The Bistable Resonator Cymbal: An Actuated Acoustic Instrument Displaying Physical Audio Effects

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ABSTRACT

We present the Bistable Resonator Cymbal, a type of actuated acoustic instrument which augments a conventional cymbal with feedback-induced resonance. The system largely employs standard, commercially-available sound reinforcement and signal processing hardware and software, and no permanent modifications to the cymbal are needed. Several types of cymbals may be used, each capable of producing a number of physical audio effects. Cymbal acoustics, implementation, stability issues, interaction behavior, and sonic results are discussed.

Author Keywords

augmented instrument, actuated instrument, cymbal, percussion, physical audio effect, mechanical sound synthesis, feedback control, tactile transducer

ACM Classification

H.5.5 [Information Interfaces and Presentation] Sound and Music Computing — Systems, I.2.8 [Computing Methodologies] Problem Solving, Control Methods, and Search — Control Theory

1. INTRODUCTION

The Bistable Resonator Cymbal utilizes a tactile transducer (i.e., actuator) driven by signals from microphones and/or piezo sensors to create an electroacoustic feedback loop which induces self-sustaining oscillations in a cymbal. Though feedback is the primary sound source in our work, the actuator is capable of driving the cymbal with an arbitrary signal as well. Resonant textures of many different qualities can be obtained by changing a microphone's position or through the use of a parametric or graphic equalizer, as well as other audio effects. The "bistable" behavior of the instrument is implemented using a conventional noise gate to activate the feedback loop only in response to a sufficiently loud strike, and a dynamic range compressor to place an upper bound on the amplitude of the oscillations.

We consider the family of feedback-actuated cymbal systems to be a sort of "meta-NIME" in the sense that a given cymbal's inherent acoustic character has a strong influence on the outcome of feedback actuation, meaning each instrument's identity is somewhat preserved despite the obvious augmentation. In addition, the signal processing design is largely generic; we have implemented two versions of the required processing, one with all analog sound reinforcement hardware, and another in a digital audio workstation, Pro Tools.

2. PRIOR ART

2.1 Feedback-Controlled Percussion

The EMdrum [11] uses voice coils attached to a drum's membranes as both sensors and actuators, and both moving-coil and moving-magnet implementations are described. The main sound source in their example musical application is a bass clarinet, but feedback capability is a fundamental design feature.

In [13] van Walstijn et al. describe the Prosthetic Conga, a drum augmented with virtual resonances by modifying feedback signals. The signal processing design is discussed thoroughly, but few hardware implementation details are given. Unlike the EMdrum, the Prosthetic Conga uses air coupling between the drum membrane and a loudspeaker to accomplish actuation.

Boutin et al. [4] have achieved active control of a xylophone bar with a proportional-integral-derivative (PID) controller, enabling independent adjustments to the resonant frequency, damping factor, and static gain of one of the bar's resonances.

2.2 Actuated Metallic Percussion

The EMvibe [5] falls into the category of metallic percussion (vibraphone bar), but this section focuses on idiophones in which the fundamental resonator is a flat plate or shallow spherical shell, e.g., gongs, cymbals, and thin plates.

The Ondes Martenot, an early electroacoustic instrument, employs a number of loudspeakers known as diffuseurs; unlike conventional loudspeakers, some of these are designed to strongly color the timbre of the instrument. One of these, the "metallique," consists of a voice coil affixed to a small gong. Jeanne Loriod [9] describes the metallique as "creating a special sort of 'halo,' as strange as it is unpredictable."

In [7], Kahrs et al. describe a system involving actuation of a large rectangular Thundersheet, an orchestral percussion instrument. As with the Ondes Martenot, the actuation signal is taken from external sources, and the resonator acts as an output-only device. Feedback control is not explicitly mentioned, but the authors state that "future work includes using the plates as sensors and processing the input."

Californian composer Matthew Goodheart has developed actuated metal percussion instruments for both performance- and installation-oriented applications [6]. Cymbals may be

NIME'15, May 31-June 3, 2015, Louisiana State Univ., Baton Rouge, LA.

driven by filtered noise, or by (many) sinusoidal oscillators tuned to the partials of the instrument. Depending on the application, control of these signals may be accomplished by a real-time gestural interface (performance), procedural algorithms (installation), or predefined sequences (composition).

2.3 Other Instruments

Cymbals have been integrated into robotic instruments [8], which approximate (possibly enhanced) human playing gestures via solenoid-driven mallets. The actuator used in our system, by contrast, is more akin to a loudspeaker and is in continuous contact with the cymbal.

Roberto Aimi has designed and built digital musical instruments which use a real cymbal as an interface [1]. Piezo contact sensors are used to drive a computer-based convolution algorithm for sound generation. The cymbal is heavily damped by a thick plastic sheet attached to its underside; this serves to isolate the impulsive sound of the stick which is used as input to the convolution stage. This also renders the cymbal's acoustic presence largely inert so that the convolution sound, when played through loudspeakers, can more effectively replace it in the room. In our system, the cymbal is both the interface and the only acoustic element involved; our actuator is attached to the cymbal's existing central mounting hole, and does not appreciably impact (i.e. dampen or otherwise alter) the normal vibrations of the instrument in the absence of an actuation signal.

3. CYMBAL ACOUSTICS

Cymbals exhibit considerable complexity in their acoustic behavior [12]. Four distinct regimes of amplitude-dependent nonlinear behavior present themselves under forced vibration by a sinusoidal shaker tuned to one of the cymbal's normal modes. At a small amplitude, the cymbal behaves linearly; in performance, this regime is somewhat impractical to use because it usually occurs at such low amplitudes. Subsequent increases of drive strength progress through the generation of harmonics, subharmonics, and finally chaotic oscillations. We do not employ a sinusoidal oscillator, but increasing the feedback loop gain results in similar progression of behaviors (see Figure 1).

In the conventional use of cymbals, a percussionist must select the proper instrument(s) to achieve the desired effect, often employing multiple cymbals to provide a diversity of timbres; this is equally true of cymbals under actuation. While actuation does considerably augment the instrument's timbral capabilities, we are not trying, nor are we able, to "turn one cymbal into another." Smaller cymbals are capable of rapid onset times and can progress quickly to a rather brash "bark"; larger cymbals are often limited to slower attack times due to their mass.

The thickness of the cymbal also plays an important role, because stiffness determines the degree to which nonlinear effects occur. Thin cymbals display the strongest nonlinearity, and chaotic vibration is sometimes the only regime that occurs at an adequate stage volume for performance. Inducing chaotic vibrations in a very thick cymbal, by contrast, may be beyond the capabilities of the actuator and amplifier; an advantage, however, of such a cymbal lies in its ability to retain a largely harmonic spectrum even at very high amplitudes.

4. SYSTEM DESIGN & IMPLEMENTATION

We emphasize the broad availability of all the components involved in the system. Tactile transducers are somewhat less well-known audio components, but they are affordable and available in numerous shapes and sizes. The parts that comprise the mounting and support system can all be readily found at a home improvement store. Common and low-cost sound reinforcement equipment, along with industry standard software in our digital implementation, handles audio.

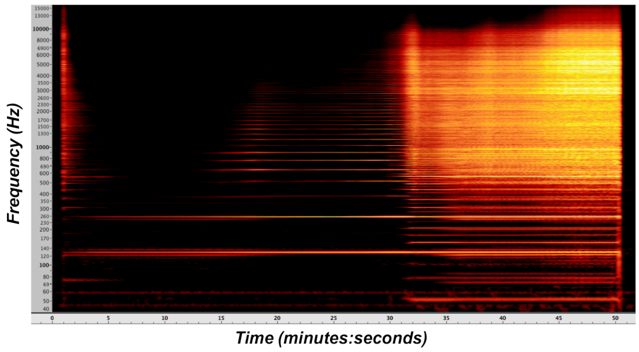

Figure 1: Spectrogram of a 14-inch thin splash cymbal displaying (nearly) linear, harmonic, subharmonic and chaotic oscillations over the course of a manually-applied volume swell.

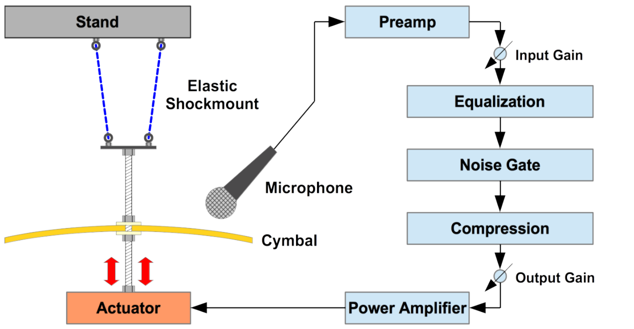

Figure 2: Simplified system layout.

4.1 Actuator Assembly and Stand

The cymbal is tightly clamped in the middle of a threaded rod between hard nylon washers. The actuator is attached to one end of the rod, and the whole assembly is hung by an elastic cord shockmount from a heavy stand made of Unistrut (see Figure 2). Thus the actuator and cymbal are tightly coupled, while the shockmount effectively isolates them from the stand. This attachment technique does not exhibit the normal "swishing" behavior typical of traditional cymbal stands (allowing the cymbal to rock back and forth with large excursions in the angle between the plane of the cymbal and the ground), but the elastic cord does allow for some swaying, and the cymbal is otherwise mostly playable just like a conventional one. One cord is sufficient for suspending and isolating the resonating elements, but can wobble enough with respect to the microphone to cause a varying phase delay which may cancel out the feedback loop; we have found that a four-cord suspension is far more stable, while still not too rigid.

Our early prototypes used an Induction Dynamics SolidDrive SD1-G tactile transducer as the system's actuator. With only 20W RMS / 100W peak power handling, the SD1-G is not capable of exciting some larger cymbals at sufficient volume; to drive these, we use a Clark Synthesis TST239 transducer. An aluminum plate with threads matching the TST239 was custom-machined for the SD1-G, allowing rapid change-out and comparison of the actuators with a given cymbal assembly.

4.2 Sensors

Microphones and piezo transducers have been explored to sense the vibrations of the cymbal. Signals from multiple sensors may be mixed together, creating further sonic variations through partial cancellations and reinforcements.

4.2.1 *Microphones*

Handheld microphones are ideal for intimate control of feedback, as changes in their position relative to the cymbal allow a performer to access a number of different resonances; a simple dynamic microphone such as a Shure SM58 will often suffice. Several different sounds may be obtained by experimentation, but the process is somewhat non-intuitive, as the phase, amplitude, and spectrum of the signal vary in complex ways due to the interaction between the cymbal's sound radiation pattern and the microphone's position and pickup pattern. In fact, a common microphone technique error often associated with inexperienced vocalists, that of "cupping the mic", can change the microphone's pickup pattern enough to cause substantial changes to the quality of feedback. Stands or flexible goosenecks are employed to free the performer's hands so they may adjust the signal processors or directly interact with the cymbal (or other instruments) while the system generates a drone.

4.2.2 *Piezo Sensors*

We have constructed a collocated sensor/actuator pair by tightly clamping a piezo pickup between the cymbal and actuator. This sensor is much more robust than microphones to acoustic crosstalk from nearby sound sources, but it cannot be moved during performance to achieve different timbres; without attending to the controls of some external equipment, the piezo on its own does not generate very expressive results.

4.3 Signal Processing

In [2], Berdahl and Smith describe a number of signal processing schemes which can alter the behavior of an actuated acoustic instrument. They motivate the inclusion of a dynamic range limiter to stabilize the control loop by limiting the growth of self-sustaining oscillations. They suggest it may be fruitful to place even commonly used audio effects into a feedback control loop, and indeed our system owes much of its crucial functionality to a conventional compressor and noise gate.

4.3.1 *I/O and Amplification*

Connectivity and signal routing in the system is handled by a Yamaha MG12/4 mixing board. Analog or digital effects processing is incorporated through channel inserts, with a MOTU 828mkII Firewire audio interface used to access Pro Tools. A QSC RMX2450 power amplifier is used to drive the tactile transducers.

4.3.2 *Polarity Reversal and Phase Adjustment*

Phase lags have a strong effect on feedback control loops; in attaching the actuator to the power amplifier, both normal and reverse polarity wiring will work, but different resonances are excited in each case. Pro Tools' built-in Time Adjuster plugin can implement a more general per-sample phase delay. This opens up the possibility of many new sound textures, but tends to suffer from zipper noise when adjusted in realtime. In our experience, these phase adjustments are not essential to the operation of the instrument, but may be worth investigating for new timbres.

4.3.3 *Equalization*

In our analog system, an Ashly GQX 3102 31-band 1/3-octave graphic equalizer affords 15db boosting and attenuation throughout the audible spectrum, as well as a sweepable high-pass filter. In a procedure analogous to a live sound engineer "ringing out a room" to provoke and then eliminate potential feedback, prominent resonances are identified and attenuated so the loop gain may be increased without perturbing them. Incrementally, this technique reveals additional resonances which only self-sustain at these higher loop gains.

There is, however, a major caveat in the usage of equalization; the phase shift introduced by a filter can have a strong impact on the resulting feedback as well. In some cases, a resonance will actually be heard to grow in amplitude when a band is attenuated! Digital parametric equalizers in Pro Tools seem to exhibit fewer of these sorts of phasing artifacts, but this renders them slightly less influential in changing timbre than the analog equalizers.

4.3.4 *Noise Gating*

Placing a noise gate at a proper threshold in the processing loop allows one to initiate feedback by striking the instrument. To stop feedback, the cymbal can be choked with conventional technique, causing the gate to close.

4.3.5 *Dynamic Range Compression*

As discussed in [2], RMS level controllers are an essential effect type for actuated instruments. In the absence of compression, high loop gains can cause a cymbal to rapidly "run away" in an unpleasantly loud burst; a 12-inch Paiste china splash was recorded as producing 110 dB(A) SPL at a distance of three feet during a typical "explosion." We have found that compression ratios of 8:1 and above can render the instrument far more playable, allowing one to ease into higher-gain regimes in a stable fashion.

5. SONIC RESULTS

The fact is that *many* possible configurations will generate some kind of feedback sound. The current equipment achieves high enough loop gain in all cases so far. It is not a matter of probing for some narrow region of the parameter space outside which the device does not function at all, but of exploring the numerous possible sounds made available.

Timbrally, the harmonic and subharmonic regimes of the instrument resemble those which can be achieved by sliding a cello bow perpendicularly across the edge of a cymbal [10]. Spectrally, chaotic vibrations somewhat resemble the early moments of a struck cymbal note, but the envelope is radically different.

5.1 Cymbals

5.1.1 *12" China Splash*

This cymbal was used in the first prototype of the instrument, and is still one of our favorites. Being fairly lightweight, it is easy to initiate self-sustaining oscillations which grow quickly. Chaotic vibrations are easy to induce, as are rich multiphonic drones.

5.1.2 *18" Flat Ride*

This larger cymbal seems to enter into chaotic vibrations somewhat gradually and only at high amplitudes, producing loud, bright tonal textures under most circumstances. We have also observed a complex, meandering multiphonic drone which takes up to a minute to settle into a steady-state oscillation.

5.1.3 14" Paper-thin Splash

Though it is capable of producing pitched sounds, this cymbal enters the chaotic phase rapidly by virtue of its very light weight.

5.1.4 13" Hi-hat Bottom

We have not been able to induce chaotic vibrations in this very heavy, thick cymbal with current hardware. Though such sounds may be within the reach of a more powerful actuator/amplifier combination, for now we can only produce pitched ringing, not noisy hissing textures.

5.2 Physical Audio Effects

This section describes some of the emergent behaviors of the instrument.

5.2.1 Latching Resonances

The "bistable" moniker of the instrument refers to the behavior exhibited by this configuration, in which the thresholds of the noise gate and compressor act to stabilize the resonator in "off' and "on" states, respectively (see Figure 3). Increasing input gain decreases the rise time of the oscillations, while the combination of the compressor's threshold and output gain determines the upper bound of actuation energy (i.e. what timbral regime it will rise to).

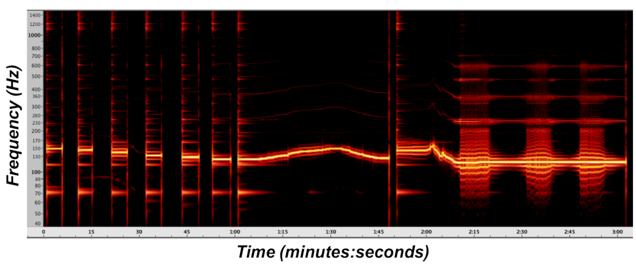

Figure 3: Spectrogram of varying pitch between latching strikes (left) and continuously (center) with a 12-inch china splash. Amplitude modulation displaying sidebands can be seen on the right.

5.2.2 Pitch Bend

One very unusual effect was observed in both the 12-inch china (see Figure 3) and 13-inch hi-hat bottom; a ≈ 125 Hz resonance induced by a large EQ boost in that band exhibited pitch bending of more than a whole step in response to varying the amplitude of the 200, 250, and 315 Hz EQ bands. As explained in [3], pitch bending requires more energy than amplitude modulation; more investigation is needed to understand why our system achieves it with this configuration.

5.2.3 Amplitude Modulation

Given the proper gain structure, the dynamic range compressor is capable of creating a slowly-varying amplitude modulation effect whose speed is dependent on its attack and release settings. Figure 3 shows the effect of manipulating these compression parameters during a sustained drone.

5.2.4 Reverse Cymbal

Reversed sound samples of cymbals are widely used as an effect in electronic music. Using either external volume control (as shown in Figure 1) or a properly-set compressor, the rise time of the feedback loop can be finely controlled to create crescendos which create a similar effect in realtime.

6. CONCLUSIONS AND FUTURE WORK

We have demonstrated the Bistable Resonator Cymbal, a flexible, extensible system for feedback actuation of cymbals. It is our hope that further development will be informed by working with composers and performers to explore musical applications of the instrument.

While the instrument's core functionality is fairly robust as of this writing, further design iterations will aim to refine its expressive capabilities. In both our analog and digital implementations, we have only investigated the use of a few basic, widely available audio processors; the use of other commercially-available as well as custom signal processing deserves further investigation. Acoustically, we already encounter a diversity of peculiar characteristics among the world's many cymbals; what new peculiarities may appear under actuation remains to be seen.

7. ACKNOWLEDGMENTS

Thanks to Edgar Berdahl, Esteban Maestre, Michael Gurevich, and Karl Yerkes.

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