

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. Waterbottles are particularly well-suited for modal modelling since they have inharmonic partials. Further, certain waterbottles have been known to have a pleasing acoustic response, while others sound notably worse. Additionally, the acoustic response of a waterbottle changes depending on the amount and the type of liquid contained within, as well as the potential placement of stickers on the exterior of the bottle. In this writing, we take measurements from a 32 oz. Wide Mouth HydroFlask¹, 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 measurements of 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.

2. MEASUREMENTS

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

¹https://www.hydroflask.com/32-oz-wide-mouth/color_cobalt_a_92_o_53

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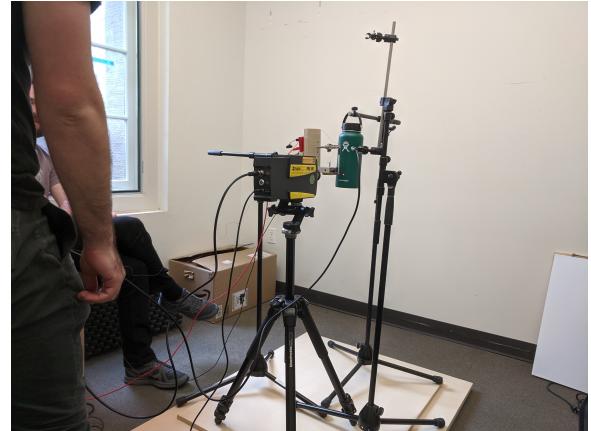


Figure 1: Measurement setup for the HydroFlask waterbottle

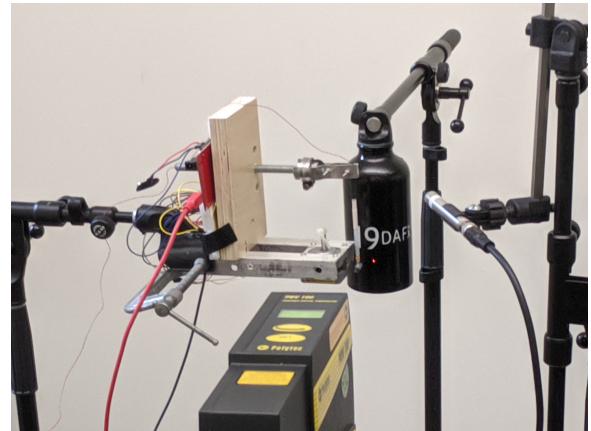


Figure 2: Measurement setup for the DAFX waterbottle

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.

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

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 [6] 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].

3.2. Water Level Analysis

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

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 because having a higher water level inside the bottle 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).

²https://github.com/jatinchowdhury18/audio_dspy

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. Mode Synthesis

For synthesizing the modes we use the Max Matthews phasor filter, as introduced in [7]. This filter is described by the difference equation:

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

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.

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++ framework³. 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 GitHub⁴.

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

The authors would like to thank Kim Kawsczinski for helping us to contact the HydroFlask brand.

³<https://github.com/weAreROLI/JUCE>

⁴<https://github.com/jatinchowdhury18/modal-waterbottles>

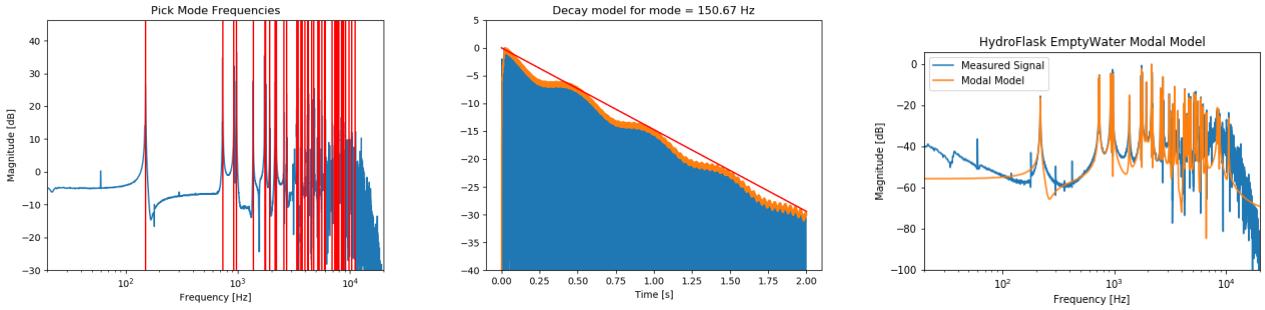


Figure 3: Modal analysis pipeline: (left) picking the mode frequencies, (center) estimating the decay rate of a single mode, (right) using least-squares to estimate the complex amplitudes of the modes that ideally resynthesize the original signal.

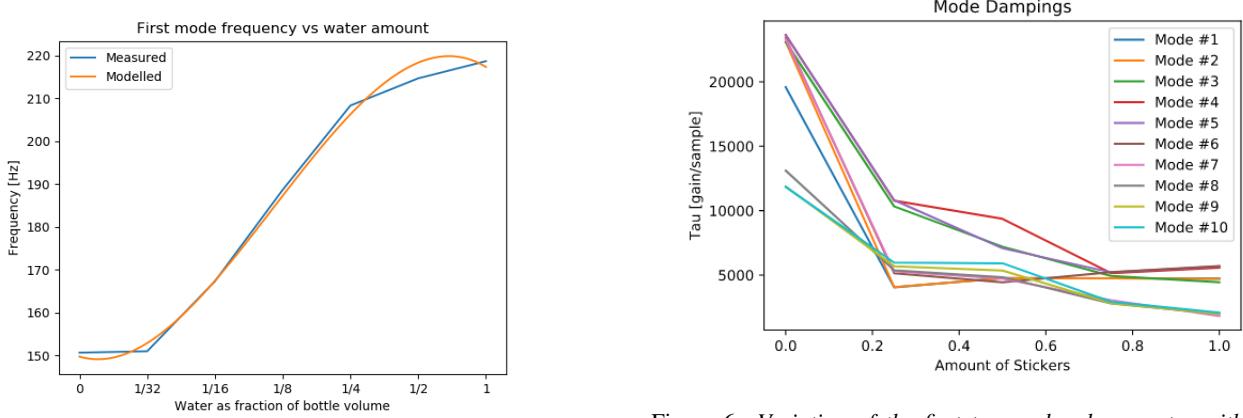


Figure 4: Variation of the first mode frequency of the HydroFlask with the amount of water in the bottle

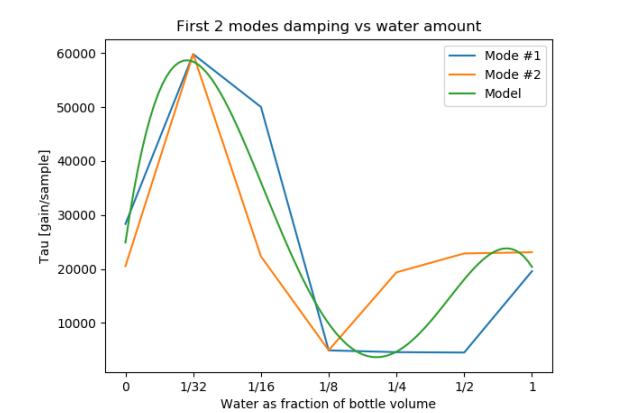


Figure 5: Variation of the first two modes damping rates with the amount of water in the HydroFlask

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