WATERBOTTLE SYNTHESIS WITH MODAL SIGNAL PROCESSING

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ABSTRACT

We present a method for accurately synthesizing the acoustic response of a waterbottle using modal signal processing. We take extensive measurements of two waterbottles with considerations for the water contained within the bottles, and stickers attached to the exterior of the bottles. We perform modal analysis of these measurements and implement a modal waterbottle model as a real-time synthesizer.

1. INTRODUCTION

Previous works have examined the use of modal signal processing for synthesizing carillon bells [1, 2], artificial reverberation [3], cymbal synthesis [4], and more [5]. In this paper, we extend this previous work to use modal synthesis for the accurate modelling of waterbottle acoustics.

Although most waterbottles are not designed to function as musical instruments, the authors have noticed that certain waterbottles can produce a pleasing resonant sound when struck with a knee, hand, or other body part. The authors further noticed that waterbottles can produce a great variety of sounds, depending not only on the shape and material of the bottle, but also on the amount and type of liquid contained within the bottle, as well as the potential placement of stickers on the exterior of the bottle. Waterbottle acoustics have not gone unnoticed by waterbottle manufacturers, as at least one prominent manufacturer claims to be well aware of the pleasing acoustic properties of their bottles [6]. In this writing, we take measurements from a 32 oz. Wide Mouth HydroFlask[1], compared to the waterbottle given to attendees of the 2019 DAFx conference, measured containing different amounts of water and maple syrup, as well different placements of stickers on the exteriors of the bottles.

The structure of the paper is as follows: In §2 we describe our methods for taking measurementsof waterbottles. §3 contains modal analysis of the waterbottle measurement data. Finally in §4 we discuss our results, and the implementation of a full waterbottle synthesizer.

[1] https://www.hydroflask.com/32-oz-wide-mouth/color,cobalt,a,92,o,53

2. MEASUREMENTS

For taking waterbottle measurements, we tap the waterbottle with a force hammer and measure the waterbottle response using a PolyTec laser vibrometer. The full setup can be seen in figs. 1 and 2.

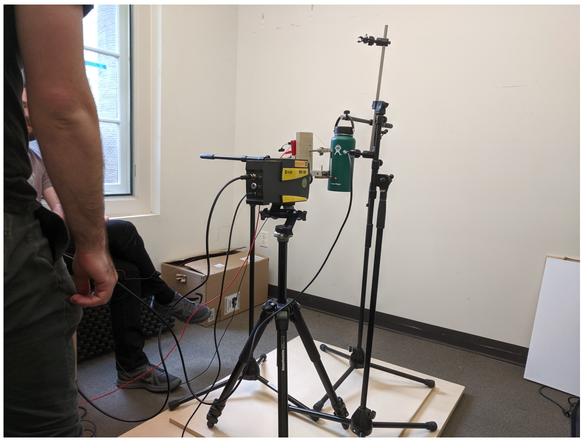

Figure 1: *Measurement setup for the HydroFlask waterbottle*

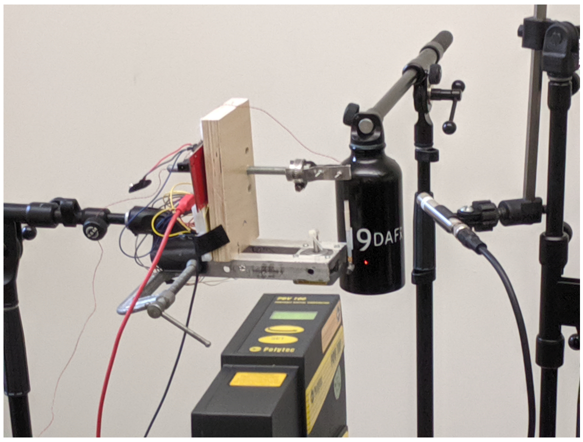

Figure 2: *Measurement setup for the DAFx waterbottle*

3. ANALYSIS

3.1. Modal Analysis

Similar to the carillon bells modelled in [1, 2], we can use modal analysis to model the waterbottle sounds as a sum of exponentially decaying sinusoids.

$$y(t) = \sum_{m=1}^{M} \alpha_m e^{j\omega_m t} e^{-t/\tau_m} \tag{1}$$

where α_m is the complex amplitude, ω_m is the mode frequency, and τ_m is the decay rate for each mode m.

For modal analysis we use the helper functions provided by the `Python` audio signal processing library `audio_dspy`[2]. This process involves the following steps:

1. Picking the modal frequencies from the original recording.
2. Estimate the decay rate of each mode.
3. Estimate the complex amplitude of each mode.

The process is shown in full in fig. 3.

For finding the mode frequencies, we use a simple peak picking algorithm over the Fourier Transform of the original signal.

For estimating the mode decay rates, we begin by filtering the signal using a 4th order Butterworth bandpass filter centered on the mode frequency, with a bandwidth of 30 Hz. We then apply a Root-Mean-Squared level detector as defined in [7] to estimate the energy envelope of the mode. Finally, we use a linear regression to estimate the slope of the energy envelope (measured in Decibels).

After computing the mode frequencies and decay rate, we can do a simple least squares fit to estimate the complex amplitude of each mode that most accurately resynthesizes the original recording. This process is described in full in [2].

3.1.1. Mode Synthesis

For synthesizing the modes we use the Max Matthews phasor filter, as introduced in [8]. This filter is described by the difference equation:

$$y_m[n] = \alpha_m x[n] + e^{j\omega_m} e^{-1/\tau_m} y_m[n-1] \tag{2}$$

where τ_m is the mode decay rate described above, α_m is the complex amplitude of the mode, and ω_m is the mode frequency. This filter structure is known for having favorable numerical properties, as well as for being stable regardless of real-time parameter modulation.

3.2. Water Level Analysis

Next we examine the how the modal response of the waterbottle changes as the water level in the waterbottle changes.

[2] `https://github.com/jatinchowdhury18/audio_dspy`

3.2.1. Frequency Variation

Measurements od the HydroFlask bottle show that as the water level increases, the first mode frequency increases, while the higher modes stay at the same frequency. This makes physical sense since the lowest mode frequency corresponds to the Helmholtz resonance of the bottle, and changing the water level effectively decreases the size of the air column inside the bottle, thereby causing the lowest mode frequency to increase (@TODO: ask Mark if this is correct).

@TODO: plot from Matlab (I think Mark has it ...)

We can use a cubic spline to model the movement of the first mode frequency as the water level changes continuously, as shown in fig. 4.

3.2.2. Damping Variation

Further analysis shows that the damping of the lowest two modes varies with water level as well. We can similarly model the variation of the mode decay rates with water level, using a quartic polynomial to fit the average of decay rates of the first two modes (see fig. 5).

3.3. Sticker Analysis

Initially, we compared two 32 oz. HydroFlask waterbottles, one with stickers, one without, and noted that they had different timbres. We then proceeded to take measurements of the bottle covered in varying amount of removable stickers. We found that the mode frequencies remained mostly unchanged with the addition of stickers, but that the mode dampings had noticeable variations (see fig. 6).

3.4. Swinging Vibrato

When a waterbottle is struck in such a way to produce an acoustic response, it often swings back and forth a little bit. This swinging causes the water within the bottle to move with the swinging, thereby causing the lowest mode frequency to oscillate. This oscillation manifests itself perceptually as a sort of vibrato effect. In order to model this "swinging vibrato" we use the following steps:

1. Measure (or estimate) the height of the bottle.
2. Calculate the swinging frequency of the bottle.
3. Synthesize an initial amplitude and damping factor for the swinging oscillations.

3.4.1. Bottle Height

In cases where the height of the waterbottle cannot be measured directly, it is possible to estimate the height from the bottle's modal characteristics. For a typical cylindrical waterbottle, the second lowest mode frequency corresponds to the bottle's resonance along it's vertical length. As such, the bottle height can be estimated as:

$$L = \frac{v_{sound}}{2f_2} \tag{3}$$

where $v_{sound} = 343m/s$ is the speed of sound in air, f_2 is the second lowest mode frequency, and L is the height of the bottle.

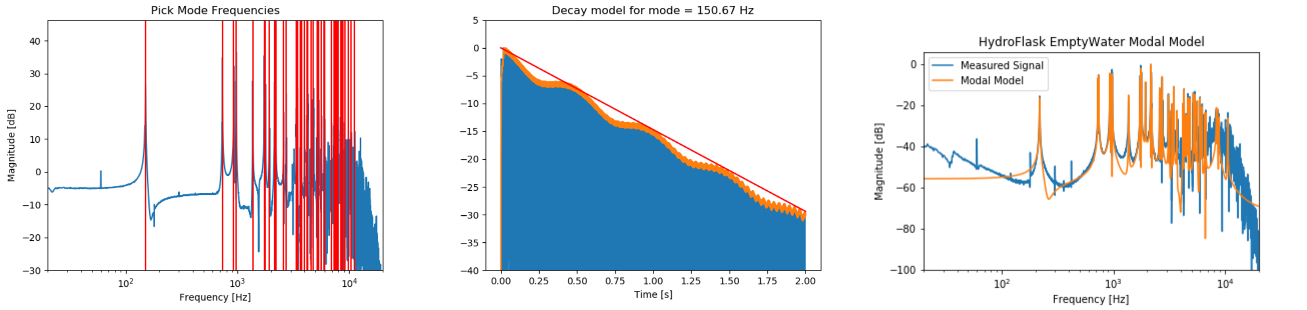

Figure 3: *Modal analysis pipeline: (left) picking the mode frequencies, (center) estimating the decay rate of a single mode, (right) using least-squares to estimate the complex amplitudes of the modes that ideally resynthesize the original signal.*

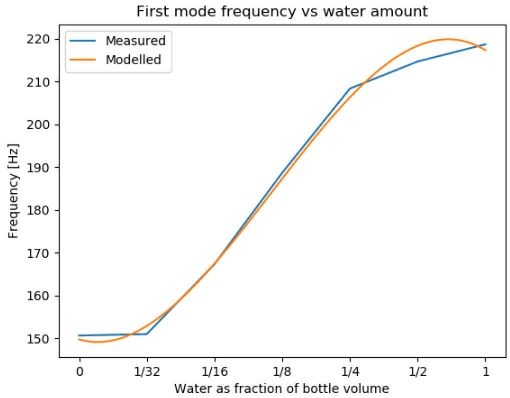

Figure 4: *Variation of the first mode frequency of the HydroFlask with the amount of water in the bottle*

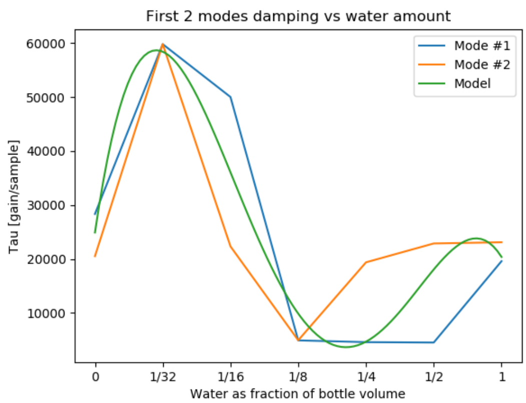

Figure 5: *Variation of the first two modes decay rates with the amount of water in the HydroFlask*

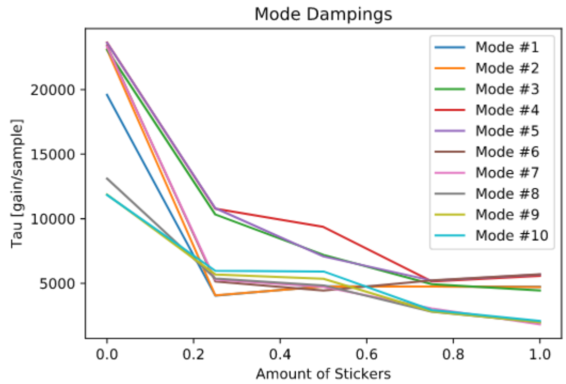

Figure 6: *Variation of the first ten modes decay rates with the amount of stickers on the HydroFlask*

3.4.2. Swinging Frequency

The frequency of a pendulum can be derived from Newton's Laws as:

$$f_{swing} = \frac{1}{2\pi}\sqrt{\frac{g}{L}} \tag{4}$$

where $g = 9.8m/s^2$ is the acceleration due to gravity at the surface of Earth.

3.4.3. Swinging Amplitude and Damping

The amplitude of a waterbottle's swinging oscillations typically depends on how hard the bottle is struck. As such, the amplitude of the swinging vibrato should vary proportionally with the desired volume of the synthesized waterbottle strike, for example with the "velocity" of a MIDI note. The damping of a waterbottle's swinging can be highly dependent on the method by which the waterbottle is anchored. As such, the damping factor is left for the reader to determine for their own specific use cases.

@TODO: make a plot for this section.

3.5. Impact Analysis

In real-world situations, a waterbottle is typically struck using a body part (knee, elbow, knuckles, etc), or using a striker that can be easily found in nature, for instance a stick. With the goal of

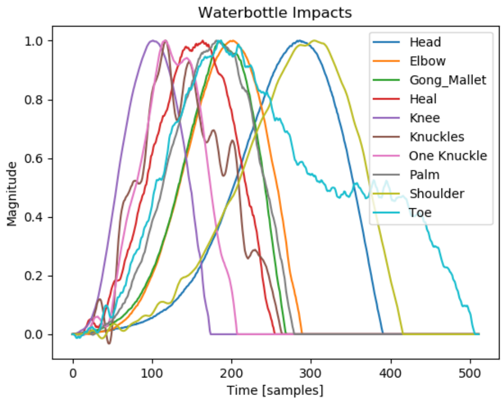

Figure 7: *asdf*

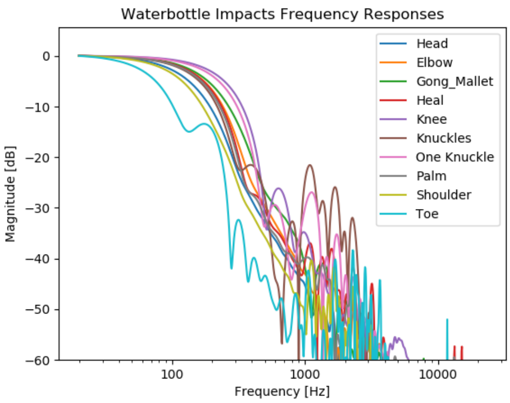

Figure 8: *asdf*

being able to synthesize these types of impacts, we used an accelerometer to measure the impacts of several body parts, as well as several types of drumsticks on a waterbottle. Figures 7 and 8 shows the time and frequency domain measurements of the various impact types.

4. RESULTS

Some general results . . .

4.1. Waterbottle Synthesizer

To demonstrate the musical power of waterbottle synthesis, we have implemented an 8-voice modal waterbottle synthesizer as an audio plugin (VST/AU), using the JUCE/C++ framework[3]. The synthesizer includes controls for the amount of water in the bottle, the number and placement of stickers on the bottle, and the option To strike the waterbottle with a variety of objects. Currently, the synthesizer implements our model of the 32 oz. Wide Mouth HydroFlask, but could easily be adjusted to model any other waterbottle with similar measurement data. The source code for this synthesizer is publicly available on GitHub[4].

[3] `https://github.com/weAreROLI/JUCE`

5. CONCLUSION

In this paper, we have discussed the sythesis of waterbottle acoustics using modal signal processing techniques. We have described the processes of making acoustic measurements of the waterbottles, as well as performing modal analysis, with specific considerations for the amount of water contained in the bottle, as well as the stickers placed on the exterior of the bottle. Finally, we have implemented our modal model of a 32 oz. Wide Mouth HydroFlask bottle as a real-time synthesizer plugin.

Future research concerns . . .

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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