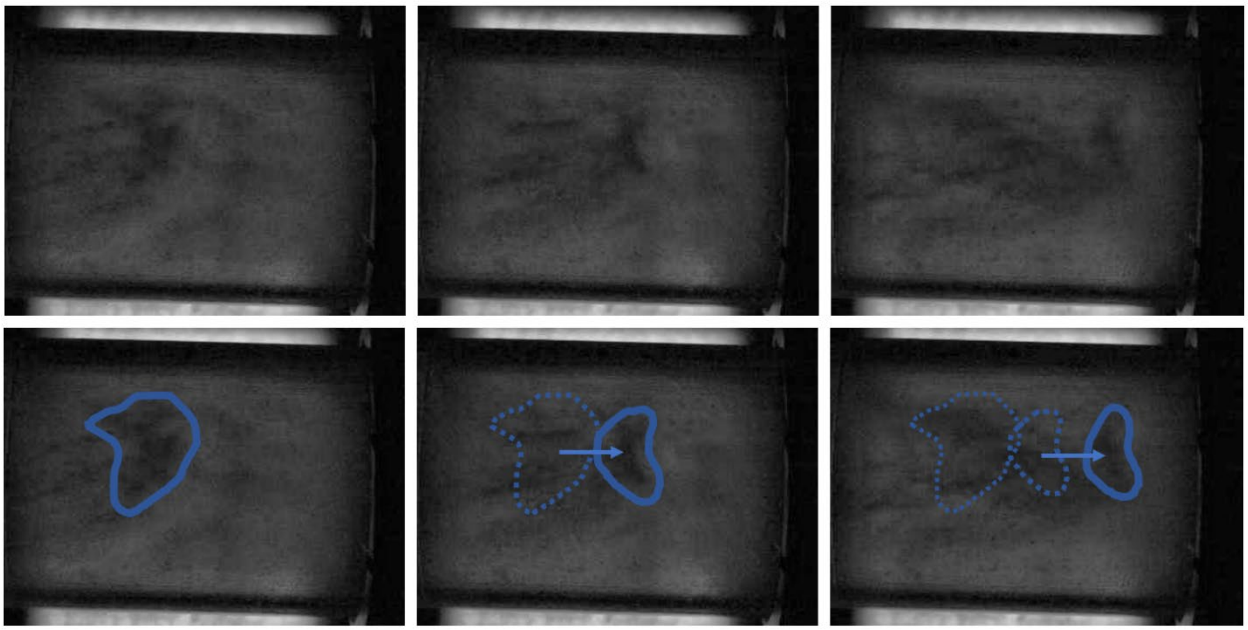

Figure 5.6: Tracking water vapor from left to right for flow velocity measurements. The first row is the same as the second but the second highlights the scheme used to calculate the flow velocity.

5.3.2 Results & Discussion

The velocity versus gauge pressure is presented in Table 2 and visualized in Fig. 5.7. In general, the stronger the vacuum, the larger the range of velocities in the flow. A larger velocity range with stronger vacuum makes sense because a stronger vacuum can typically accelerate fluid to a higher velocity than a weaker vacuum. In addition, there is still the no slip condition which requires there to be some fluid at rest on the surface of the tube. The mean velocities for the baseline geometry does not have a well-defined relationship to vacuum level. The mean velocity of the wrapped insert, however, does increase with vacuum pressure but is lower in magnitude than the baseline velocity for each vacuum pressure. Because the flow is mainly air, it is highly compressible. The air converts the potential energy of the pressure gradient into potential energy due to being compressed rather than kinetic energy i.e. choked flow. The mean velocity of the baseline geometry may become choked at 150-160 m/s based on the pressure gradient from the bowl to the valve location where vacuum initially was introduced. The wrapped insert introduces vacuum pressure farther downstream which likely causes the pressure difference between ambient and vacuum pressure to be spread along the tube. A smaller pressure gradient means less potential energy to be converted into kinetic energy so the wrapped tube has a lower mean flow velocity.

Table 2: Mean flow velocity for various initial gauge vacuum levels for the baseline and wrapped insert tubes in addition to the corresponding velocity ranges

	-20inHg	-18inHg	-16inHg	-14inHg
Baseline Mean Flow	151	139	165	132
Wrapped Mean Flow	139	128	119	99
Baseline Range	121 - 210	108 - 191	157 - 180	113 - 153
Wrapped Range	126 - 171	107 - 139	107 - 129	85 - 114

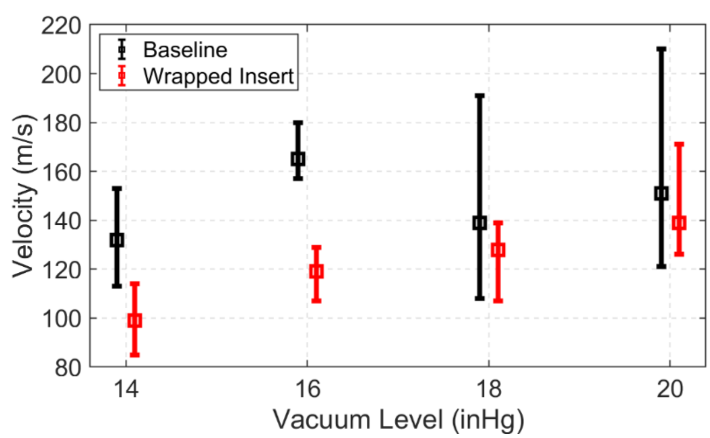

Figure 5.7: Flow velocity versus vacuum level. Vacuum levels are reported as positive vacuum which is negative gauge pressure. The squares represent the mean velocity value while the bars represent the range of velocities.

One major motivation for this section is to determine a relationship between the flow velocity and the radiated noise. Figure 5.8 shows that for the baseline geometry, there is not an obvious trend since the mean velocity is approximately 150 m/s for all vacuum levels. One might be able to convince oneself of a 0.1 dB per m/s slope (e.g. 150 m/s is 5 dB louder than 100 m/s) for at least the wrapped insert and maybe the baseline tube if the velocity range were considered instead of the mean velocity.

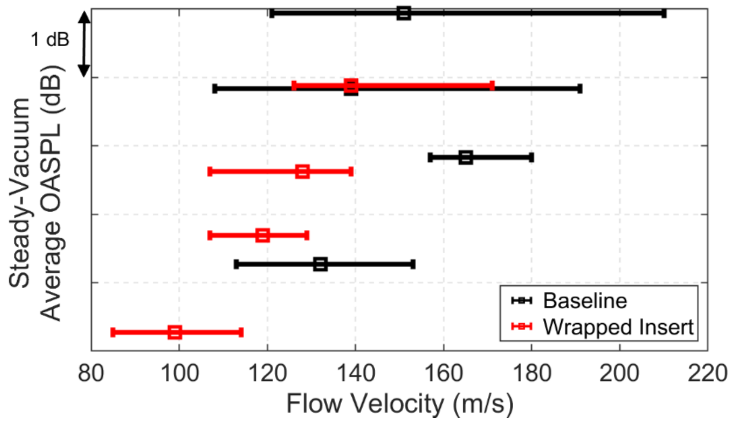

Figure 5.8: Flow velocity versus average OASPL during the steady-vacuum phase.

Some interesting differences between the baseline and wrapped tube running OASPL are shown in Fig. 5.9. The initial peak is wider, the steady-vacuum noise level is lower, and the closing peak is higher for the wrapped tube. These results look different than those in Chapter 4 because the rinse is delayed until after the valve is completely open. Since the initial peak is present for a wrapped tube flush with a delayed rinse, it is apparent that the rinse is still required for full effectiveness of the wrapped tube.

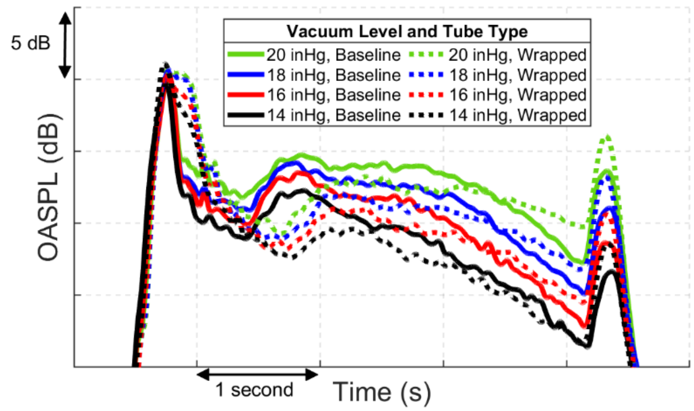

Figure 5.9: Running OASPL for each vacuum level and tube geometry. The rinse was delayed until after the valve is completely open.

5.4 Conclusion

In-tube measurements show evidence of pressure magnitude decay upstream from the valve to the bowl. This indicates there is likely evanescent decay through the tube while the valve is opening. No significant pressure magnitude decay was found through the tube during the steady-vacuum phase indicating that if there is evanescent decay, it is of modes being generated as the valve is opening but not while it is completely open. The pressure magnitude decay is typically less than the total noise reduction magnitude of the initial peak for a standard rinse which indicates that the tube allows for the rinse to more effectively reduce the peak noise. Some initial measurements have shown that the peak noise level is sensitive to the rinse timing.

Flow velocity was measured for the baseline and wrapped insert tube configurations in a clear portion of tube just downstream of the valve. A weak correspondence between flow velocity and sound level suggests that a change in velocity is likely not the mechanism for improved noise control performance of the wrapped insert.

Chapter 6

Valve Modifications

6.1 Introduction

As has been discussed in Section 4.1.2 and Section 5.3.2, the valve has a high impact on the noise generated. Therefore, valve opening and closing speed, effects of multiple valves, valve cutout geometry, and swing direction are explored in this chapter.

Flow across orifices in tubes have been studied by many. In particular, Ward-Smith wrote "Internal Fluid Flow"[19] and "Pressure Losses in Ducted Flows"[26] which show different flow patterns over varied orifices at high Reynolds number. Figure 4.3 in "Pressure Losses in Ducted Flows," shows free jet flow over an orifice. The Reynolds number and geometry of the tube-orifice system is the most similar to that of a vacuum-assisted toilet during a flush. The free jet flow is the expected fluid flow field while the valve is opening and is also the field with the strongest flow separation and recirculation zones as compared to the other types of flow in Ward-Smith's figure.

6.2 General Methods

Similar to the rest of the chapters in this work, a commercial vacuum-assisted toilet system was used in the BYU variable acoustics chamber in the hemi-anechoic chamber configuration. Sound measurements were made with a ½" free-field microphone located 1 m above the front edge of the toilet.

6.3 Opening and Closing Speed

During the valve opening and closing events, the valve plate can be described as a discontinuity in the flow. As was described in Sections 5.3 and 6.1, discontinuities can create complex flow fields that look like free jets with flow separation and recirculation regions. Flow separation inherently has shear forces which can oscillate and generate aeroacoustic noise. The fact that the flow is multi-phase complicates the flow field even more. Varying the speed at which the valve opens and closes might change the noise the valve generates.

6.3.1 Experimental Setup

The flush valve provided with the commercial toilet is not reprogrammable. In order to change the valve speed, a stepper motor-driver-Arduino system was built to programmatically swing the valve open and closed at a predefined velocity profile. The stepper motor receives at least four parameters: the minimum velocity when beginning and ending the cycle (V_{min}), the maximum velocity permitted during the cycle (V_{max}), the percentage of the angle to accelerate to the maximum velocity (% up) and the percentage of the angle to decelerate to the minimum velocity (% down).

Fast, moderate, and slow valve maximum speeds with moderate and slow ramp up and down times were tested, where moderate speed and ramp up time correspond to that of the sponsor's flush valve speed and ramp up time. Figure 6.1 shows a few programmed velocity profiles and their associated angular positions for opening the valve. The running OASPL-A curves shown below are associated with these four profiles.

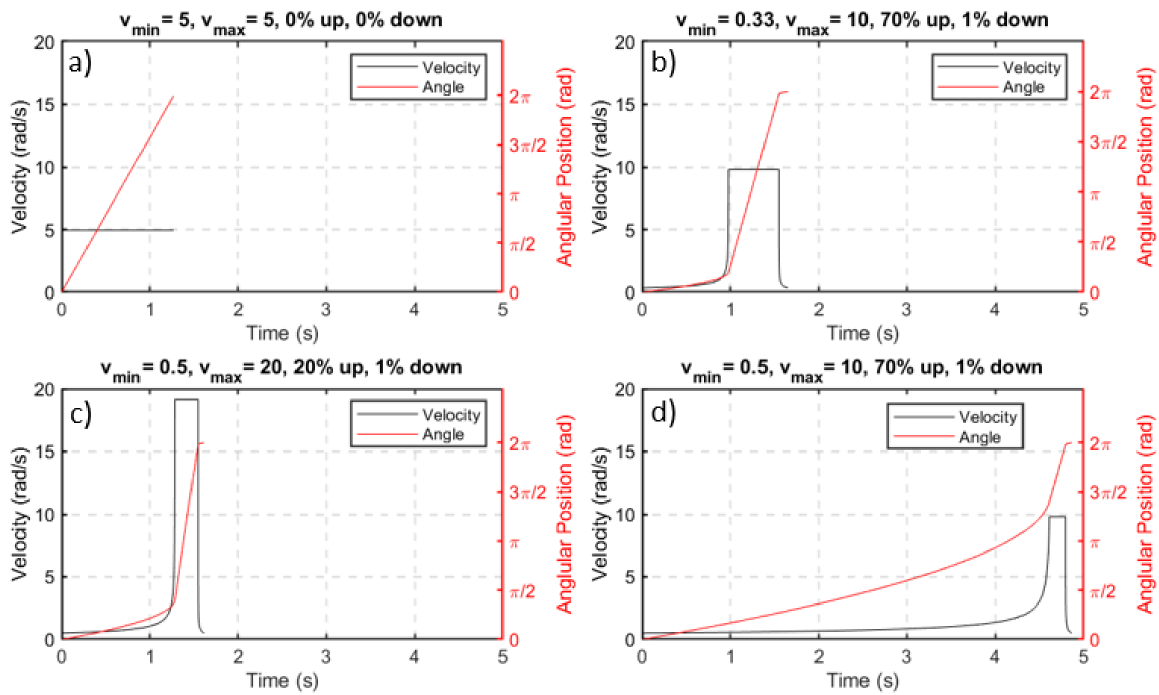

Figure 6.1: A few programmed velocity profiles and their associated angular positions for opening the valve.

6.3.2 Results

Increasing the valve speed improved the overall noise level during the valve opening event as shown in Table 3. The faster velocity profile improved the initial peak by 4.5-5.5 dB regardless of timing the rinse within 0.1 seconds while the standard velocity profile only improved the initial peak by 5 dB when the rinse was delayed by 0.3 seconds. Having a faster valve speed shows that the radiate noise is less sensitive to rinse timing i.e. more rinse timings produce significant peak noise reduction when the valve opens quicker.

Slowing down the valve did not improve the overall noise level as shown in Fig. 6.2. Figure 6.1b shows an example of the “slower” velocity profile and Fig. 6.1d shows an “even slower” velocity profile. For the “slower” velocity profile, the opening peak is similar to the standard profile but the closing peaks are broadened. This opening and closing behavior is likely because the valve has already built up speed before the cutout in the flush plate had begun to reach the tube while the closing event starts at a very slow speed so that the tube is partially obstructed for longer than the opening event (see Fig. 6.9 for a photo of a flush plate). The "even slower" profiles result in OASPL-A that are broader when opening and extremely broad during the closing. The OASPL-A is louder during the whole flush because the valve flush plate partially obstructs the flow for nearly the whole flush cycle.

Table 3: Peak level of some faster valve speeds and rinse delay times compared to the standard valve velocity and rinse time

Valve Speed	Rinse Time +0.0 s	Rinse Time +0.3 s
Standard	+0 dB	-5 dB
4x Faster	-4.5 dB	-5.5 dB

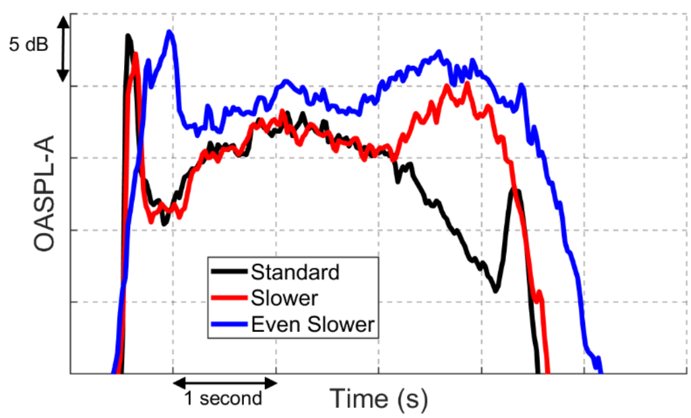

Figure 6.2: Some overall slower valve speeds and their associated running OASPL-A.

6.4 Multiple Valves

6.4.1 Experimental Setup

Multiple valves can also be very effective at reducing the noise generated when beginning and ending the flush cycle. A second valve at the waste tank, shown in Fig. 6.3, can separate the vacuum pressure from atmospheric pressure rather than the primary valve mounted to the toilet. By opening the valve near the toilet first while the secondary valve near the tank is still closed, no significant noise will be generated near the toilet bowl outlet. Opening the valve near the tank afterwards, the flow begins and valve noise is generated significantly downstream which can be much quieter above the toilet than if generated near the toilet bowl.

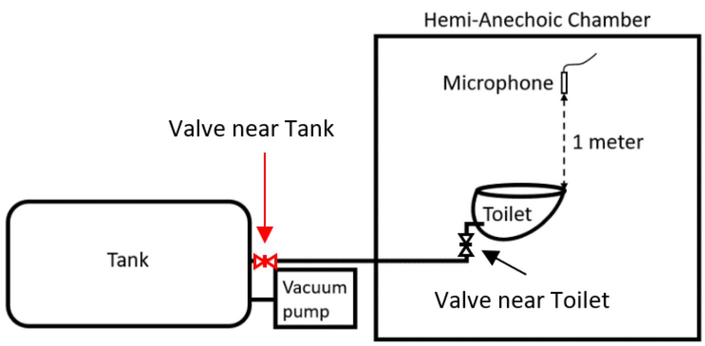

Figure 6.3: Schematic showing the addition of a valve near the septic tank

Reducing the closing valve noise can be achieved the same way as reducing the opening valve noise with a secondary valve but the process is done in reverse. Since high velocity flow is passing through the system, closing the valve near the toilet will make a lot of noise. Therefore, closing the valve near the tank first will cut off the flow path allowing the valve near the toilet to close without generating significant noise. Because of experimental necessity, no valve was placed near the bowl while the programmable valve was placed near the tank. Since the valve near the bowl opens before and closes after the flush cycle begins and ends, it is experimentally unnecessary. However, for odor control on a toilet in service, a valve near the toilet is recommended.

6.4.2 Results & Discussion

A comparison is made between the baseline 90-degree tube attached to the bowl and the wrapped insert attached to the bowl while the valve is installed near the tank 5 meters downstream. Figure 6.4 shows that placing the valve near the tank for either tube attached to the bowl removes the opening and closing peak down to the steady state level. By replacing the baseline tube with the wrapped tube, an extra 3 dB reduction can be achieved during the steady vacuum phase.

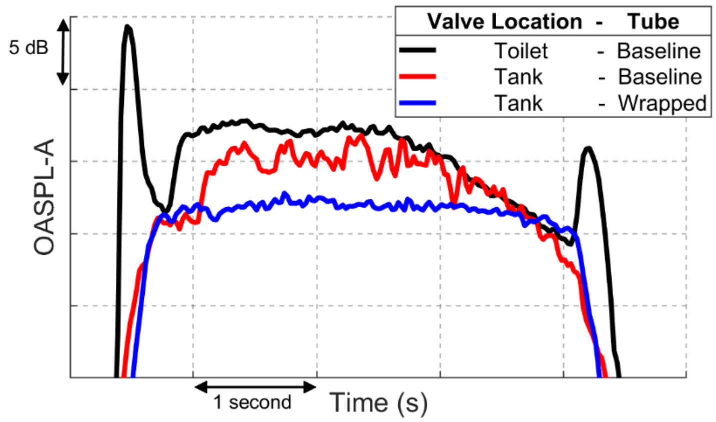

Figure 6.4: Running OASPL-A of flushes with the valve at the tank compared to the valve at the toilet. The valve at the tank with the baseline tube was not averaged.

In addition to valve position and tube geometry, rinse parameters were varied which also changed the peak and steady-vacuum levels drastically. Figure 6.5 shows that for the 90-degree tube with a valve attached at the tank, a standard rinse as described in Section 2.3 brings the initial peak level down by 14 dB with little modification to the steady-vacuum noise level. A long rinse can bring the peak down by 17 dB and the steady-vacuum noise level by 12 dB and the closing peak by 8 dB. Figure 6.6 shows that for the wrapped insert tube and a standard rinse, the initial peak is masked by the steady vacuum-level i.e. the noise level rises smoothly to the steady-vacuum noise level without an initial peak. A long rinse knocks the steady-vacuum noise level down by 14 dB which unmasks the initial peak which is reduced by 19 dB while the closing peak is again reduced 8 dB. These are not small values. For example, 19 dB correlates to almost 89% reduction in rms sound pressure.

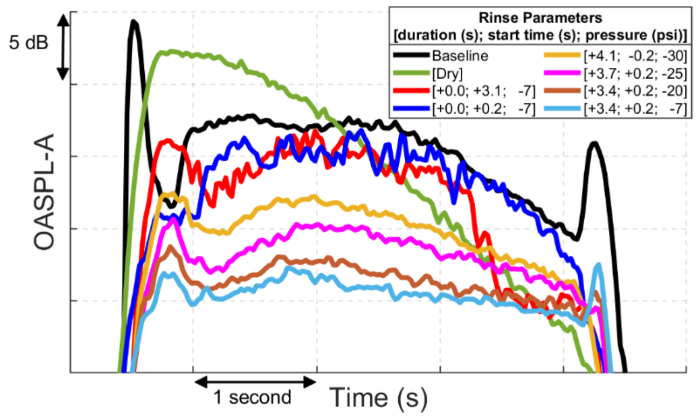

Figure 6.5: The programmable valve installed near the tank 5 meters downstream from the standard 90-degree tube attached to the bowl. Varying the rinse changes the peak and steady-vacuum levels drastically.

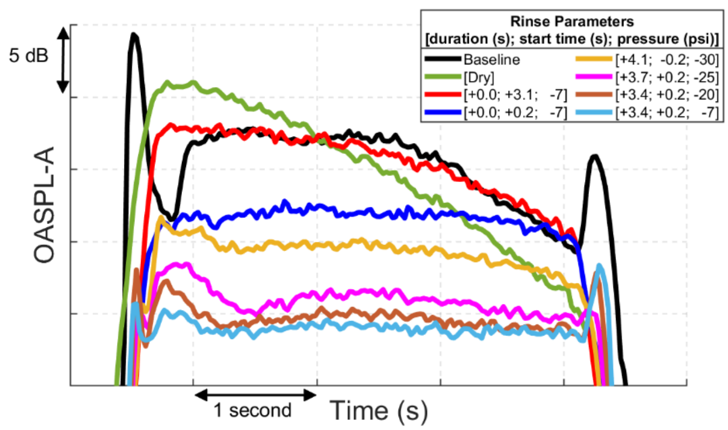

Figure 6.6: The programmable valve installed near the tank 5 meters downstream from the wrapped insert tube attached to the bowl. The wrapped tube improves the noise reduction by 2-4 dB for each rinse combination.

The wrapped tube insert improves the noise control performance of the dual valve technique. Figure 6.7 and Fig. 6.8 reorganize the data shown in Fig. 6.5 and Fig. 6.6 to directly compare the 90-degree baseline tube to the wrapped insert. For the standard rinse, the wrapped tube allows the steady-vacuum noise to maintain the level the short pulse of rinse achieved while the 90-degree baseline tube returns to a 4-5 dB higher level after the rinse has cleared the toilet. The wrapped tube is slightly quieter for a dry flush and slightly louder for the late rinse that was successfully targeted to reduce the closing peak for the baseline tube.

Longer rinses show even more pronounced performance improvement with the wrapped insert tube. Since the point of a vacuum-assisted toilet is to reduce water per flush, it is counterproductive to rinse with a significant amount of water more than what a vacuum-assisted toilet currently flushes with. To achieve a long rinse while keeping the rinse volume low, the rinse pressure may be reduced to regulate the rinse flow rate. For -30 psi relative to the standard rinse, the wrapped tube improves steady-vacuum noise levels by 1-2 dB (7 dB overall). For -25 psi relative to the standard flush, the wrapped tube improves the steady-vacuum noise levels by 3-4 dB (10-11 dB overall). For -20 psi, 2-3 dB (12 dB overall), and for -7 psi, 2-3 dB (13 dB overall).

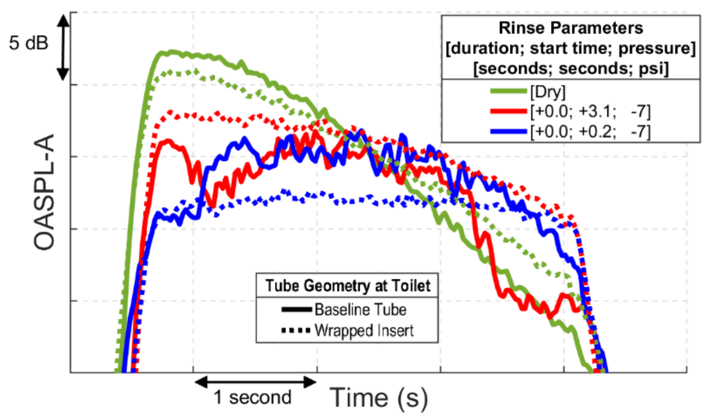

Figure 6.7: Dual valve dry, standard, and late rinses for the 90-degree baseline tube and wrapped insert

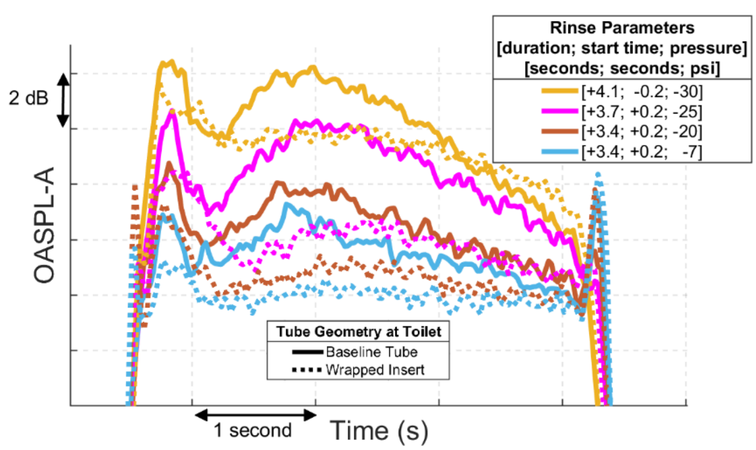

Figure 6.8: Dual valve long rinses with varying rinse pressure for the 90-degree baseline tube and wrapped insert. Notice that there are only 2 dB per division now.

Installing a second valve near the tank would require electrical communication between the toilet and tank. The design of the electrical connection for a transport vehicle waste system in general is beyond the scope of this project. Hopefully, the effectiveness of this solution may motivate further consideration of the dual-valve concept.

6.5 Valve Cutout Shape and Swing Direction

6.5.1 Experimental Setup

Finally, the shape of the cutout in the valve flush plate can be modified. The sharp edge of the flush plate can be beveled and the circular cutout can be made like a tear drop. By beveling the sharp edge, less shear forces will act on the flow to generate noise. The tear drop shape can modify the rate at which the vacuum suction is introduced, similar to the valve speed effects.

Three valve cutout shapes were compared: the baseline (or stock) cutout which is a circle with squared edges, the beveled baseline which is still a circle but the upstream edge is beveled, and the “shark fin” which is a tear drop or shark fin cutout with square edges.

Figure 6.9: Photograph of the baseline, beveled, and shark fin valve variations

Changing the swing direction of the valve modifies the flow field near the valve. The baseline setup described in Section 4.2.2 and shown in Fig. 4.6, in addition to the discussion of flow in bends in Section 4.1.2, reveals that the preferential direction the flow will take is along the outside of the bend. The valve may open from the outside swinging toward the inside or from the inside swinging toward the outside of the bend. It is thought that swinging in harmony with the preferred flow (outside to inside for the valve opening and inside to outside for the valve closing) reduces the noise while the valve is swinging.

Changing the valve swing direction is as simple as rotating the whole flush valve system by 180 degrees so that any flow that would have gone left out of the toilet now goes right or vice versa. In addition to comparing valve swing directions, the combination of valve cutout shape and valve swing direction were investigated.

6.5.2 Results & Discussion

Introducing different valve cutout shapes and swing directions reduced the peak noise level for some configurations while also increased the peak noise level for other configurations. Table 4 shows the peak noise level results of the baseline, beveled, and shark fin cutouts relative to the baseline swinging open from the inside to the outside of the bend or swinging closed from the outside to the inside of the bend. For all cutouts, swinging open from out to in is 4-5 dB quieter than swinging open from in to out. Since the valve currently swings the opposite way to close as it does to open, the valve would swing closed from in to out which is louder by 0.3-3.0 dB than swinging closed from out to in. If the valve were able to swing open and closed from out to in, the 4-5 dB reduction advantage could be coupled with the 0-1.7 dB closing peak reduction swinging closed from out to in.

Table 4: Peak OASPL Reduction (dB) relative to the valve swinging open from the inside to the outside of the bend and swinging closed from the outside to the inside of the bend

	Peak OASPL Reduction (dB re Open in to out or Close out to in)			
	Open in to out	Open out to in	Close out to in	Close in to out
Baseline	0	3.8	0	-3.0
Beveled	0.1	4.7	1.0	-0.3
Shark fin	2.7	5.5	1.7	-2.2

6.6 Conclusion

From the valve modification investigation, it can be concluded that the most effective technique for reducing valve noise is to use the dual-valve technique. The cutout shape of the valve plate may reduce the noise but is dependent on swinging from the outside of the bend to the inside of the bend to open and swinging from the outside to the inside of the bend to close. This would likely require a valve plate that could swing 360 degrees.

Chapter 7

7.1 Conclusions

This thesis presented the effect on radiated noise from a vacuum-assisted toilet by various noise control strategies. Chapter 3 was a paper in the Proceedings of Meetings on Acoustics (POMA) that shows the effect of applying constrained layer damping materials to the bowl. Chapter 4 was a paper being prepared to be submitted to the Noise Control Engineering Journal that presents the effect of increasing the bend radius of the tube near the bowl and increasing the tube length between the valve and bowl. Chapter 5 was a series of experiments that measure evidence of the noise control mechanisms behind the successes in Chapter 4. Chapter 6 explored the possibility of modifying the valve velocity profile and location for better reduction of the initial and final noise peaks of the flush cycle.

The frequency response between 10 and 2000 Hz of a vacuum-assisted toilet was measured with a 3D SLDV. Mode shapes associated with the frequency band from 300 to 500 Hz were used to inform the optimal placement of damping layers. While Velcro was able to reduce peak mechanical vibrations by 20 dB, the effect only translated into a 3 dB reduction in the radiated acoustic noise for the opening valve event. This suggests that structural vibrations (though present) are not a significant contributor to the noise from a vacuum-assisted toilet.

This investigation of radiated noise from a vacuum-assisted toilet indicates that a 1.7 m tube with a bend radius of 16.5 cm wrapped 2 times underneath the toilet can reduce the radiated noise of a vacuum-assisted toilet by 14 dB during the valve opening and 4 dB during the "steady-vacuum" phase. After an investigation of placing a spiral tube behind the toilet, a similar noise reduction was achieved with a tube length of 0.77 m and bend radius of 9.5 cm. Using a tube with either a smooth or corrugated inside surface did not affect the overall levels but did have some impact on the spectral content which is linked to sound quality. We designed a tube to fit underneath the toilet bowl or fit completely behind the bowl in a compact manner while applying these tube length and bend radius constraints. Noise reduction performance was maintained with both smaller configurations. These advances may help provide an improved experience for transport vehicle lavatory users and passengers. Ongoing and future investigations may use this tube design in concert with other noise control strategies.

In-tube measurements show evidence of pressure magnitude decay upstream from the valve to the bowl. This indicates there is likely evanescent decay through the tube while the valve is opening. No significant pressure magnitude decay was found through the tube during the steady-vacuum phase indicating that if there is evanescent decay, it is of modes being generated as the valve is opening but not while it is completely open. The pressure magnitude decay is typically less than the total noise reduction magnitude when using the spiral tube which indicates that there are more mechanisms than just evanescent decay with increased tube length.

One possible mechanism that could be contributing to the noise control of the increased tube length is the limited access to pressurized air the valve has when placed significantly downstream. Combined with a well-timed rinse that slows down air from outside the tube, the air inside the tube quickly moves from upstream to downstream as the valve is opening. Soon, the valve does not have a supply of pressurized air passing over the partially opened valve until the rinse passes over the valve. Without a supply of air, there is little fluid to generate noise while the valve is opening. This effect is short lived but long enough to cut out the opening peak. Unfortunately, no attempt has been made yet to measure this effect.

Flow velocity was measured for the baseline and wrapped insert tube configurations in a clear portion of tube just downstream of the valve. A weak correspondence between flow velocity and sound level suggests that a change in velocity is likely not the mechanism for improved noise control performance of the wrapped insert.

From the valve modification investigation, it can be concluded that the most effective technique for reducing valve noise is to use the dual-valve technique. In situations that prohibit a secondary valve near the tank, ensuring that a tube insert similar to the wrapped insert used in this work to add tube distance between the bowl and valve may still bring several dB reduction to the opening and steady-vacuum noise levels. The cutout shape of the valve plate may reduce the noise but is dependent on swinging from the outside of the bend to the inside of the bend to open and swinging from the outside to the inside of the bend to close. This would likely require a valve plate that could swing 360 degrees.

7.2 Recommendations for Future Work

Although the achievements of this work are promising, there are still many things yet that can be done. Some future work is: the dog food test, maintaining the valve open for only one second, designing a variable rinse, standing water with variable valve speed, dual valve timing, improved tube designs, and additional sensors to monitor the flow.

One of the most common questions that is raised concerning the tube inserts is if the functionality of the toilet is affected. One test that can be done is the “wet dog food” test. This consists of wetting a cup of dog food and placing it in the toilet bowl for each flush. If the toilet is successful at transporting the wet dog food reliably to the septic tank, there can be reasonable assurance that solid waste during normal use will also successfully be transported to the septic tank. This test has been left for later because the outcome was not a critical component of the investigation not to mention the difficulty posed by cleaning up the septic tank.

Another investigation that is yet to be done is measuring closing peak effects since our septic tanks do not supply constant suction throughout the flush. The idea here is to shorten the time the valve is kept open so that the main suction does not deplete the vacuum supply before the valve closes. Currently the valve is kept open for approximately 3 seconds but it is proposed to cut that time to 1 second. This will allow for more consistent closing peak levels and more representative valve closing noise to that generated on vacuum-assisted toilets currently installed commercially. The closing peak noise control performance in this work may be validated with this shorter steady-vacuum phase.

Another and very promising idea is to vary the rinse during the flush cycle. Ideally, a sizeable burst of water first injected while the valve is opening will help clean the bowl and knock down initial sound levels. Rinsing during the steady-vacuum phase has been shown to also significantly reduce the noise level during the steady-vacuum phase. However, rinsing during the full 3-4 seconds of steady vacuum may be water intensive. The rinse can be varied such that the volume of water injected during the steady-vacuum phase is significantly less than the volume injected during the valve opening event. This will minimize the water consumption while still allowing the steady-vacuum phase to benefit from added mass to the flow. Finally, injecting another burst of water right when the valve closes may be helpful at knocking down the closing peak which tends to be the part of the flush this work struggled to control.

The typical use of a vacuum-assisted toilet results in liquid waste sitting in the bowl before the flush button is pressed. Nearly all the investigations recorded in this work do not explore the effect of standing water in the bowl before flushing. Some preliminary investigations were done that essentially showed that standing water reduced sound levels of the initial 0.5 to 1 seconds but for significant results, 0.5 liters or more was necessary. Also, the protocol outlined by the aircraft manufacturers buying the vacuum-assisted toilets from the sponsor specified that nothing was to be in the bowl during an acoustic test. We built our noise control strategies around that requirement. One investigation that was not carried out that could be interesting is to use the variable valve in combination with standing water to optimize a valve speed for standing water situations.

The dual valve concept was implemented only at a preliminary level. A valve was placed near the tank which removed the opening and closing peaks. Part of the dual valve concept is that in between the toilet valve and the tank valve is air at essentially ambient pressure, not vacuum pressure. No investigation was made into timing the opening and closing of either valve to ensure that air pressure condition.

Several months were spent trying to gather high-speed video to view flow structures and measure the flow velocity. It is recommended to place a flow meter that will record the flow velocity or mass flow rate since that is a metric that helps determine the functionality of the toilet. Also, since this is a very turbulent system, modifying velocity will modify the turbulence which is a source of radiated noise.

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