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Noise control of a vacuum-assisted toilet: structural vibration damping

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Vacuum-assisted toilet noise can be unsettling and even uncomfortable. One common way to reduce noise levels is to damp structural vibrations that radiate sound. Constrained layer damping (CLD) treatments were investigated for their effectiveness to reduce the radiated noise level on a vacuum-assisted toilet. To find the modal response of the toilet bowl, a commercial vacuum-assisted toilet was excited with a shaker and measured the velocity response of the inside of the bowl with a 3-dimensional scanning laser Doppler. The bowl was also scanned with an accelerometer during a repeated flush cycle. A microphone placed one meter above the bowl measured the radiated sound level. 3M 4014, Pyrotek Decidamp CLD, and Velcro were each applied to the bowl to determine the reduction in structural vibrations and sound radiation. The front-half of the bowl's rim had the largest velocity amplitude. Structural vibrational energy concentrated around 100-500 Hz while radiated sound concentrated around 300 Hz–2 kHz. Applying damping materials reduced structural vibrations, sometimes by 20 dB. Lightweight treatments certainly can reduce structural vibrations.

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1. INTRODUCTION

A. BACKGROUND

Vacuum-assisted toilets reduce the amount of water needed per flush to transport waste to a tank. They replace gravity with vacuum suction as the transportation mechanism. Vacuum-assisted toilets typically only require half a cup of water for lavatory service which is 98% less water than conventional gravity toilets. These toilets are advantageous for more reasons than just water conservation. Less water reduces the weight a transport vehicle (such as airplanes, trains, and cruise ships) must carry for lavatory service. This reduces fuel costs which makes vacuum-assisted toilets a popular product for transportation vehicles that take long trips.

In addition to reduced water, weight, and fuel costs, vacuum-assisted toilets are loud. A valve on the toilet separates a pressure difference of about 2/3 of an atmosphere 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 by conduction 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.

B. NOISE CHARACTERIZATION

The noise from a flush can be characterized by three events associated with the status of the valve. The first and loudest sound is while the valve is opening. This only lasts for a fraction of a second. The second is while the valve is completely open. This event's noise is characterized by a high and relatively steady noise level over roughly 3 seconds. The third is while the valve is closing. The radiated noise level spikes again but not as high as the initial peak when the valve opened. Figure 1 a) shows the running overall sound pressure level (OASPL) (flat and A-weighted) measured by a single microphone one meter above the toilet and Fig. 1 b) 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 a) shows the running rms acceleration from a single location on the bowl (measured by an accelerometer) and Fig. 2 b) a spectrogram of the acceleration level by frequency. The acceleration on the bowl concentrates in the 300 to 500 Hz frequency band which is also a strong band in the radiated noise as shown by the white rectangle in both spectrograms of Figs. 1 b) and 2 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.

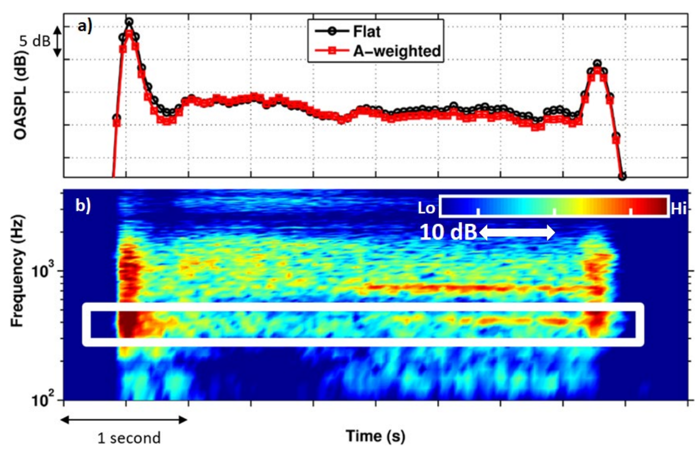

Figure 1: Plot of the running overall sound pressure level (a) and a spectrogram (b) during a flush cycle of a vacuum-assisted toilet measured by a microphone one meter above the front edge of the toilet. The white box encloses the frequency range that correlates to structural vibrations on the bowl.

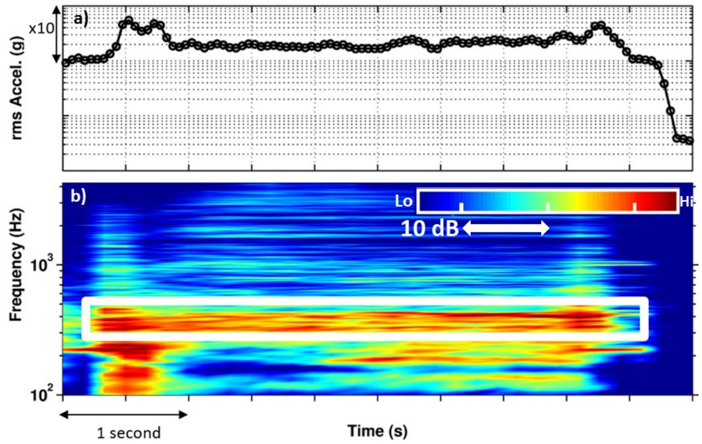

Figure 2: Plot of the running rms acceleration (a) and a spectrogram (b) during a flush cycle of a vacuum-assisted toilet measured by an accelerometer attached to the side of the bowl of the toilet. The white box encloses the frequency range that correlates to radiated sound.

C. STRUCTURAL DAMPING

Structural vibrations can lead to radiated noise.[1] Constrained layer damping (CLD) has been shown to reduce structural vibrations.[2] Constrained layer damping is the dissipation of mechanical energy into thermo-viscous losses by the application of a viscoelastic material onto a vibrating surface.[3,4] 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.[1] 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.

2. SCANNING LASER DOPPLER VIBROMETER

A. 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. 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 4 shows the laser vibrometer scanning the bowl (red lines added). Figure 5 shows the grid density that was scanned on the surface of the bowl.

Figure 3: 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.

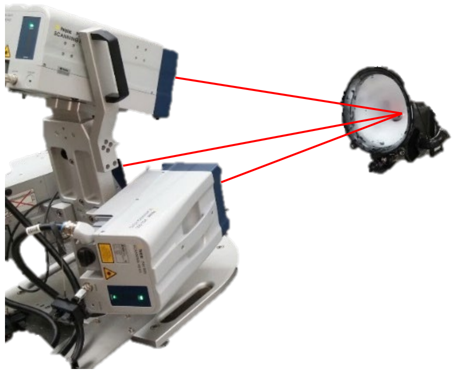

Figure 4: A picture of the 3D scanning vibrometer ready to scan the inside of the bowl.

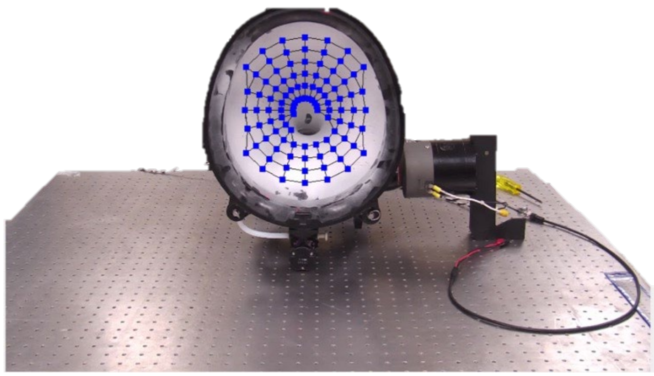

Figure 5: A photo of an example grid where the blue points represent measurement points. Most locations near the rim of the bowl have at least one laser obstructed by the rinse ring making those locations impossible to measure.

B. SLDV RESULTS

Operational velocities were measured on the surface of the vacuum-assisted toilet bowl. Figure 6 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 at 387 Hz shown in Fig. 7. The operational velocity shapes throughout this band appear very similar to the one shown in Fig. 7. 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. 7 is not symmetric. This is likely either because the bowl is attached to a valve assembly that is not symmetric and 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.

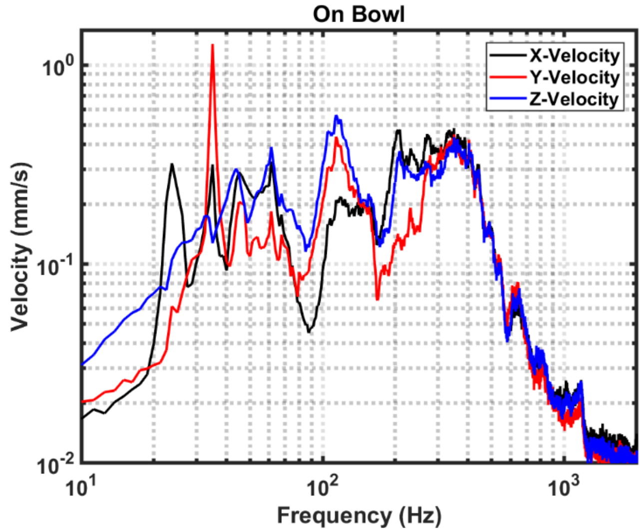

Figure 6: Spectra of the x, y, and z components of the velocity magnitude. Since many points were measured, these curves represent the averaged magnitude.

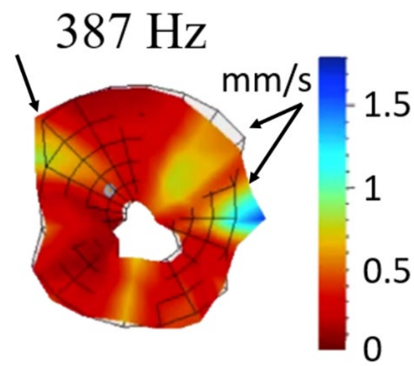

Figure 7: Visualization of the velocity operational shape at 387 Hz of the bowl. Scanning points near the forward right and left portions of the rim of the bowl (indicated by the black arrows) measured the highest velocity amplitude.

3. FLUSH CYLCE

A. EXPERIMENTAL SETUP

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. 8. 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. 9. 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.

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.

Figure 8: A photo of the Pyrotek constrained layer damping material applied to the bowl.

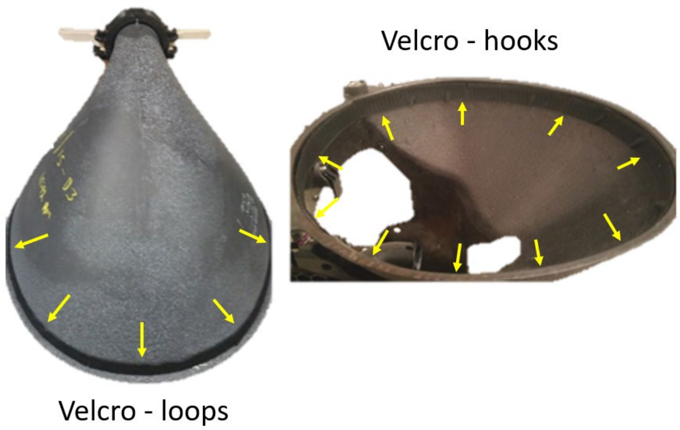

Figure 9: Two photos of the bowl. The first shows the loops side of the Velcro attached to the outside of the bowl. The second shows the hooks side of the Velcro attached to the inside of the chassis where the bowl makes contact.

B. 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 10 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 11 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.

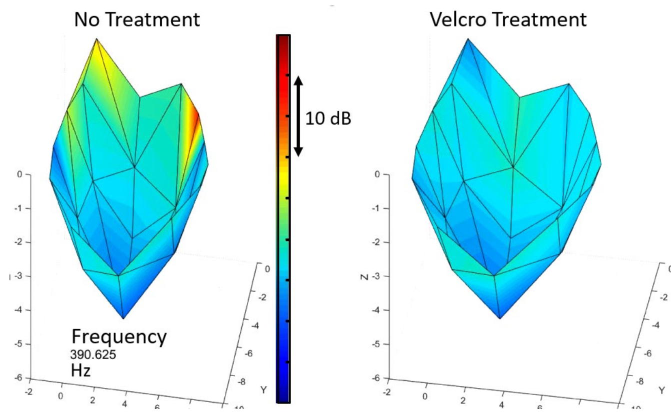

Figure 10: Visualization of the measured acceleration on the bowl surface during a dry flush with and without Velcro treatment at 390 Hz. A 20 dB reduction can be seen in the upper right and left sides of the bowl.

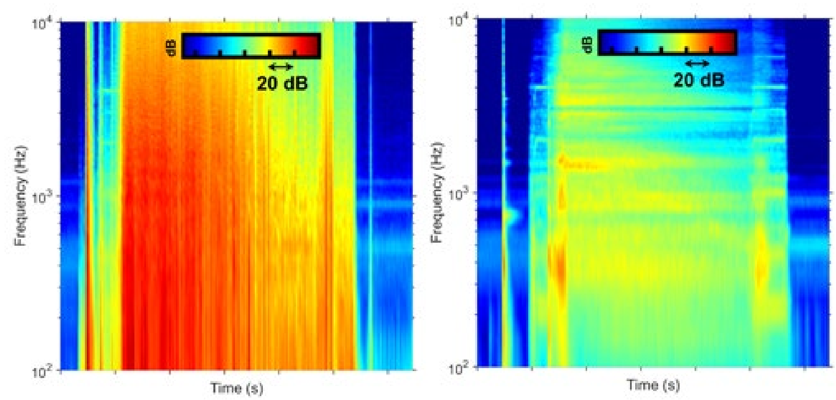

Figure 11: Two spectrograms of the acceleration measured near the top right of the bowl. The left spectrogram has no damping treatment while the right spectrogram has Velcro attached.

C. FLUSH CYCLE ACOUSTIC RESULTS

Figure 12 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.

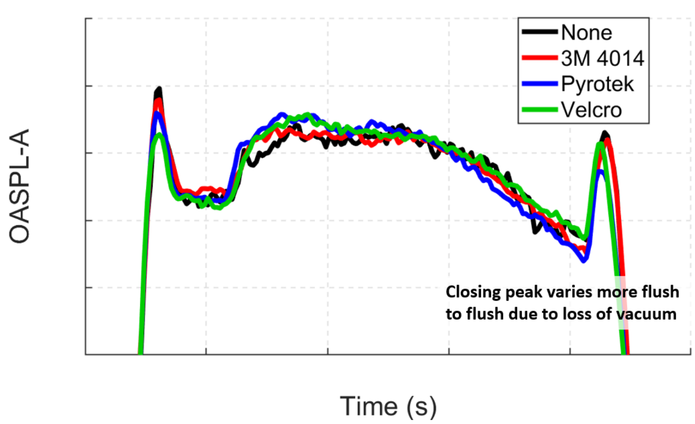

Figure 12: A plot showing the running overall sound pressure level A-weighted one meter above the toilet when the toilet was flushed under 4 conditions: 1. No damping treatment, 2. 3M 4014 CLD applied, 3. Pyrotek CLD applied, and 4. Velcro applied. The Velcro reduces the opening peak the most with a 3 dB reduction.

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.

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REFERENCES

1. Kruger, D. H. and Mann, J. A. (1999). "Minimizing the sound power radiated by a cube as a function of the size of constrained layer damping patches," The Journal of the Acoustical Society of America 105, 1714.
2. Oosting, N. J., Hennessy, J., Hanner, D. T. and Fang, D. (2005). "Application of a Constrained Layer Damping Treatment to a Cast Aluminum V6 Engine Front Cover,". SAE International, May 16, 2005. ISSN 0148-7191
3. Kerwin, E. (1959). "Damping of flexural waves by a constrained viscoelastic layer," The Journal of the Acoustical Society of America 31, 952.
4. Shafer, B. (2013). "An overview of constrained-layer damping theory and application." Proc. Mtgs. Acoust. 19, 065023.