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Actuated Musical Instruments
A State of the Art

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Abstract
This article provides an overview of the state of the art in research driven towards the modification of the timbral properties of acoustic musical instruments through the use of electromechanical actuators (actuated instruments), allowing for synthetic sound generation to blend with the sound diffusion patterns of acoustic instruments. A selection of acoustic instruments and experimental research representing four Hornbostel-Sachs classes (idiophones, membranophones, chordophones and aerophones) is presented and their nouvelle characteristics and subsequent implementation is discussed, focusing on the techniques employed in the acoustical actuation.

Keywords
Acoustic-aggregate-synthesis
Actuated acoustic instruments
Actuators
Feedback control
Modal active control
Programmable
Prosthetic instruments
Sensors

Introduction

"(...) while most structural engineers seek to prevent structural vibrations, instrument builders seek to create sustained structural vibrations." (Berdahl 2009, 16)

Acoustic musical instruments have the ability to change their timbre namely through the excitation or attenuation of overtone frequencies of a fundamental, attained through different playing techniques. Paradigms such as extended techniques intend to take these a step further, allowing to reach a denser sound palette, but are nonetheless restricted to the acoustical properties of a given instrument as well as the physical constraints of a human performer. Recent technological advancements enabled finer modelling of the acoustical properties of musical instruments in real-time, leading to a new set of acoustical musical instruments whose synthesised sound components are actuated through electromechanical means in the instrument's resonant body. Actuated acoustic instruments,[1] also referred as prosthetic instruments (Walstijn & Rebelo 2005) or feedback controlled musical instruments (Berdahl, Niemeyer and Smith 2008), have the ability to 'escape' the constraints of the human body and the mechanics of acoustic instruments, much like a prosthetic exoskeleton has the potential to harvest an amount of force never attainable by a human being. Therefore this article provides a state of the art of actuated musical instruments by outlining a set of characteristics and techniques used to develop such instruments and subsequently referencing a group of instruments representing the Hornbostel-Sachs (H-S) top classification of acoustic instruments: idiophones, membranophones, chordophones and aerophones. The system developed for such instruments will be discussed in terms of its mechanical augmentation (sensors and actuators), the active technique applied to their modification and their sonic augmentations. A reasonably large set of instruments is provided so instead of providing in-depth analysis of each instrument, the relatively simple analysis of each of these techniques serves as a comparison between actuated instruments as well as to inform and help building premises relative to different instruments of different H-S families.

The concept of actuated acoustic instrument provides a huge potential in electroacoustic music practice, bestowing both the performer and the composer with an augmented timbral palette for an instrument while being able to maintain at the same time its original acoustic properties. Although this is also true for augmented instruments,[2] actuated musical instruments possess the particularity of having similar sound radiation patterns as the acoustical counterpart, since the 'artificial' sound is actually radiated from the instrument's body via coupled actuators, in opposition to the augmented musical instruments which conventionally radiate the 'artificial' sound component through a generalised and non-idiomatic set of speakers that is physically detached from the acoustic counterpart.

1.Feedback Control

Through the perspective of systems control theory a musical instrument can be described and analysed as a *closed loop* system, depicted in Figure 1:

- *r* represents the excitation force applied to the instrument by a performer;
- *G(s)* represents the system under control, in this case the musical instrument;
- *v* represents the system state, in this case sound radiation;
- and *u* represents the controller output which is added back to the system as negative feedback with a force *F*, a result of both the excitation applied by the performer and the controller output. (Berdahl, Niemeyer and Smith 2008)

1 *"We define actuated musical instruments as those which produce sound via vibrating element(s) that are co-manipulated by humans and electromechanical systems."* (Overholt, Berdahl and Hamilton 2011, 155)

2 Refer to Miranda & Wanderley (2006) for a comprehensive literary revision of augmented musical instruments.

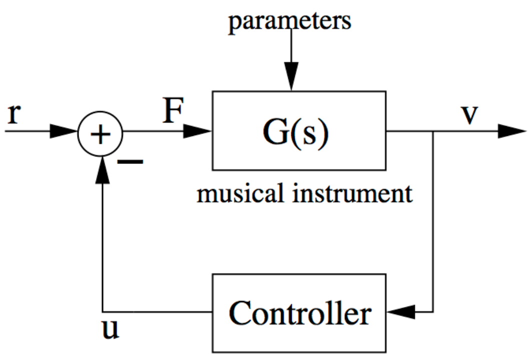

Figure 1. Simple block diagram for feedback control of an acoustic musical instrument. (Berdahl, Niemeyer and Smith 2008)

Regarding musical instruments one can think of the controller unit as the instrument's body resonance and vibration modes, providing haptic feedback to the performer as well as continuously interacting with sound radiation. E.g. a performer playing a trombone would create an excitation force through the mouthpiece, which sets an air column to interact with the instrument's body, resonating it and radiating sound through the bell, which is then perceived by the performer not only by the sound emanating through it but also as small vibrations that reach to the performer's hands and lips. Although the complex intricacies of the acoustics of musical instruments as well as systems control theory is out of the scope of this article, the reader can find valuable information in Chaigne & Kergomard (2016) and Warwick (1996), respectively.

Going beyond this closed-loop control mechanisms of acoustic instruments, it is possible to augment such instruments using feedback control techniques recurring to mechanical, electronic or digital components. A common application of feedback control has been used extensively by electric guitar players, using acoustic feedback between power amplifiers and the guitar's strings to produce self-oscillations or continuous tones. (Berdahl, Niemeyer and Smith 2008)

Another example is the *EMdrum,* an electromagnetically actuated concert bass drum that uses two coil drivers: one acting as an actuator responsible to induce vibrations on the membrane, and the other, in reverse polarity, acting as a sensor picking up the electromagnetic field of a metal rod attached to the membrane traveling both through the actuator and sensor coils (Fig. 2). This is a good technique to avoid parasitic feedbacks from sound travelling through air, like it would happen with common microphones, ensuring that the feedback comes solely from vibrations in the membrane. Which can be intentionally achieved when, for example, playing a bass clarinet near the membrane, as exemplified by Rector and Topel. (Rector & Topel 2014)

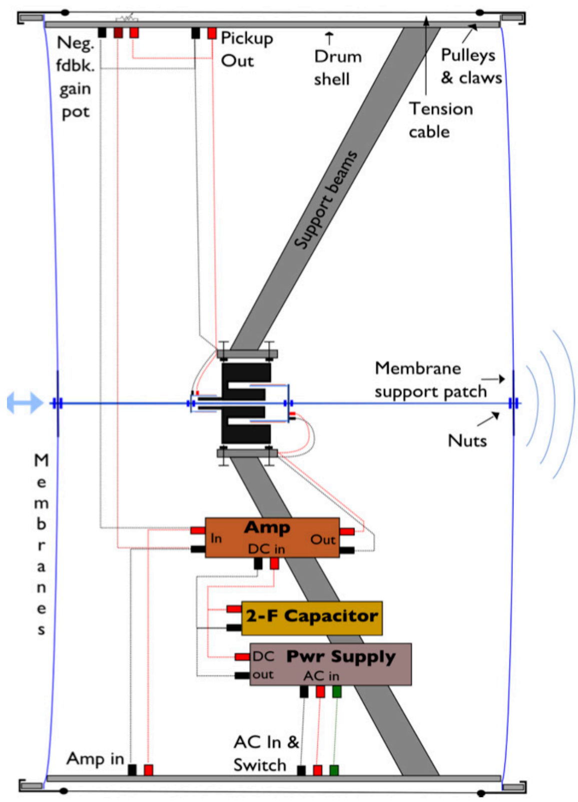

Figure 2. Moving-coil implementation, complete. (Rector & Topel 2014)

The acoustic applications of feedback controllers are obviously not constrained to musical instruments and there has been a significant surge of interest in the development of public address (PA) systems, hearing aids, and speech applications. (Troyer 2014)

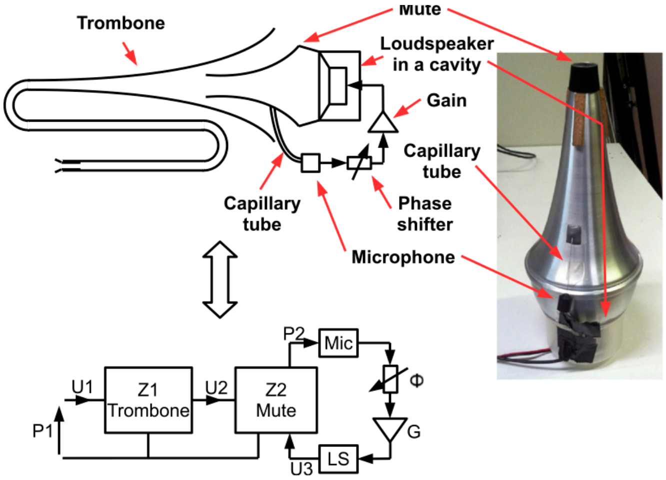

Figure 3. (Color online) (Top left) Schematic diagram of a straight mute with embedded microphone and speaker, and control system. (Right) Photograph of the active straight mute. (Bottom left) Equivalent electric circuit of the trombone coupled to the mute with control system. (Meurisse et. al 2015b)

Figure 4. Top: Simplified bass clarinet (a cylindrical tube with a bass clarinet mouthpiece and a reed) with embedded control setup with co-located microphone and speaker. Top right corner: control setup removed from the instrument. (Meurisse et. al 2015a)

2.Modal Active Control

Modal active control is the modification of a system's damping and resonant frequencies. (Meurisse et. al 2014) The majority of applications in musical instruments make use of audio feedback control systems, but not entirely. (One good example is the actuated clarinet mouthpiece presented by René Caussé (2014, 12'25'') in a lecture at the Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT, Montreal, Canada), where a water-actuated contraption inside the clarinet's mouthpiece acts as a mute, providing continuous control as opposed to traditional mutes, which exhibit a static behaviour.)

Most common modal active control applications on musical instruments also include the use of sensors, usually capturing the sound through mid-air (e.g. the active trombone mute (Meurisse et. al 2015b) or the simplified bass clarinet shown in Figure 4), coupled to the instrument's resonant body (e.g. Chinese gong (Jossic et. al 2017), monochord (Benacchio et. al 2016), decoupled guitar (Lee 2014) and xylophone bar (Boutin, Besnainou and Polack 2015), or through electromagnetic fields generated by parts of the instrument such as the magnetic resonator piano by McPherson and Kim (2010) which also applies optical sensors in order to determine which keys of the piano are being pressed.

A necessary component for modal active control is the actuator, which is responsible for physical actuation of the system's extended damping and resonance. These can induce vibrations in the instrument through electromagnetic fields as seen in McPherson and Kim's piano (2010), through air using loudspeakers with a membrane cone (e.g. Meurisse and colleagues' simplified bass clarinet (2015a) or the active trombone mute in Figure 3) or coupled to the instrument's resonant body, using surface-borne drivers (e.g. Jossic and colleagues' actuated gong (2017) and etc.).

The system controller unit then receives data from the sensor(s), transforming and sending it to the actuator(s), either using simple Phase Inversion techniques (e.g. Meurisse et. al, see Figure 3), or more elaborate techniques[3] such as Phase Locked Loops (McPherson and Kim 2010), Transfer Functions (Lee 2014, Meurisse et. al 2015a and 2015b), Luenberger observers (Benacchio et. al 2016 or Jossic et. al 2017), Proportional Derivatives and Proportional Integral Derivatives (Boutin, Besnainou and Polack 2015).

3.Acoustic-Aggregate-Synthesis

Acoustic-aggregate-synthesis is a technique used in actuated acoustic instruments which intends to fuse synthetic and acoustic sources in order to achieve a semi-acoustic re-synthesis of a predefined acoustic model, often aiming to maintain the original amplitude envelope and diffusion patterns while overriding the acoustic instrument's timbral identity. To achieve such phenomena acoustic-aggregate-synthesis makes use of similar setups found in modal active control (sensor-controller-actuator) although in this case the controller unit deals with more parameters than just signal phase in order to achieve its goals. (Clift 2012)

The resulting transformations are, to a certain extent, similar to a digital technique known as convolution, although in acoustic-aggregate-synthesis one part of the convoluted signal is actually acoustic, while the other, despite coming from a digital source, collides with the original signal in the acoustic medium resulting in a new identifiable timbre. This technique has an enormous compositional potential, portraying the sensation, or illusion, of morphing two different instruments.

An example of this technique can be found in the work of Paul Clift and colleagues (2015) on a bass clarinet and on a trombone, experimenting with the 'convolution' of these instruments with other acoustic instruments such as flutes or oboes, equipping both instruments with specific microphones and speakers designed specifically for their acoustic specifications (Fig. 5, 6 and 7). (Clift et. al 2015)

Figure 5. Trombone mouthpiece with an integrated piezo microphone. (Clift et. al 2015)

Figure 6. Loudspeaker which has been permanently integrated into a trombone tuning-slide. (Clift et. al 2015)

3 The mathematical foundations of such techniques is out of the scope of this article, where the reader should refer to the mentioned references for more information or to (Havelock, Sonoko and Vorländer 2008) for a general understanding of signal processing techniques in applied acoustics.

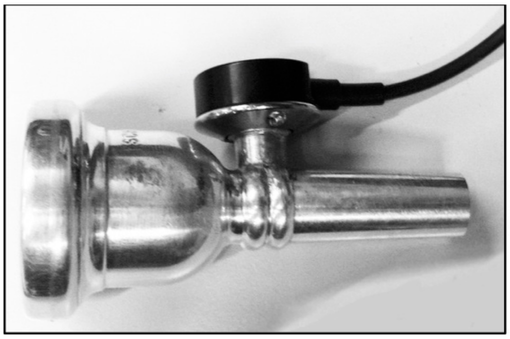

Figure 7. An ad-hoc device fashioned to suit the bell of a bass-clarinet.(Clift et. al 2015)

4.Prosthesis and programmable extensions

The concept of prosthetic instrument or instrument prosthesis, introduced by Rebelo and colleagues, is a practical metaphor to refer to some actuated instruments, since it implies a relationship between an artificial or foreigner component — the prosthesis — and a body — the instrument. Furthermore, it introduces the notions of potential, extension, mimicry and rejection. (Rebelo and Walstijn 2004)

Other metaphors can nonetheless be applied to actuated musical instruments, especially those with a digital controller unit. Thus taking advantage of the intrinsic programmable nature of digital systems, which can go beyond the notions of mimicry or extension of a natural or preconceived instrument morphology and resonant behaviour. Providing on one hand a wide range of active acoustic augmentations and on the other the use of an acoustic instrument's resonant body as a mere resonator for the diffusion of arbitrary sounds, going beyond the mimicry metaphor into, hypothetically, a question and answer or time-lapse metaphor, where sounds appear from the instrument's body without being attached to the performer-excited amplitude envelopes (e.g. *Overtone Fiddle* by Daniel Overholt (2011) or Neal Farwell's *eMute* (2006), see Fig. 8 and 9).

Figure 8. eMute in use. (Farwell 2006)

Figure 9. The Overtone Fiddle - first prototype. (Overholt 2011)

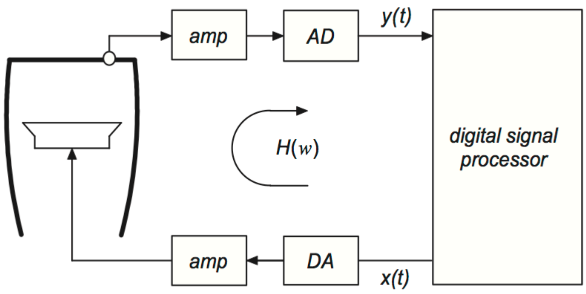

Figure 10. Prosthetic Conga sound reinforcement and membrane vibration monitoring. (Walstijn & Rebelo 2005)

The notions of prosthesis and programmable extensions is in the same chapter because the distinction between the two is not quite binary, although it can be assumed that prosthetic instruments exert some sort of feedback control system (see Fig. 10), containing at least one sensor, where a programmable actuated instrument may or may not apply these techniques and may or may not have any sensor (e.g. eMute). Additionally, an actuated instrument with a programmable extension might be capable of applying a feedback control algorithm or not according to a given musical composition or section.

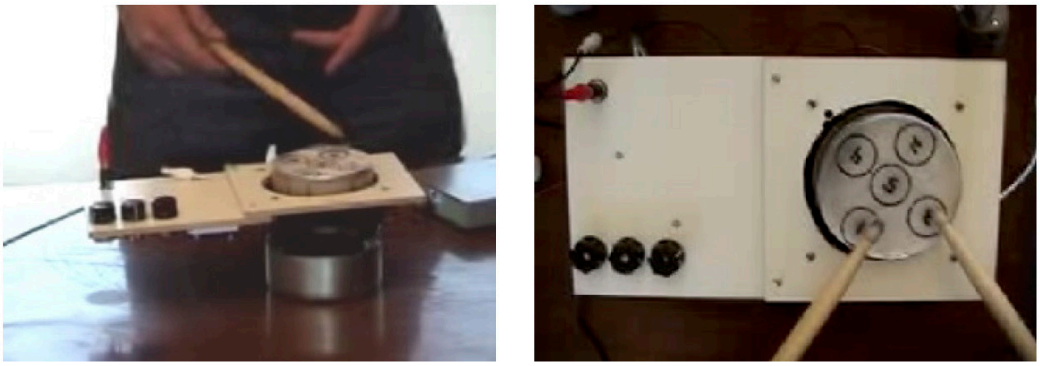

Figure 11. Haptic drum v1. (Berdahl 2009)

Prosthetic synthesis can thus be seen as a form of dynamic modal actuation, where the instruments' damping and resonance behaviours can be dynamically modified during a course of a composition or from different compositions or musical sections. (e.g. prosthetic conga (Walstijn and Rebelo 2005), prosthetic mbira (Vriezenga and Rebelo 2011), Lähdeoja (2016) acoustic guitars, Berdahl's feedback resonance guitar (Overholt, Berdahl and Hamilton 2011) or bistable resonator cymbal (Piepenbrink and Wright 2015)) Also, a good example of a prosthetic actuated instrument is the haptic drum developed by Berdahl (2009), which uses a woofer as a drum membrane with a set of sensors attached to it (see Fig. 11), triggering impulses to the voice coil whenever the sensors are activated, resulting in a quasi-automatic drum roll able to reach speeds that would be otherwise impossible to achieve.

On the other hand of the spectrum is the *EMvibe* (Britt, Snyder and McPherson, 2012) and Bloland's electromagnetically-prepared piano (2007), which do not make use of any acoustic sensor technology, recurring only on actuators to excite a vibraphone's bars and the strings of a concert piano respectively (see Fig. 12 and 13) using arbitrary computer generated sounds that follow a musical score.

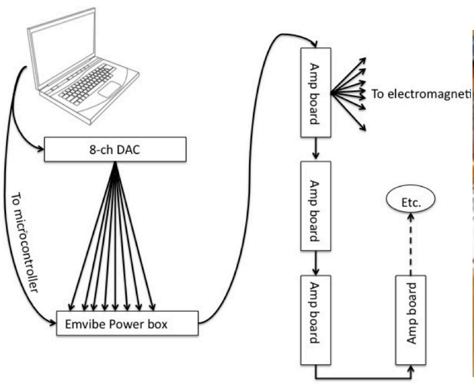

Figure 12. Electromagnets in a grand piano. (Bloland 2007)

Figure 13. EMvibe signal flow (McPherson & Kim 2010)

Conclusions

This article provided a comprehensive overview of the state of the art of actuated musical instruments. Several actuated instruments belonging to the four H-S classes of acoustic instruments — idiophones, membranophones, chordophones and aerophones— were presented and their characteristics were discussed whenever possible in the viewpoint of hardware/software and control systems. From this overview it is possible to condense and reach the following abstractions:

- Activated wind instruments pose some difficulties in the choice and implementation of transducers, although some new commercially available products start to emerge;[4]
- The idiosyncrasy observed in the instruments here discussed will most certainly prove to be an obstacle when attempting to develop a generalised system that may apply to several instruments. Although grouping the instruments by classes and hence their properties might cause this task to become slightly more manageable;
- The development of highly efficient feedback control systems are highly dependent on timing (very short delay times) and hence computational speed. Luckily there has been quite some progress in the past years with smaller and more powerful platforms for embedded systems capable of low-latency audio, such as Bela;[5]
- Despite several technical issues, actuated musical instruments seem to excel where digital musical instruments have struggled, namely the notions of embodiment and engagement with the performer, since their 'synthetic' component is applied in the acoustic medium it is automatically captured by the performer's haptic apparatus. With some exceptions, namely idiophones that are not played with bare hands.

In general active control of musical instruments, damping or attenuation proved to be a lot more difficult then excitation, which might hypothetically lead towards finer developments of the programmable paradigm and, although both paradigms can coexist, from the viewpoint of composition the latter, at least for the time being, seems more promising.

4 PiezoBarrel® Wind Instrument Pickups (http://www.piezobarrel.com)

5 https://bela.io

Benacchio, Simon, Baptiste Chomette, Adrien Mamou-Mani, and François Ollivier. 2016. "Modal Proportional and Derivative State Active Control Applied to a Simplified String Instrument." JVC/Journal of Vibration and Control 22 (18): 3877–88.

Berdahl, Edgar. 2009. "Applications of Feedback Control to Musical Instrument Design." Stanford University.

Berdahl, Edgar, Günter Niemeyer, and Julius Smith III. 2008. "Feedback Control of Acoustic Musical Instruments." California, USA.

Bloland, Per. 2007. "The Electromagnetically-Prepared Piano and Its Compositional Implications." International Computer Music Conference, no. June: 125–28.

Boutin, Henri, and Charles Besnainou. 2008. "Physical Parameters of the Violin Bridge Changed by Active Control." The Journal of the Acoustical Society of America 123 (5): 3656–3656.

Boutin, Henri, Charles Besnainou, and Jean Dominique Polack. 2015. "Modifying the Resonances of a Xylophone Bar Using Active Control." Acta Acustica United with Acustica 101 (2): 408–20.

Britt, N Cameron, Jeff Snyder, and Andrew McPherson. 2012. "The EMvibe : An Electromagnetically Actuated Vibraphone." Proceedings of the International Conference on New Interfaces for Musical Expression, 31–34.

Caussé, René. 2014. "Acoustics and Contemporary Music (Revisited)." Montreal, Quebec, Canada: CIRMMT - Centre for Interdisciplinary Research in Music Media and Technology. https://youtu.be/iQuCpLuhBWk. (accessed February 5, 2018)

Chaigne, Antoine, and Jean Kergomard. 2016. Acoustics of Musical Instruments. New York: Springer Verlag.

Clift, Paul. 2012. "Acoustic-Aggregate-Synthesis." In Proceeding of the International Computer Music Conference, 120–23. Ljubljana.

Clift, Paul, Adrien Mamou-Mani, and René Caussé. 2015. "Extending Brass & Woodwind Instruments with Acoustic-Aggregate-Synthesis," 338–41.

Farwell, Neal. 2006. "Adapting the Trombone: A Suite of Electro-Acoustic Interventions for the Piece Rouse." Proceedings of NIME, 358–63.

Havelock, David, Kuwano Sonoko, and Michael Vorländer. 2008. Handbook of Signal Processing in Acoustics. Springer.

Jossic, Marguerite, Adrien Mamou-Mani, Baptiste Chomette, David Roze, François Ollivier, and Christophe Josserand. 2017. "Modal Active Control of Chinese Gongs." The Journal of the Acoustical Society of America 141 (6): 4567–78.

Lähdeoja, Otso. 2016. "Active Acoustic Instruments for Electronic Chamber Music." Proceedings of the International Conference on New Interfaces for Musical Expression 16: 132–36.

Lee, Byungjoo. 2014. "The Decoupled Acoustic String Instrument: A New Concept for an Acoustic String Instrument." Leonardo Music Journal 24: 61–63.

McPherson, Andrew P., and Youngmoo Kim. 2010. "Augmenting the Acoustic Piano with Electromagnetic String Actuation and Continuous Key Position Sensing." In Proceedings of the 2010 Conference on New Interfaces for Musical Expression (NIME 2010), 217–22. Sydney, Australia.

Meurisse, Thibaut, Adrien Mamou-Mani, Simon Benacchio, Baptiste Chomette, Victor Finel, David B. Sharp, and René Caussé. 2015a. "Experimental Demonstration of the Modification of the Resonances of a Simplified Self-Sustained Wind Instrument through Modal Active Control." Acta Acustica United with Acustica 101 (3): 581–93.

Meurisse, Thibaut, Adrien Mamou-Mani, René Caussé, and David Sharp. 2014. "Simulations of Modal Active Control Applied to the Self-Sustained Oscillations of the Clarinet." Acta Acustica United with Acustica 100 (6): 1149–61.

Meurisse, Thibaut, Adrien Mamou-Mani, René Caussé, Benny Sluchin, and David B. Sharp. 2015b. "An Active Mute for the Trombone." The Journal of the Acoustical Society of America 138 (6): 3539–48.

Miranda, Eduardo, and Marcelo Wanderley. 2006. *New Digital Musical Instruments: Control and Interaction beyond the Keyboard.* Middleton, Wisconsin: A-R Editions, Inc.

Overholt, Dan. 2011. "The Overtone Fiddle: An Actuated Acoustic Instrument." Proceedings of the International Conference on New Interfaces for Musical Expression, no. May: 30–33.

Overholt, Dan, Edgar Berdahl, and Robert Hamilton. 2011. “Advancements in Actuated Musical Instruments.” Organised Sound 16 (2): 154–65.

Piepenbrink, Andrew, and Matthew Wright. 2015. “The Bistable Resonator Cymbal : An Actuated Acoustic Instrument Displaying Physical Audio Effects.” Proceedings of the International Conference on New Interfaces for Musical Expression, 227–30.

Preumont, Andre. 2011. “Vibration Control of Active Structures, An Introduction 3rd Edition.” Springer Netherlands, 436.

Rector, David, and Spencer Topel. 2014. “EMdrum : An Electromagnetically Actuated Drum.” Proceedings of the International Conference on New Interfaces for Musical Expression, 395–98.

Troyer, Akito Van. 2014. “Composing Embodied Sonic Play Experiences: Towards Acoustic Feedback Ecology.” Proceedings of the International Conference on New Interfaces for Musical Expression, 118–21.

Vriezenga, Ciska, and Pedro Rebelo. 2011. “The Prosthetic Mbira: Prosthesis As Design Stategy.” In Proceedings of the International Computer Music Conference 2011, 697–700. Michigan Publishing, University of Michigan Library.

Walstijn, Maarten van, and Pedro Rebelo. 2005. “The Prosthetic Conga: Towards an Actively Controlled Hybrid Musical Instrument.” In International Computer Music Conference 2005, 1–4.

Warwick, Kevin. 1996. *An Introduction To Control Systems*. 2nded. Singapore: World Scientific.