BLIKSEM: An Acoustic Synthesis Fuzz Pedal

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ABSTRACT

This paper presents a novel physical fuzz pedal effect system named BLIKSEM. Our approach applies previous work in nonlinear acoustic synthesis via a driven cantilever soundboard configuration for the purpose of generating fuzz pedal-like effects as well as a variety of novel audio effects. Following a presentation of our pedal design, we compare the performance of our system with various various classic and contemporary fuzz pedals using an electric guitar. Our results show that BLIKSEM is capable of generating signals that approximate the timbre and dynamic behaviors of conventional fuzz pedals, as well as offer new mechanisms for expressive interactions and a range of new effects in different configurations.

Author Keywords

acoustic effect pedal, augmented instrument, nonlinear acoustic synthesis, transducers, actuators, distortion, fuzz pedal, cantilever hysteresis, electric guitar

CCS Concepts

•**Applied computing** → **Sound and music computing;**
Performing arts; •**Hardware** → *Physical synthesis;*

1. INTRODUCTION

Integration of physical materials into sound synthesis processes allows musicians to exploit the acoustic properties of specific materials to offer expressive timbral and sonic variation. [1] This is a notable feature of augmented instruments, effects, and more generally sonically augmented objects [6]. We present BLIKSEM: an electromechanical interface employing acoustic synthesis, shown in Figure 1. This interface is a variant of our previous driven cantilever instrument system consisting of four active components: excitation source, bridge, resonator, and receiver [17, 4, 5]. In this system, the excitation source is a transducer connected to a cantilever bridge, which is then coupled to a soundboard resonator. The soundboard has two piezoelectric pickups located at either end of the soundboard that function as the receiver.

A key part of this design is the bridge between a driven cantilever and the surface of a soundboard or resonator

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[1]A video abstract of this paper can be found at: `https://vimeo.com/313748106/a257802fc8`
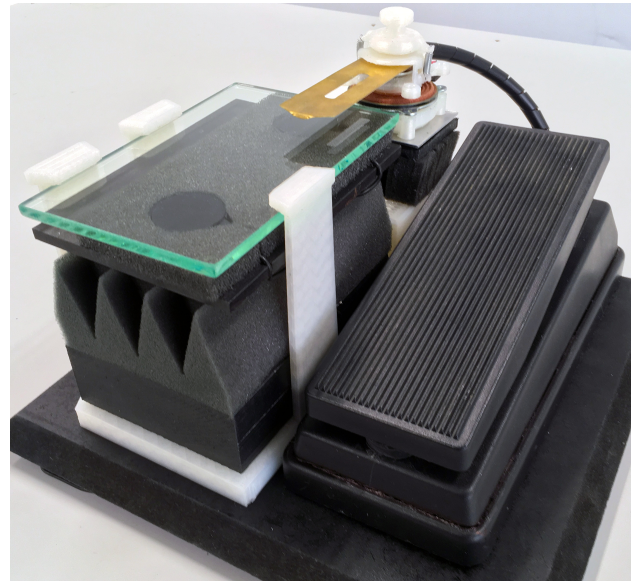
Figure 1: BLIKSEM acoustic synthesis fuzz pedal.

called the tip-surface interaction. By using an electromagnetic transducer, we produce an intermittent time-varying motion on the cantilever that results in the production of intermodulation sideband components. The relative position of the cantilever to the soundboard changes the tip-surface interaction, altering both the timbre and dynamic response of the system. To achieve this change in position, we employ a foot pedal allowing the musician to raise and lower the cantilever, allowing for precise control the device.

Similar to other pedal effects, the signal input to BLIKSEM can range from electric guitars to synthesizers to a processed signal from another effect pedal or source. Likewise, the user can also blend between the dry input and either of the pickups located on the soundboard that corresponds to either a direct or diffused sound quality.

The paper is structured as follows: We first discuss the motivations and prior work on guitar pedal effects in Section 2, followed by a description of nonlinear acoustic synthesis as it relates to the driven cantilever design in Section 3. In Section 4, we discuss the design of BLIKSEM and related features. Section 5 presents the main application and comparison methods which are evaluated and discussed in Section 6, followed by conclusions in Section 7.

2. MOTIVATION AND PRIOR WORK

Musicians frequently search for new sounds and the means to produce them. With the arrival of recording technology and electric synthesizers, a new universe of sounds be-

came accessible for composition, improvisation, and performance. In particular, nonlinear synthesis modulation techniques that include amplitude modulation, frequency modulation, and intermodulation, allowed a musician to generate complex timbres from relatively simple sources. Exploiting the fact that physical systems are inherently nonlinear we can therefore expressively evoke rich and complex timbres with similarly simple sources found in electronic music.

Thus, our motivation is to produce electronic effects in the acoustic domain through manipulation of physical materials. In the case of BLIKSEM, we aim to illustrate how the nonlinear effects in fuzz pedals have corollaries in the acoustic synthesis domain using previously discovered techniques.

2.1 Electromechanical Effects in Studio and Live Contexts

Our system speaks to the tangible, physical forces that shaped the sound of the early electric guitar. One of the first electromechanical audio effects used in studio and live applications were artificial reverberation systems, commonly referred to as reverbs. Spring reverberation systems were developed by Hammond in the 1920s for inclusion in organ systems. These compact systems transduced incoming audio signal through a helical spring to produce a reverberation that was bright with distinct echoes [18].

Another popular physical reverberation system is plate reverberation. These units were introduced by EMT in the 1950s, and create an artificial room reverberation with no clear or distinct echos by transducing the incoming signal through a metal plate via a speaker positioned closely to the plate. This reverb was warmer, muddier and unlike the reverberation chambers that were previously used [18].

In the case of amplification, the dynamic output of an acoustic guitar's was often too low for big band applications, which largely contributed to the popularization of the easily-amplified electric guitars by early pioneers such as Leo Fender and Les Paul [10]. The amplified electric guitar provided a novel platform for experimentation with effects such as over-driven vacuum tubes and the spring reverb tanks included in early combination amplifiers. The first tube driven spring reverb system included in amps by Gibson and Premier in the late 1950s with the Fender Vibroverb popularizing the in-amp effect in 1964 [14]. These amplifiers, with built-in spring reverb tanks, were frequently knocked and dropped to create warbles and iconoclastic reverb chirps [10]. These early effects would go on to define the sonic signature of entire genres of music, such as surf rock's iconic spring reverb guitar tones.

These early electromechanical effects illustrate the wide array of sonic possibilities present in the amplified electric guitar system. Contemporary effects pedals often seek to emulate and re-imagine the sound of these early physical effects in a compact and affordable form. Guitar effects pedals now reach millions of players every year, putting effects that were once confined to high-end studios into the hands of musicians [10].

2.2 Distortion Effects in Guitar Music

Distortion is present in guitar music as over-driven tube amplifiers used by the pioneers early Blues [10]. This style of distortion included a form of soft clipping, which is achieved by over-driving a vacuum tube or diode, giving rise to the colloquial phrase 'over-drive," used to describe these milder and often dynamic distortions. More aggressive forms of sonic experimentation occurred as the electric guitar increased in popularity, such as Dave Davies, guitarist for The Monkees, cutting holes in the speaker of his amplifier which

mimicked a harder form of clipping, typically referred to as distortion [12]. Distortion effects circuits, such as the RAT and Boss DS1 typically utilize op-amp gain stages as the main clipping mechanism [8, 9]. These aggressive and compressed distortions became popular among rock and punk guitarists.

The first reported recording of a hard clipped distortion, traditionally refereed to as fuzz, appeared on the bass solo (1:26-1:46) on Marty Robbins's 1961 *Don't Worry*. The fuzz tone was a result of a faulty channel strip in engineer Glenn Snoddy's console [15]. This sound would go on to inspire the development of the "fuzz box", the Maestro Fuzz Tone, famously used by Keith Richards in the "(I Can't Get No) Satisfaction" riff [7, 11].

This led the development of many notable fuzz pedals, including the Arbiter Fuzz Face, Electro-Harmonix (EHX) Big Muff and ZVex Fuzz Factory. Each pedal became known for their unique timbral and dynamic characteristics [12]. The Gamechanger Audio Plasma fuzz pedal is a notable physical effect pedal that arcs an incoming signal across a xenon filled tube [2]. This unique method of clipping creates distinct harmonic and in-harmonic partials. The manipulation of the pre-amp voltage allows for both gating and timbral control. Zachary Vex developed the ZVEX Candela Vibrophase, which uses a stirling engine powered fly-wheel to periodically interrupt the light received by a photo-cell which is used as the clock input to a vibrato and phaser circuit [1].

3. THEORY OF OPERATION

Distortion effects are often a result of harmonic and intermodulation distortion produced from hard and soft clipping. In analog circuits, these effects are a result of driving tubes, diodes, opamps, and transistors at the top or above their respective operating ranges [10, 12]. Digital emulations of these effects can be modeled by the following equations for hard clipping:

$$f(x) = \begin{cases} 1, & x \leq -1 \\ x, & -1 \leq x \leq 1 \\ 1, & x \geq 1. \end{cases} \tag{1}$$

where x indicates the current input sample $x(n)$ and $f(x)$ denotes the output [13]. Soft clipping occurs when the edges of the clipping exhibit a smoother roll-off as the value of x approaches the upper and lower limits, and is often modeled as the cubic nonlinearity shown in equation 2 [16].

$$f(x) = \begin{cases} -\frac{2}{3}, & x \leq -1 \\ x - \frac{x^3}{3}, & -1 \leq x \leq 1 \\ \frac{2}{3}, & x \geq 1. \end{cases} \tag{2}$$

An alternative way to model distortion more generally is using the arctangent function [19]. Since BLIKSEM is a physical system, and therefore continuous, we can model the distortion behavior in BLIKSEM with the following expression:

$$f(x) = \frac{1}{\pi} \int_{-1}^{1} \arctan(\alpha \cdot sin(x)) dt \tag{3}$$

where $f(x)$ is a nonlinear system driven with some periodic frequency $sin(x)$, with the relative amount of amplitude set by the coefficient α, which in turn is limited by the arctan function resulting in distortion. With approximation, $0 \leq \alpha \leq 10$ models soft-clipping behaviors, whereas $\alpha \geq 10$ models hard-clipping with steeper curves as α approaches infinity.

Figure 2 illustrates the relationship between low α and high α values when plotted with an arbitrary sinusoidal function. As α approaches infinity, the corners of the roll-off become hard-edged. It is notable that the values required for α to reach these extremes is quite high, and in a physical system, such as BLIKSEM, these values would likely not be possible without extreme levels of energy and mechanical robustness, which we discuss further in Section 3.2.
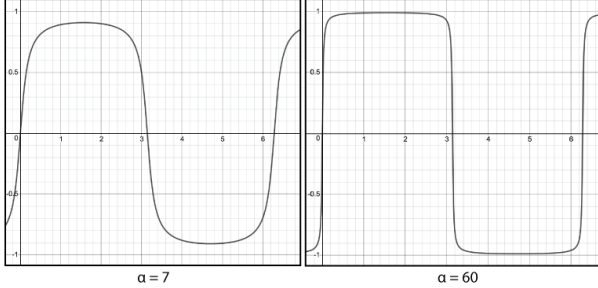
Figure 2: graph of equation 3 with $\alpha = 7$ (left) and $\alpha = 60$ (right)

3.1 Nonlinear Acoustic Synthesis

When one or more signals are injected into BLIKSEM, nonlinear acoustic modulation and distortion in the form of intermodulation occurs [17, 4, 5]. The forces responsible for this modulation are a result of the nonlinear coupling between an input and an output via a cantilever. This signal is bridged to a soundboard with a metal cantilever, and the signal is captured with a piezoelectric pickup.

The cantilever operates as a resonator-bridge between the transmitter and the receiver, and the tip-surface interaction is responsible for the nonlinear acoustic synthesis [17]. A cantilever in this context is free beam fixed at one end. When driven with a signal, two things can occur. First, the cantilever itself is a resonator, enhancing harmonics closest to its modes. Second, the cantilever interacts intermittently with a soundboard resulting in intermodulation. Utilizing this approach allows for a wide range of timbral variation. In the particular case of BLIKSEM, we employ the cantilever properties that generate higher-order intermodulation products [4].

3.2 Cantilever Hysteresis and Hard-Clipping

The intermittent time-varying motion of the cantilever can be thought of as a physical interpretation of the traditional hard-clipping of transistors used to create fuzz effects. Further comparing extreme digital or analog distortion, commonly referred to as hard-clipping, to BLIKSEM distortion, the α values shown in Equation 3 correspond to the amplification of the total electromechanical energy injected into the system. Since the physical system is less efficient than the electrical ones, much higher α values would be required to achieve the same relative levels of hard-clipping distortion in an electrical system, which is further restricted by the mechanical limits of the system resulting in transformation of electromechanical energy into heat or other types of mechanical failure.

To mitigate the effects of electromechanical failure in a physical distortion system, we exploit a special property of cantilevers called hysteresis. In an over-driven state, the cantilever will enter hysteresis and result in a significant increase in nonlinearities [3]. This over-driven state offers the benefit of effectively lowering the amplitude threshold α for the hard-clipping condition characterized in Equation 3.

Furthermore, these nonlinearities exhibit behavior similar to relaxation oscillators and chaotic oscillators. Such resulting nonlinearities of the motion generated by the cantilever in this over-driven state translate into the interruption of the contact between the input and output, and therefore further weaken both the strength and coherence of the output signal in ways very similar to behaviors observed in fuzz pedals.

4. BLIKSEM DESIGN

BLIKSEM combines the primary components of the driven cantilever system with a guitar foot pedal design [17]. The driver-cantilever model enables either strong or weak intermittent coupling between a signal source carried by the cantilever, and a receiver source attached to a soundboard. The amount of contact between the tip and surface affects the sound quality since the strong coupling results in a more complete transduction of the signal, and a weak coupling results in a more chaotic transduction of the signal. This control of this tip-surface interaction is achieved through a mechanical dual rack-pinion actuator controlled by an expression foot pedal. The actuator allows the musician to precisely control the amount of contact the cantilever has with the surface of the soundboard using the foot pedal, similar to other guitar effect pedal systems such as *Wah* and volume control pedals.

In addition to the pedal control, this system differs from previous designs because it is a single-driver system utilizing stiffer materials in the cantilever for the purpose of generating higher frequency distortion. When the cantilever is in full contact with the soundboard, the effect is a strongly coupled, resonant filter that exhibits fewer non-linear distortion elements, especially in the low-frequency range of the electric guitar. As the cantilever is raised, the system exhibits an increasing amount of non-linear distortion components. If the cantilever is raised to where only very intermittent contact is made with the soundboard, a sputtery signal is achieved, akin to the "dying battery" sounds of early voltage-starving circuits and of modern fuzz pedals [10].

Additionally, users can swap cantilevers and soundboards, allowing for timbral selection to occur between songs or long pauses in the music. Any soundboard that can physically fit inside the device may be used, allowing for an nearly infinite variety of DIY sounds and textures. Soundboards can also be fabricated, modified, or printed to generate specific resonance patterns, as discussed in Section 5.

4.1 Implementation

BLIKSEM consists of three main components: an actuated-cantilever head unit that contains two linear voice-coil actuators with a removable cantilever, an expression pedal mechanism that changes the height of the cantilever head unit, and an acoustically isolated soundboard platform with two piezoelectric pickups. The electronics are housed at the bottom of the soundboard platform in a removable box. The structural components of the entire system were 3D printed using a Prusa MK 2.5 printer with clear PLA filament, with additional materials consisting of sound isolating foam, wood, and metal hardware. Figure 3 details the components of the BLIKSEM acoustic distortion effect.

The actuated cantilever head unit was adapted from a prototype of the Syrinx Acoustic Synthesizer designed by Topel and Chang. It consists of two linear actuators, a primary driver consisting of a Dayton Audio DAEX25FHE-4 Framed High Efficiency 25mm Exciter, and a smaller secondary driver consisting of a Tectonic TEAX13C02-8/RH
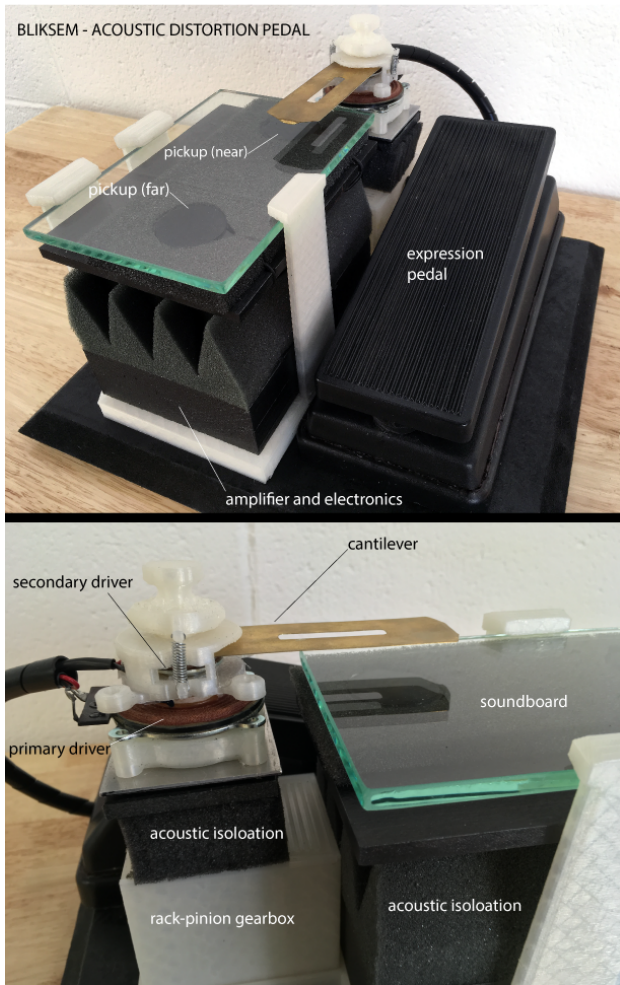
Figure 3: BLIKSEM acoustic distortion pedal prototype with annotated labels of the system, with the front facing perspective (top), and left-side perspective closeup of the cantilever mechanism (bottom).

13mm Exciter. [2] A fabricated cantilever of brass or steel is coupled to the secondary driver using a positioning frame attached to the cantilever and a spring locking mechanism placed above the cantilever. By releasing the locking mechanism, users can swap different cantilevers from the unit.

An expression pedal allows the musician to raise and lower the head unit via a dual rack-pinion system housed within the foot pedal mechanism and a gearbox located below the head unit, and coupled by a 1mm diameter carbon-fiber rod. A foam spring coupled to a metal plate stabilizes, isolates, and supports the head unit. When the expression pedal is pushed down, the cantilever is lowered causing the cantilever to make contact with the soundboard. When depressed further, the cantilever begins to deflect with the surface of the soundboard result in a stronger linear coupling with the surface and a different expression of the harmonic content.

The interchangeable soundboard system consists of a foam isolation layer below a platform with two piezoelectric pickups placed at opposite ends, shown in Figure 3. The pickup (near) captures more of the direct cantilever interaction with the soundboard while pickup (far) captures more of the

indirect signal with stronger resonance components of the soundboard. A soundboard can then be quickly clamped onto the platform with three positioning arms integrated into the base, allowing for the user to rapidly switch different soundboards as desired. An optional electronics box can be housed at the bottom with the necessary inputs and outputs which allows the musician to set the amplitude of the driver or drivers, the pre-amplifier level, and the near/far mix from the two pickups.

BLIKSEM features three types of customization that alter the devices timbre, dynamic response, and noise envelope. Sound boards of different dimension and materiality can be used and affect the resonances of the system as well as the timbre of the fuzz. These soundboards can be manually altered to reduce or accentuate resonances within the system or to create different unique effects, with the only restriction placed on the sound board customization being its outer dimensions.
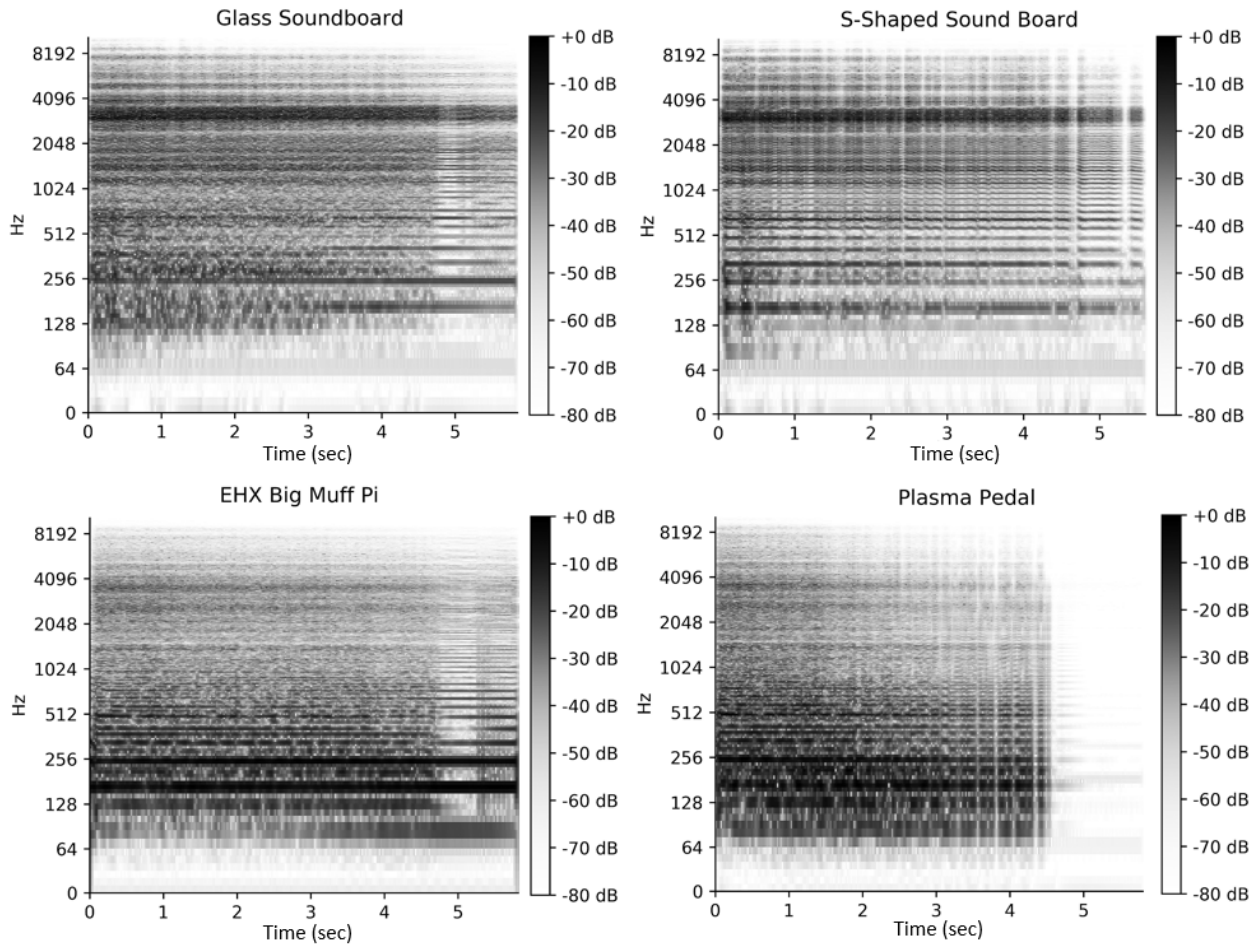

Figure 4: A selection of soundboards of different materiality and customization used during the development of BLIKSEM. From left to right: HDPE, Corrugated ABS, Aluminum, Poplar wood and three modified composite boards.

The cantilever used to excite the sound can be changed resulting in a wide array of dynamic behaviors from the near-linear response of a short and stiff cantilever to the non-linear and chaotic behavior of a long and flexible cantilever. The cantilevers themselves also impact the resonance of the system while the sharpness of the tip varies the amount of contact noise, the transient-noise envelope, and the overall timbre of the system. The height of the cantilever relative to the soundboard can be altered in real-time by up to 15mm. This offers users a highly performative timbral and dynamic control mechanism designed for hands-free engagement. When the cantilever is lowered below the soundboard, the system begins to approximate a linear filter.

5. APPLICATION AND COMPARISON

BLIKSEM was compared to three popular fuzz pedals, namely the EHX Big Muff Pi, ZVEX Fat Fuzz Factory, and the Gamechanger Audio Plasma[3]. The objective of this comparison is not a rigorous emulation per se, but rather a qualitative comparison between existing fuzz pedals and BLIKSEM. When BLIKSEM is put in a conversational

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[2]For the purpose of evaluation, the secondary driver was not utilized, as further experimentation with feedback, side-chaining and other effects will be explored in future work.

[3]Sound examples are available on Vimeo: https://vimeo.com/329339577 and SoundCloud: https://soundcloud.com/user-397987918/sets/bliksem-an-acoustic-synthesis-fuzz-pedal-sound-examples

Figure 5: Power spectrograms of an E2 power chord played through the BLIKSEM with glass soundboard (top left), with s-shaped wood composite sound board (top right), EHX Big Muff Pi on high sustain (bottom left) and the Gamechanger Audio Plasma Pedal at low voltage setting (bottom right).

comparison with popular fuzz pedals, both the shared and unique properties of BLIKSEM become apparent. These unique nonlinear acoustic synthesis properties particular to BLIKSEM are a result of the cantilever-soundboard interaction.

Each of the pedals were qualitatively compared by playing identical audio sample of seven guitar phrases, recorded using a Fender 2012 Stratocaster through each of the pedals. The output was then played through a low-gain Fender Deluxe guitar combo amplifier and recorded with a Shure SM57 placed off-axis through a Focusrite 18i20. The attack, gate, transient-noise envelope, and timbre of each of the systems were qualitatively compared using spectral analysis.

The EHX Big Muff Pi produces a smooth, highly-compressed, and sustained fuzz. Its smooth dynamic response is a result of its low gating setting which cannot be explicitly controlled. The ZVEX Fat Fuzz Factory is highly customizable with controls for compression, gating and signal stability/feedback. This pedal can produce sputtery, 'dead battery' fuzz sounds, and can be heard on Eagles of Death Metal's "Wanna Be In LA" as well as Muse's "Plug Baby".

The Gamechanger Audio Plasma is the most similar to the BLIKSEM in our evaluatio as it uses non-transistor or diode-based method of signal clipping. The Plasma arcs the signal across a xenon tube, producing a gated response with a unique timbral profile. The amplification gain before the signal is arced can be adjusted, altering the timbral and gating profile of the pedal. There is no capability for

modification of this, nor is there a mechanism for ease of real-time control such as a foot pedal.
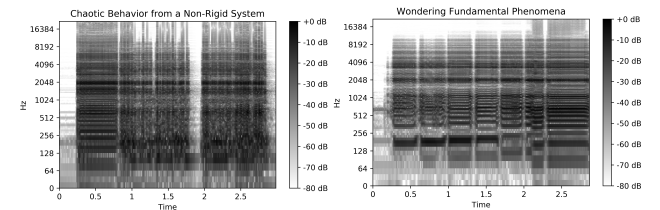
Figure 6: Power spectrograms of an E2 power chord played through the BLIKSEM with a 152x101x5mm glass sound board and a non-rigid 55x19x0.2mm brass cantilever (left) and a strictly ascending chromatic line played through the BLIKSEM with a 5mm thick S-shaped composite wooden sound board and a semi-rigid 55x19x0.2mm brass cantilever (right).

6. RESULTS AND DISCUSSION

The spectrograms in the left column of Figure 5 compare BLIKSEM with the glass soundboard configuration to the EHX Big Muff Pi. Both have a long sustain with rich harmonic distortion patterns and strong, continuous harmonics. The BLIKSEM glass configuration includes additional
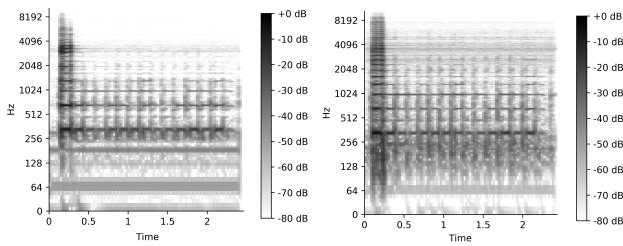
Figure 7: Power spectrograms of E3 notes of differing attack strength played through the BLIKSEM with a 152x101x6.3mm wooden poplar soundboard (left) and the ZVex Fat Fuzz Factory on a medium gain and gate setting (right).

low frequency noise components and strong distortion resonance in the $2KHz - 4.1KHz$ range as compared with the EHX Big Muff Pi. Both BLIKSEM with s-shaped soundboard and the Plasma Pedal at a low-voltage setting, the right-most panels in Figure 5, illustrate gated-fuzz sputter behaviors. This behavior of the periodic interruption of signal is indicated by the presence of vertical lines in the spectrogram. Figure 7 illustrates the dynamic response of BLIKSEM with a wooden poplar soundboard to notes of varying attack intensities. The amount of distortion is strongly correlated to the attack of the incoming note, similar to the responsive gating on the ZVex Fat Fuzz Factory. This pedal has additional distortion harmonics present in the $120Hz - 250Hz$ range, but exhibit a similar dynamic response pattern.

While BLIKSEM's behavior shares some sonic characteristics with common fuzz pedals, it is also capable of producing a wide array of novel timbral and dynamic effects. A variety of unique phenomena are a product of the the harsh resonances that specific configurations of the system produce. Frequency-specific distortion effects can be achieved in which only fundamentals in a specific frequency range produce distortion effects. This can result in an arbitrary weakening of the fundamental for a given tone, illustrated by the $5th$ through $7th$ segments (notes) shown in Figure 6, where an increasing chromatic line is played.

The adjustment of the height of the system can produce interesting dynamic patterns such as timbral attack accents in which the cantilever only strikes the sound board during the transient of the note. Paired with unique combinations of cantilevers and sound boards, the system can retain a relatively clean signal with accented transients.Chaotic, noisy, and percussive tones can be created through the incorporation of a non-rigid cantilever, as shown in Figure 6.

7. CONCLUSIONS AND FUTURE WORK

In this paper, we introduce BLIKSEM, a novel physical synthesis fuzz effect pedal utilizing an actuated cantilever and stationary soundboard system to induce non-linear distortion and hard-clipping effects in audio signal. The customization of the cantilever, its height, and the soundboard resulted in various fuzz-like distortion effects which were qualitatively compared to three existing popular fuzz pedals. Novel effects were also generated and described, such as wondering fundamental phenomena and chaotic noise response. Future work includes the design of a user interface for control over the blending of pick-up and direct signals, as well as exploring the inclusion of side-chaining, feedback, and modulation with additional inputs.

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