# EFFICIENT SNARE DRUM MODEL FOR ACOUSTIC INTERFACES WITH PIEZOELECTRIC SENSORS

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## ABSTRACT

This paper describes a computationally efficient synthesis model for snare drum sounds. Its parameters can be modulated at audio rate while being played. The input to the model is an acoustic excitation signal which carries spectral information to color the output sound. This makes it suitable for *acoustic interfaces* – devices which provide excitation signal and control data simultaneously. The presented synthesis model builds up on work done by Miller Puckette[1] and processes audio input from a piezoelectric microphone into a nonlinear reverberator. This paper details a strikingly simple but novel approach on how to make use of the momentary DC offset generated by piezoelectric microphones when pressed to simulate the changes in drumhead tension. This technique is especially of interest for interfaces without pressure sensing capabilities. In the design process we pursued an experimental approach rather than a purely mathematical. Implementations of the synthesis model are provided for *Pure Data* and *FAUST* as open source.

## 1. OBJECTIVE AND LIMITATIONS

The goal for this research was to create a computationally efficient synthesis model which can run on embedded systems like the *Raspberry Pi*, *Beagle Board + Bela cape* [2], or even microcontrollers [3]. Parameters should be adjustable in real time. Nonlinear reverberators fulfill this requirement. The reverberator shall act as a resonator for an audio signal from structure-borne sound. A given restraint shall be that impact pressure information is not available from the touch sensor due to limitations of capacitive sensing technology.

## 2. THE TICKLE INSTRUMENT

The *Tickle* (see Fig. 1) is an acoustic interface (in the literature also referred to as "hybrid instrument" [4]). It combines control rate sensors (touch position) with audio signals from a piezoelectric microphone in one surface. The contact microphone is providing the excitation signal to the digital resonator. Through this acoustic input we achieve intuitive interaction and intimate control. For a in-depth description of the instrument see [5], [6] and [7].

Figure 1: The Tickle instrument

The signal bandwidth of piezoelectric sensors goes below the range of human hearing.[1] What can be an adverse feature in many applications is used in the described algorithm to model the increased tension in the drumhead when struck.

### 2.1. Turning flaw into advantage

Capacitive touch surfaces sense a position by measuring the capacitance of an electrode. That means it can detect water containing – or otherwise conductive – materials, including fingers. Oftentimes it is desired by the application to sense the finger pressure. This is technically impossible to implement with capacitive touch, but since it correlates with the number of sensors in a matrix which are triggered and the **level** of capacitance, either are commonly used to estimate pressure. Touchscreens on current smartphones work this way. However, even though the **size** of the touch area may correlate generally, with the **force** applied, both are not the same and for a musical controller, the actual pressure is more meaningful.

The *Tickle* instrument (see Fig. 1) has a capacitive sensing matrix on its surface and therefore can't measure force applied to the surface with the control rate sensors. However, the instrument also has a piezoelectric sensor to pick up vibrations on the surface for the use as excitation signal in resonators.

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* Author of the FAUST implementation

[1] See e.g. [8, p. 631] in particular the chapter on piezoelectric microphones.

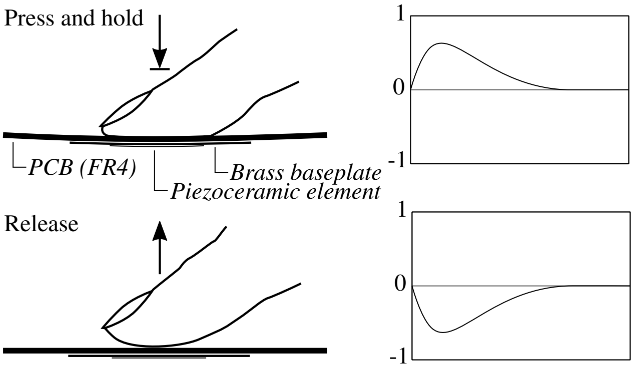

Figure 2: Visualization of the momentary DC offset while piezoelectric element is bent (top) and released (bottom). Simplified signal behavior on the right.

Piezoelectric sensors are commonly used to pick up structure borne sound and are relatively cheap components. Piezoelectric microphones typically come as a thin disk, which is mounted on a larger brass disk. The top is coated with a silver conductor. The ceramic material induces an electric charge when squeezed or bent. The voltage between the two sides of the piezo is proportional to the sound pressure introduced into the piezo. As, in theory, this effect is not limited to a certain frequency band, either audible sound or infrasound can be transformed this way.[2] In the *Tickle* instrument the piezoelectric disk is placed under the surface, so it can capture vibrations as well as impact force. We receive a signal of pressure change and bending on top of which the audible vibrations are modulated.

The bending and bending-back generate an electric charge. From the moment of holding the pressure the charge decays in roughly 15 ms. When the pressure is released we see an opposite voltage charge and decay (see Fig. 2). If bending or releasing happens slower than the decay, there is no signal. In common musical contexts, this so called DC offset, is removed very generously. The audible frequency band starts with 20 Hz and everything below this mark is typically considered an undesired signal and removed by a high-pass filter.[3]

In our case, the frequency band between 4 and 100 Hz is separated from the excitation signal, using steep high and lowpass filters. In this way, we “clean” the audible part of the signal, while generating a low frequency band that is used as an envelope signal for shaping parameters of the synthesis that model the tension of the drum head. Fig. 3 is showing the two signals after separation. This technique of turning a flaw (the undesired DC offset on bending) into a feature (the extra control signal at audio rate) might be simple or obvious, but we are unaware of any existing implementation or publication describing it.

In combination with the snare drum synthesis model we can use this extra control signal to mimic the stretching of the drum membrane when struck harder so that the slight changes in pitch can be made audible. This detail in the synthesis adds to the credibility of the synthesized sound and augments the intimate interaction quality with the instrument.

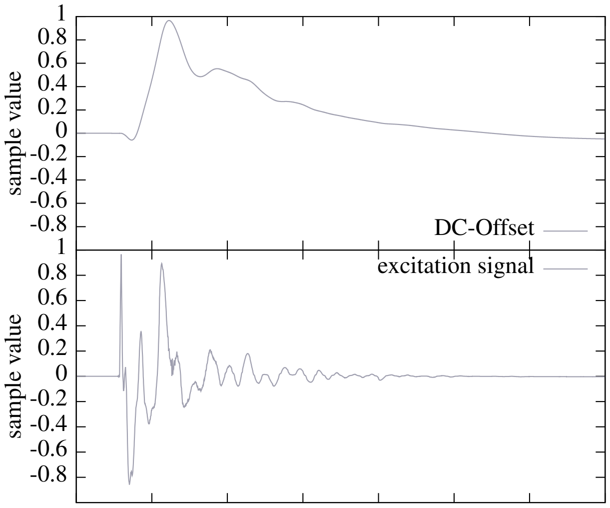

Figure 3: Comparison of a sample readout from the sensor split in DC offset and “clean” excitation signal.

## 3. MODEL

The synthesis model is based on research on nonlinear reverberators done by Miller Puckette[1] and implemented in *Pure Data*. Instead of a two-channel unitary delay network, the model uses a network of four cascaded delay lines coupled with rotation matrices $R$ and nested in an outer delay line (see Fig. 4). The input is the audio from the piezoelectric disk.

With given inputs $x_1(n)$ and $x_2(n)$ and angle of rotation $\theta$, the output of the rotation matrix can be described as

$$y_1(n) = cx_1(n) - sx_2(n)$$
$$y_2(n) = sx_1(n) + cx_2(n)$$

where $c$ and $s$ are given by $c = \cos(\theta)$ and $s = \sin(\theta)$ (cf. [10, p.190ff])

The angle of rotation $\theta$ as well as the delay times $d$ may be fixed or modulated by a signal at audio rate. The delay times determine pitch and timbre of the instrument. In our snare drum model, the delay times $d_1$ and $d_5$ are modulated to tune the drum head, $d_2$ and $d_3$ are fixed at 2.2 and 2.5 milliseconds and $d_4$ is fixed at 1 sample delay. Puckette proposes to make $\theta$ depend on the time-varying signal power in the network to imitate the effect of stretching a drum membrane. In our model, to mimic the rattling of the snares, the rotation angles in $\theta_1$ and $\theta_4$ are modulated by a lowpass filtered noise signal instead. $\theta_2$ and $\theta_3$ are fixed at $\pi$ and $\pi/3.57$. Furthermore, by lowpass filtering the excitation signal from the piezo-disk, we extract a little amount of DC offset which is added to the delay time $d_5$ to imitate the rising pitch of the drum that occurs when the drum membrane is struck, due to the increase in tension of the membrane.

As opposed to the elaborate mathematical modeling of a physical drum as in [11], the delay network in our model is not informed by the properties of an acoustic instrument. For the authors, the most viable route in the design process was experimentation and tuning with the guidance of the ear. Consequently parameters like delay times $d$ and the angles of rotation $\theta$ were found though this process of performance and experimentation.

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[2] For a detailed description of the piezoelectric effect including a physical model of how force is transformed to charge, see e.g. [8, p. 621]

[3] [9, p. 16]

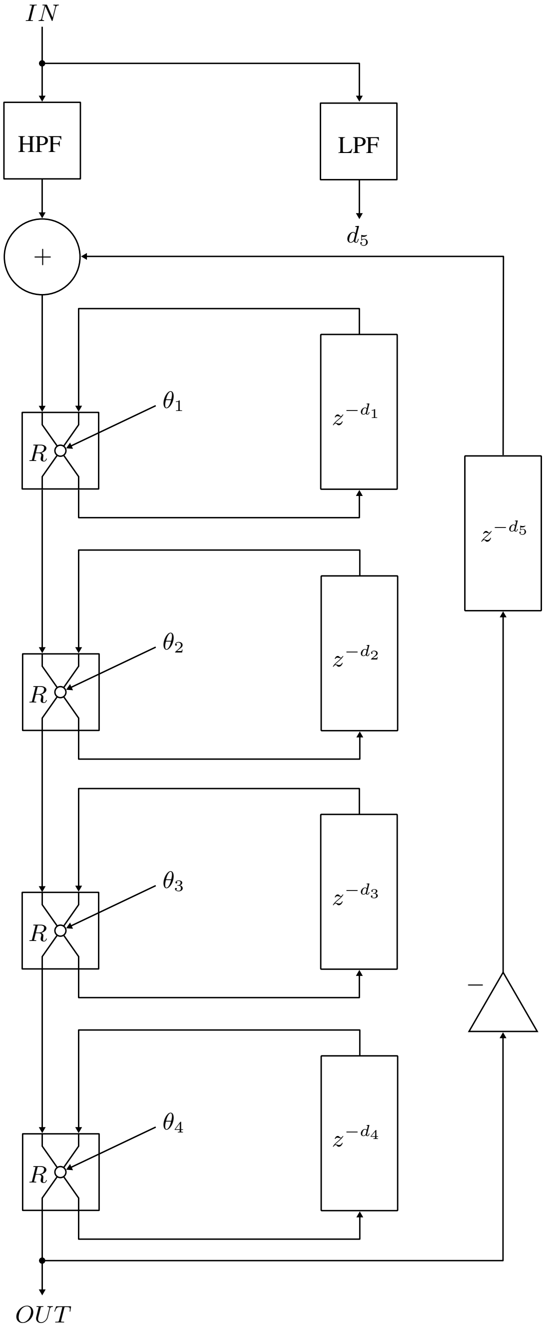

Figure 4: A network of four cascaded delay lines and rotation matrices nested inside a fifth delay line with an inverted signal.

The model may be tuned to approximate different percussive instruments, e.g. with shorter delay times and less amount of modulation, the timbral texture approaches that of cymbal. The Pure Data patch and FAUST code is available through our Git repository.[4]

## 4. SOUND QUALITY

To estimate how faithful the sound of our synthetic instrument might be [12], we conducted an online listening survey.[5] The test is available online.[6] If you are curious to take the test yourself, we recommend that you stop reading at this point and take the test now in order to be unbiased before reading the results here. Our survey had 42 participants, 35 indicated that they are instrumental musicians and 30 indicated that they are electronic music producers. The participants were provided with 9 listening examples, 4 of which were randomly chosen single hit samples of different types of real snare drums, recorded at close range. Another 4 examples were samples of our synthetic snare drum with different parameter settings. The model was excited by a hit of a fingertip on the surface of the *Tickle*. As a baseline we provided a drum machine sample that, to our understanding would be easily identifiable as being synthesized. The participants were allowed to listen and compare the samples repeatedly.

The listeners were asked to assess their confidence in what they are hearing as “surely recording (of an acoustic drum)”, “likely a recording”, “likely synthesized” or “surely synthesized”.

Out of a total of 378 votes, 15 (8.9%) classified our synthesis model as “surely recording” and 39 (23.6%) as “likely a recording”. The recorded snare drums were identified by 55 votes (32.7%) as “surely recording” and 63 (37,5%) as “likely a recording”. The baseline example was classified by 0 votes as “surely recording” and 3 (7.2%) as “likely a recording” (see Fig. 5).

29 participants classified at least one of our snare drum samples as “surely recording” or “likely a recording”. Only two participants were able to identify all our samples as “surely synthesized”. This indicates that, even if compared to listening examples of a real snare drum, most listeners find it difficult to identify our snare drum model as being synthesized.

A video demonstrating playing techniques and sound characteristics[7] can be found on our website.

## 5. FURTHER RESEARCH

Snare drums in the physical world have more affordances then the ones which can currently be simulated in our model. Size, material, resonant head tension and head characteristics may be the most obvious ones. It could be worthwhile to investigate how they may be represented in the filter graph.

Also, as stated before, the algorithm can easily be changed to approach other instrumental sounds. This aspect has already been

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[4] gitlab.chair.audio (mirror: github.com/chairaudio)

[5] We decided against an in-person survey of participants interacting with the hybrid instrument because the rich interaction quality of our synthesis compared to a mere triggering of samples would immediately bias against the recorded samples. Another reason was to avoid physical contacts in times of the pandemic.

[6] Listening survey: https://discourse.chair.audio/t/efficient-snare-drum-model-for-acoustic-interfaces-with-piezoelectric-sensors/65

[7] Demo video: https://discourse.chair.audio/t/videos-and-demos/49

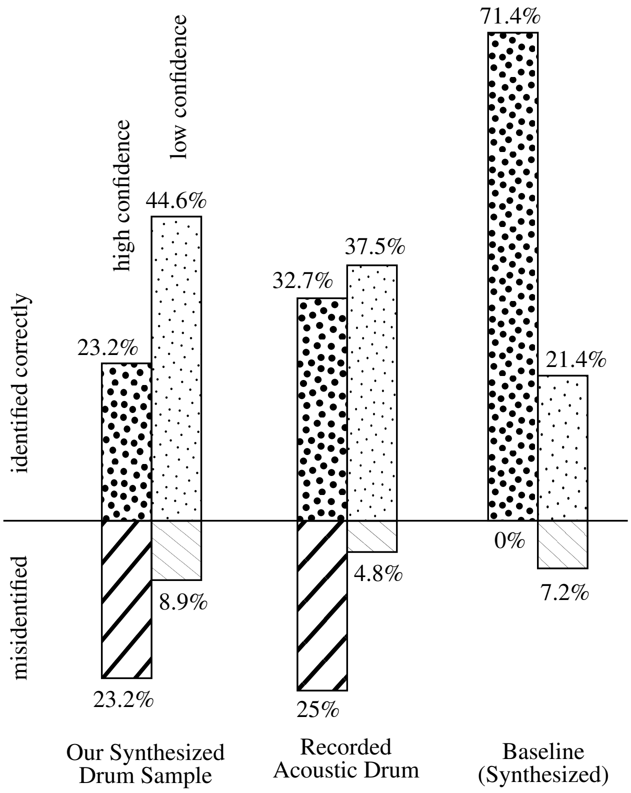

Figure 5: Results of the online survey show that the overall uncertainty over whether the sound is synthesized or a recording of an acoustic drum is significantly increased for our drum model.

considered in a patch that enables the user to play different instruments on each of the hexagons of the tickle. Collecting more experiences using the described synthesis will facilitate more multifaceted sounds to be accessible for the *Tickle*.

Another development is the port of the *Pure Data* patches to *FAUST*. *FAUST* provides a very flexible interface into a diversity of platforms. Especially the possibility to generate highly efficient C++ code will be especially useful it comes to the development of instruments running on embedded hardware platforms.[8]

## 6. CONCLUSIONS

With complex delay networks we can create convincing snare drum sounds with real time control over parameters like top head tension, snare rattle tension and damping. By utilizing the momentary DC offset when bending piezoelectric sensors to modulate the delay line of the filter we can create a computationally cheap simulation of the detuning spike which happens when the top head of the drum is being hit.

## 7. ACKNOWLEDGMENTS

Algorithms in this research are inspired by a lecture by Miller Puckette [13]. The Tickle instrument is conceived by Clemens Wegener.

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[13] Miller Puckette, “Music 206: Feedback and Distortion,” 2015.

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[8] *FAUST* also provides a huge library of physical models. Some of them, like the djembe can be used on the *Tickle* without adaptations. For others, like the flute or the clarinet models, the use of an excitation signal is currently lacking in the model.