Symbaline: An Electromagnetically Actuated Wine Glass Instrument

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Abstract

The Symbaline is a wine glass instrument, producing sounds by exciting a set of wine glasses using electromagnets. The electromagnets are driven by audio signals generated using any musical instrument, allowing musicians to play the Symbaline using their own instruments without additional training. Symbaline sound customization is achieved by applying various audio effects on the input signal, as well as assembling different sets of ready-made wine glasses. This paper describes the Symbaline's operation and sound characterization, and explores different usage modes. These include playing by a classical guitar and playing by custom designed virtual instruments, controlled with a MIDI keyboard.

1 Introduction

The musical potential of wine glasses has long interested musicians, composers and instrument designers. The most common wine glass instrument, the glass harp, first appeared during the 18th century, with origins that trace back to antiquity. Mozart, Beethoven and others had composed works for the glass harmonica – a successor to the glass harp, designed by Benjamin Franklin in 1761. Glass music is still alive today, with active musicians, instrument makers and numerous glass music videos online.

Figure 1: A proposed design of the Symbaline, played by an acoustic guitar, alongside all required system components – Audio interface, Amplification module and PC. (Guitar model: Milos Golijanin, Laptop model: Gopal Kundu).

The glass harp is traditionally played by rubbing the rim of the glasses using a moistened finger. This playing technique may pose some limitations on both playing and instrument design. In the first place, due to the physical size of the glasses, glass harps ranging over several octaves are physically large and require great dexterity to play. Furthermore, as a player can typically play a single glass at a time with each hand, the playing of chords and harmonies is also somewhat limited. To overcome these limitations, a single glass harp is sometimes played by more than one musician simultaneously. In addition, the friction excitation technique offers little control over sound characteristics such as timbre and attack time. Franklin's Harmonica offers improvements by way of compacting the instrument, as does the Verrophone – consisting of glass tubes rather than glasses [22]. However, both still use the traditional friction sound production method.

We introduce here a new approach for wine glass sound production, which uses wine glasses as radiators of audio signals generated by existing instruments. The Symbaline consists of a set of tuned wine glasses. Small magnets are fitted on the surface of each glass and actuated by electromagnets. The electromagnets are driven by an amplified signal generated by any existing amplified or electronic musical instrument, such as a guitar, a violin or a MIDI keyboard. The Symbaline thus acts as an additional sound radiator for the existing instrument. The Symbaline offers players several possibilities of customization: by using different sets of wine glasses, by using different instruments as signal sources and by electronically processing the input signal. The Symbaline gets its name from the Bulen-bulen (Lyrebird), an Australian bird known for its exceptional ability to mimic natural and artificial sounds [19], and from its operation method of producing sympathetic-like sounds generated by other instruments. Figure 1 shows a proposed design of the Symbaline, played by an acoustic guitar, alongside all required system components.

We propose two main configurations for the Symbaline: the first drives the Symbaline using an amplified string instrument. This configuration was inspired by Indian instruments such as the sitar and sarangi. These instruments are characterized by sympathetic strings: an additional set of strings mounted on the instrument, but not directly excited by the player. Rather, the sympathetic strings respond to vibrations transmitted from the main playing strings, and create a unique effect. (See sound sample 1). The Symbaline's string driven configuration is an attempt to recreate the sympathetic effect using wine glasses as a substitute to the sympathetic strings. This configuration, along with complementary sound effects, is explored in sections 4 and 5. The second configuration uses a MIDI controller and a virtual instrument to play the Symbaline. This configuration uses either existing virtual instruments, or virtual instruments custom designed for the Symbaline. The Symbaline-MIDI configuration is explored in section 6. Section 7 describes preliminary evaluation sessions performed by musicians.

2 Related Work

2.1 Sympathetic String Instruments

Sympathetic resonance in string instruments have received relatively little treatment by way of scientific study. Weisser and Demoucron [26] provide an overview of Indian sympathetic string instruments and an acoustic analysis of the sympathetic strings' contribution to the overall sound in a sarod, a sitar and a sarangi. The sarangi is further studied by Demoucron and Weisser[4], along a with a study of the sympathetic vibrations of the playing strings of a western violin. Demoucron, Weisser and Leman [5] provide an additional analysis of both sarangi and sitar in the broad context of classical Indian music.

The Symbaline in its string driven configuration aspires to reproduce a similar sonic effect to sympathetic instruments, by using wine glasses instead of the sympathetic strings. The string vibrations of the amplified string instrument are transmitted to the wine glasses via the electromagnets, and induce sympathetic-like vibrations in the glasses. The resulting overall sound is somewhat similar in nature: a reverberating sustained sound, following the lead melody.

2.2 Wine Glass Instruments

Musical wine glasses are surveyed in several works. Gallo and Finger [7] discuss the rich and often amusing history of glass instruments. Meyer and Allen [16] provide an acoustic analysis of Franklin's glass harmonica. Several works have thoroughly examined wine glass acoustics [11, 21], providing insights necessary for the Symbaline development. Finally, Koopmann and Belegundu [12] have tuned a wine glass by attaching small weights to its surface. This method is useful to our work both as a complementary tuning method, and for understanding the effect of the surface magnets.

2.3 Actuated and hybrid instruments

Various musical instruments and accessories use electromagnetic actuation for sound generation. An early example of electronic actuation of an acoustic instrument is found in the Ondes Martenot, a 1928 electronic instrument equipped with several different speakers (diffusers). One of the speakers, Métallique, uses a gong as the diaphragm [13]. A contemporary noteworthy example is the EBow [9]; a commercial electromagnetic hand-held device used to infinitely sustain sounds on an electric guitar using a feedback loop.

A thorough overview of actuated musical instruments and their effect on the musical ecosystem is given by Overholt et al. [17]. Several examples are given including the Overtone Fiddle and the Feedback Resonance Guitar. Both instruments incorporate different sensors and feedback actuators, and are actuated by various sources, including other amplified instruments. McPherson [14] developed a magnetic resonator piano, where electromagnets excite piano strings. This piano reinforces the natural string vibrations using feedback loops. Other works dealt with a conga drum [25] and a xylophone bar [2]. Britt, Snyder and McPherson [3] created the EMvibe: an electromagnetically actuated vibraphone, by attaching neodymium magnets to the vibraphone bars. The EMvibe is driven by computer generated signals rather than feedback loops. McPherson [15] provides invaluable information on the various technical aspects of electromagnetically actuated instruments.

More recent examples include the Self-resonating Feedback Cello [6]. Among the different configurations explored is an installation where two actuated cellos are autonomously excited by environmental sounds and by each other. The Feedback Lap Steel is an actuated instrument where the strings are excited by physical vibrations generated by a tactile transducer [8]. Driving the Feedback Lap Steel by external instruments effectively uses it as a sympathetic strings instrument.

The Symbaline differs from the above instruments in two main aspects: First, the Symbaline is primarily designed to be excited by an amplified musical instrument rather than by feedback loops or by computer generated signals. Second, all sound radiating components are simultaneously excited by a single processed input signal with the intention of creating a reverberation effect, as in sympathetic string instruments.

Zoran and Paradiso [27] describe the Chameleon Guitar development - an acoustic guitar with a replaceable resonator. This guitar shares a common trait with our work: it combines elements of a customizable acoustic instrument with sound enhancing digital signal processing. In the Chameleon Guitar's case, customization is achieved by replacing the guitar's soundboard, while sound radiation is performed by a standard loudspeaker. In the Symbaline, the wine glass set is used for both customization and sound radiation. Easy customization of the glass set is possible thanks to the wide availability of ready-made wine glasses, requiring no custom fabrication by the user.

Ishiguro and Poupyrev [10] describe the development of 3D printed electrostatic speakers. The electrostatic technology enables the creation of speakers with complex radiator geometries, as opposed to the traditional conic radiators of electromagnetic speakers. While the electrostatic speakers may resemble the Symbaline's radiators by having complex shapes, the projects differ in their acoustic responses. The electrostatic speakers have mostly flat frequency responses, optimal for reproducing audio signals, while the Symbaline's radiators are characterized by having strong resonance frequencies, tuned to frequencies of musical notes.

2.4 Mechanical sympathetic wine glass instruments

A previous attempt of recreating a sympathetic resonance effect with strings and wine glasses was made by the authors using mechanical coupling mechanisms [1]. String vibrations were transmitted to a wine glass using either a customized coupling device, or by direct string-glass contact. The resulting string-wine glass systems generated wine glass sounds when the coupled strings were plucked. While fulfilling its intended goal by creating a novel sonic effect, the mechanical mechanism offered limited control over the wine glass sound characteristics. Thus, development of an electromagnetic excitation mechanism, incorporating signal processing, was chosen as an alternative.

3 Design

3.1 System overview

The Symbaline system is composed of an existing musical instrument, referred to as the source instrument; a digital module, comprising a computer with a multiple-output audio interface; an amplification module; and a set of tuned wine glasses fitted with electromagnets. Here we describe a prototype of the system, developed for experimental purposes, in which the wine glass set consists of 12 glasses. Figure 2 shows a block diagram of the current system prototype. The sound of the system is the combination of the source instrument's radiated sound R^{src} and the Symbaline's radiated sound R^{gls}. The source instrument's signal V^{src} can be further amplified and radiated by a standard speaker (R^{aux}).

The wine glass sounds of the Symbaline are produced by electromagnetic actuation. Each wine glass is fitted with neodymium magnets, held in place solely by magnetic attraction. Electromagnets are placed in proximity to the glass's magnets, one per glass, and are driven by amplified audio signals ($V_1^{amp}, V_2^{amp} \dots$) generated by the source instrument. The magnetic field generated by the electromagnets causes vibrations in the magnets, which in turn generate vibrations in the wine glasses and cause wine glass sound radiation (R^{gls}).

3.1.1 Wine Glass acoustics

Wine glass frequency response is excitation method dependent. Rubbing the rim of a wine glass typically only excites the (2,0) vibrational mode, consisting of four nodal points on the rim. The sound produced by this method contains the

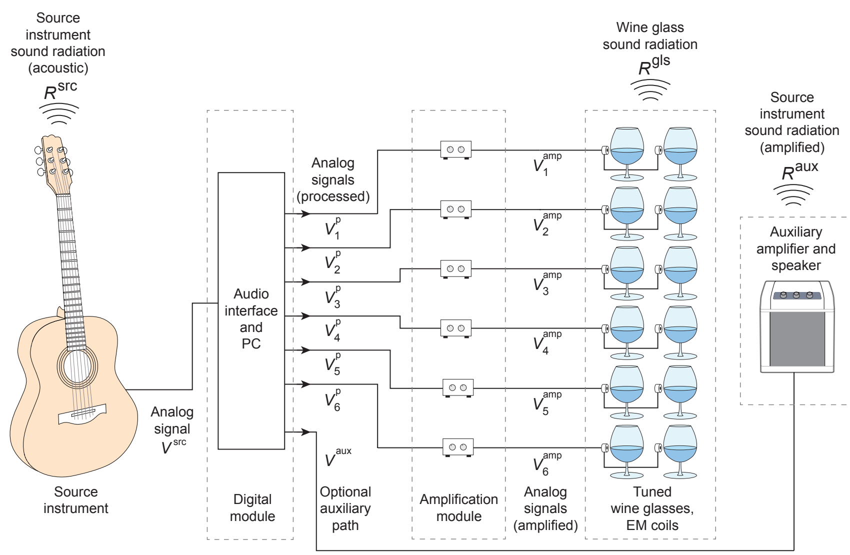


Figure 2: Block diagram of the Symbaline system, with an amplified classical guitar as a source instrument. The guitar sends an audio signal, V^{src}, to the digital module (shown separately in Figure 5), where it is processed and split into $V_1^p \dots V_6^p$. The signals are then amplified by the amplification module ($V_1^{amp} \dots V_6^{amp}$) and radiated as acoustic sounds by the wine glasses using electromagnetic coils. An optional auxiliary signal, V^{aux}, is routed to a standard amplifier and speaker.

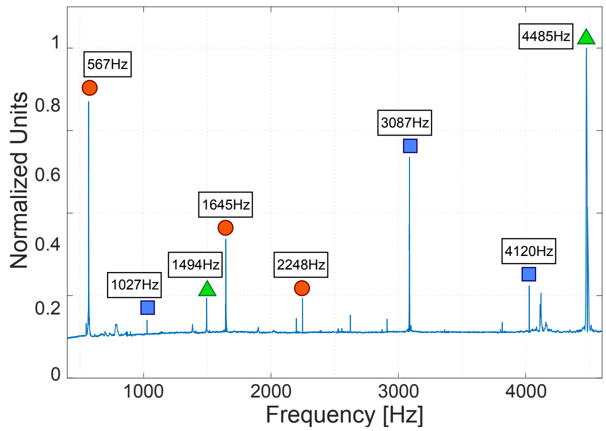


Figure 3: A frequency sweep of a party filled wine glass with surface magnets. The colored markers indicate harmonically related partials. Note the relatively high ground level, indicating the audible sounds produced by the glass even at arbitrary frequencies.

fundamental frequency along with several harmonic overtones. Striking a wine glass with a mallet excites the higher vibrational modes as well. The resulting tone contains a combination of several harmonic series; each vibrational mode contributes a different fundamental tone and several harmonic overtones (Rossing, 1994). We also verified these findings in several preliminary experiments, with both empty and liquid filled glasses.

Using electromagnetic actuation, however, it is possible to excite intense responses at different frequencies, some of them harmonically related. In addition, some small non-linearity occurs, with low energy harmonics of the excitation frequency appearing in the glass sound. These harmonics have a negligible effect on the glass tone. Figure 3 shows an electromagnetic actuation frequency sweep of a partially filled wine glass, normalized by the maximum value. The resulting frequency response contains several harmonically related resonances. The resonance frequency 567Hz appears along with its 3rd and 4th integer multiples (1645Hz, -58.8cents; 2248Hz, -16.25cents), the resonance frequency 1027Hz appears along with its 3rd and 4th integer multiples (3087Hz, +3.37cents; 4120Hz, +5.04cents) and the resonance frequency 1494Hz appears along with its 3rd integer multiple (4485Hz, -1.93cents). For each resonance frequency, the typical bandwidth and Q factor are 2-8Hz and 300-800 respectively.

Throughout the spectrum, the base intensity level is around 0.1 (normalized by the maximum value), while the actual noise floor in the absence of input signal is close to 0. That is, even when excited by non-resonance frequencies, the glass produces audible sounds. Consequently, glass sounds permit perceiving the diverse timbres of the original excitation tones, as described in sections 4, 5 and 6. Note that as wine glasses are highly non-standard, large differences may be expected from glass to glass. While the frequency sweeps of other glasses also contain several resonance frequencies, each with several integer multiples, the precise location of the resonances and the number of integer multiples vary from glass to glass.

The placement of magnets on the glass' surface increases the weight of the vibrating mass, thus lowering the resonance frequencies. The neodymium magnets used by the Symbaline, each with a 2mm thickness and a 6mm diameter, lower the resonance frequencies by 2-6Hz. In addition, the magnets may affect the glass warble – a beating amplitude modulation effect. Warble is most usually caused by subtle geometric or material imperfections in the glass, breaking its circular symmetry and causing a frequency difference between the components of a mode doublet [23]. A similar increase in warble can be achieved by tilting the water-tuned glasses, thus increasing the asymmetry [18].

With an ideal glass, the magnets force an asymmetry, causing a mode doublet. However, many actual glasses already contain some asymmetry. Attaching magnets to an already asymmetric glass may have several effects, depending on the magnets' location around the surface, the angle of the excitation and the glass asymmetry. Figure 4 compares the frequency response of a specific wine glass around the resonance frequency in two such cases. An arbitrary excitation point denoted as $0°$ was chosen on the glass surface. The glass was struck at this point with a soft mallet. Without surface magnets, the glass exhibits a mode doublet around 440Hz, with a 7 cents discrepancy between the frequencies. When magnets are placed at the $0°$ point, they exaggerate the existing asymmetry, thus increasing the frequency difference of the mode doublet to 14 cents. The magnets and excitation point were then shifted to different locations around the surface, each producing a slightly different frequency response. When both magnets and strike angle are shifted by $45°$, the frequency difference is decreased to 4.5 cents, most likely due to the magnets counter-balancing the glass asymmetry. The magnet positions used in the current system prototype were chosen arbitrarily.

3.1.2 Signal source – An existing musical instrument

Playing the Symbaline requires only an analog audio signal; therefore, it can be played by practically any existing musical instrument serving as the source instrument. Electric instruments, such as the electric guitar and electric violin, can be used straightforwardly in the same manner they are normally used with standard amplifiers. Acoustic instruments, such as classical guitars, wind instruments, pianos or even percussion instruments, can be used once amplified. Amplification can be obtained by any available means, such as pickups or microphones. The analog output signal from the source instrument, V^{src}, is routed to the audio interface.

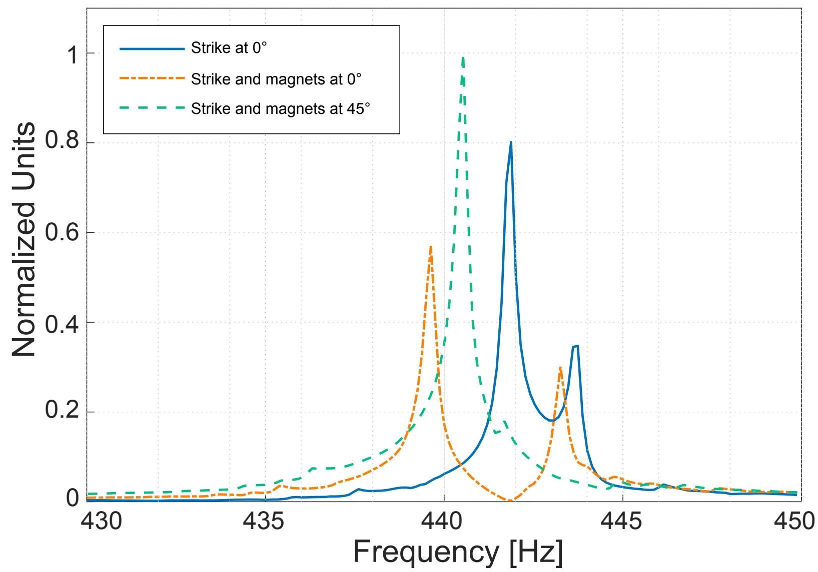


Figure 4: The lowest fundamental frequency of a glass excited by striking, demonstrating a 7 cents frequency split between the two orthogonal modes. The addition of surface magnets at the original strike angle (0°) increases the split to 14 cents, while shifting the magnets and strike angle by 45° decreases it to a total of 4.5 cents.

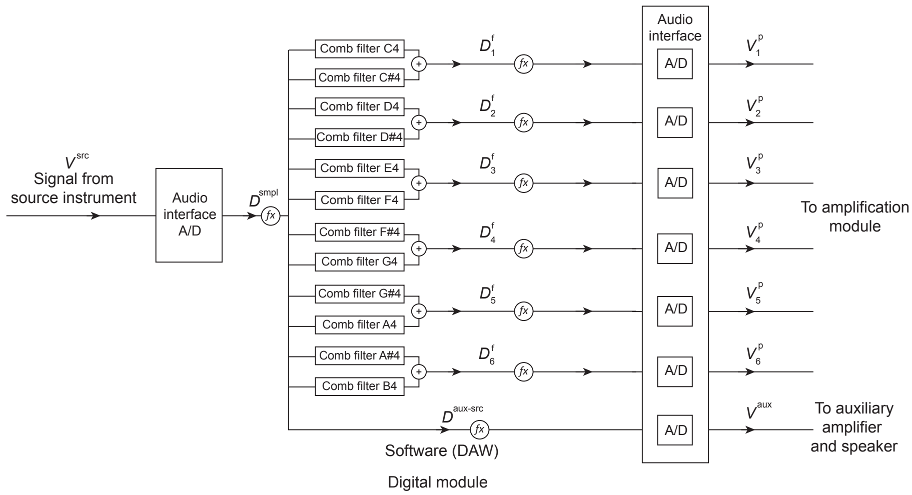


Figure 5: Block diagram of the digital module (expanded from Figure 2). The signal V^{src} coming from the source instrument is sampled (D^{smpl}), split and filtered by comb filters. The filtered signals ($D_1^f \dots D_6^f$) are reconstructed ($V_1^p \dots V_6^p$) and sent to the amplification module. An optional auxiliary signal, $D^{aux-src}$, is processed, reconstructed (V^{aux}) and routed to a standard amplifier and speaker. Additional digital effects may be inserted at any stage marked by 'fx' (D^{smpl}, D_i^f, $D^{aux-src}$).

3.1.3 Digital module - Audio interface and PC

The digital module is used for splitting and processing the source instrument's analog signal. It is comprised of an audio interface with multiple analog outputs, and a PC running custom configured audio software (DAW – Digital Audio Workstation). Figure 5 shows the schematic structure of the digital module. The source instrument's analog signal, V^{src}, is sampled by the audio interface and converted to a digital signal (D^{smpl}). Once sampled, the signal is digitally split and processed for noise suppression and audio effects by the DAW, as described in Sections 3.2 and 5. Once processed, the split digital signals $D_1^f, D_2^f \dots$ are converted back to analog signals ($V_1^p, V_2^p \dots$) and routed to the amplification module by the audio interface.

As the current prototype consists of 12 electromagnets, an audio interface of at least 12 output channels is seemingly required. While audio interfaces of 12 channels exist, they are uncommon and target the high-end audio market. As a practical compromise, an audio interface of eight output channels is used. The electromagnets are organized in pairs and driven using six channels, as described in Sections 3.1.5 and 3.2.1. The additional channels are used for source instrument radiation and monitoring.

3.1.4 Amplification module

The amplification module amplifies the analog signals coming from the audio interface ($V_1^p, V_2^p \dots$). The amplified analog signals ($V_1^{amp}, V_2^{amp} \dots$) are then routed to the electromagnets. A single amplifier is required per each analog output channel of the audio interface. Experimentations with various amplifiers, including commercial guitar amplifiers, have shown only slight differences between the Symbaline sounds produced by different amplifiers. Previous versions of the amplification module consisted of six TDA2030 9W amplifiers. The current version consists of three commercial stereo amplifiers based on TDA1519 6W ICs housed in a metal enclosure. These amplifiers, having sufficient power output, were selected due to their relative compactness and robustness, to improve the Symbaline's portability.

3.1.5 The Symbaline prototype

The Symbaline prototype consists of a set of 12 wine glasses, tuned by partially filling with water. The glasses are held by the stem and attached to a frame by custom fitted holders. Two disc-shaped neodymium magnets, 2mm thick and 6mm in diameter, are fitted on the surface of each glass. The magnets are placed against each other, at waist height, on both sides of the glass's surface. The magnets hold each other firmly in place, obviating the need for adhesives. Small foam pads are placed between the magnets and the glass to prevent rattle noises in very high input amplitudes. Other soft materials such as fabrics and paper towels may also be used for padding. A single electromagnet is positioned about 2mm away from each glass, facing the magnets. Each electromagnet consists of 250 winds of 28 AWG wire around a ferrite core. The entire electromagnet is placed inside a tubular housing, filled with molten wax, for attenuating any acoustic noise generated by rattling in the electromagnet itself. Figure 6 shows a wine glass, fitted with magnets, placed next to an electromagnet.

Each electromagnet's DC resistance is 4.7Ω. The 12 electromagnets are arranged in six serially connected pairs, resulting in a total DC resistance of 9.4Ω each. This resistance is within the typical range for loudspeaker input resistance. The electromagnet pairs require six analog channels. Each pair is connected to a different amplifier's output channel.

The Symbaline frame is built of T-slot aluminum extrusions. This frame allows extensive customization and easy replacement of all system components. Moreover, the frame allows for changing the number of glasses and using other idiophones, such as bells and bowls. This implementation of the Symbaline prototype is shown in Figure 7.

3.2 Noise suppression and sound enhancement

3.2.1 Untuned responses

Optimal glass sounds are produced when the fundamental frequency of the excitation signal matches the glass' lowest fundamental frequency. In addition,

Figure 6: A wine glass fitted with 2 neodymium magnets, one on each side of the glass surface, padded by black foam pads. An electromagnet is placed 2mm away from the outer magnet.

higher harmonics of the input signal may overlap existing glass resonance frequencies, shown in figure 3. In such a case, the glass radiates a bright ringing sound (tuned response). However, when the glass is excited by an input signal without any matching glass resonance frequency, the glass response is typically a low and dim sound (untuned response). Consider a configuration of the Symbaline where the 12 glasses, tuned to 12 different notes, are simultaneously excited by an identical signal at a given pitch. This excitation would result in a sound composed of two main components. The first component is the single bright tuned response, containing mostly harmonic partials, produced by the glass corresponding to the excitation pitch. The second component is the sound emitted by the other 11 glasses, tuned to different pitches. This component is characterized by being dim and fast decaying. (See sound sample 2). Figure 8 shows the spectra of the combined untuned responses of 11 glasses. Early experimentation with this configuration demonstrated the need for reducing the untuned responses intensity, which are often perceived as unpleasant.

Rather than reducing the untuned responses once they had been radiated by the glasses, a method was devised to prevent them from occurring in the first place. A set of digital comb filters were designed to process the sampled input signal, D^{smpl}, within the digital module, as shown in Figure 5. Each comb filter passes the harmonic series of a single musical note, while attenuating most harmonics of all other notes. A total of 12 filters are used, one for each glass

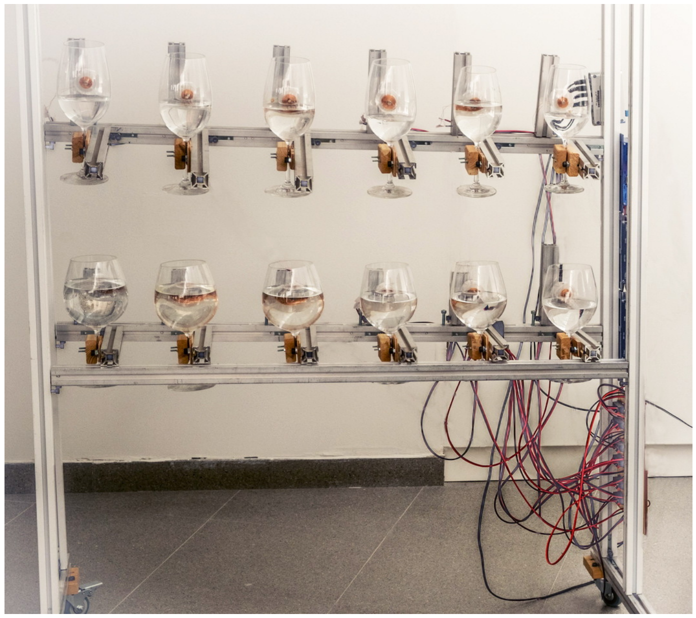


Figure 7: The Symbaline prototype, implemented using T-slot aluminum extrusions, with 12 wine glasses tuned by water to all notes from F_4 (bottom row, left) to E_5 (top row, right). This implementation allows for maximal customization.

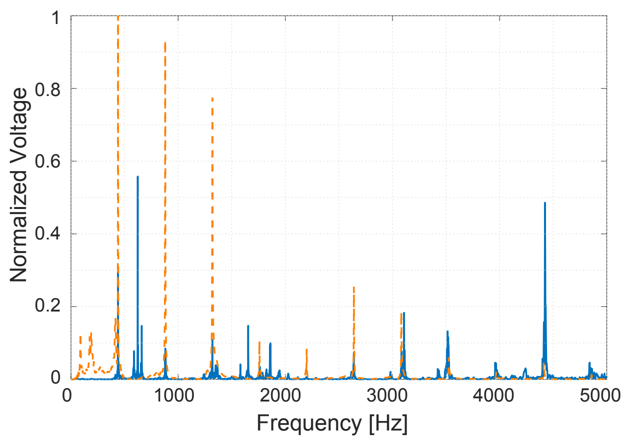


Figure 8: [Orange, dash]: A classical guitar A_4 excitation tone (V^{src}). [Blue]: The Symbaline's untuned response of 11 glasses (R^{gls}), with the A_4 glass excluded. This response is typically undesired. The purpose of the comb filters (Figure 5) is to reduce this response.

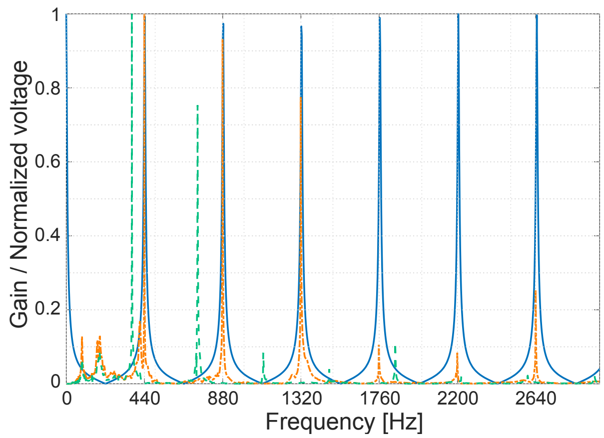


Figure 9: [Blue]: Comb filter A_4, passing 440Hz and its harmonic series. [Orange, dash-dot]: Classical guitar A_4 tone (V^{src}), intended not to be attenuated by the filter. [Green, dash]: Classical guitar $F\#_4$ (367Hz) tone (V^{src}), intended to be attenuated by the filter. Placing this comb filter before the A_4 glass, prevents this glass from being excited by tones in other pitches, thus reducing the untuned responses.

tuning. Each comb filter thus ensures that its corresponding glass is only excited by input signals with a partial matching the glass' lowest resonance frequency. Higher glass harmonic resonance frequencies, if present, are excited by higher harmonics of the input signal, if present. Figure 9 shows a comb filter designed to pass the harmonic series of A_4 (440Hz) next to spectra classical guitar $F\#_4$ (370Hz) and A_4 tones. Note how most of the $F\#_4$ spectrum is attenuated by the comb filter, while the A_4 spectrum is mostly unaffected.

As the current prototype of the Symbaline consists of 6 analog channels, each channel simultaneously excites two glasses via two serially connected electromagnets (Figure 2). The glasses of each pair are tuned to notes with an interval of one semitone: F_4 and $F\#_4$, G_4 and $G\#_4$ etc. These glass pairs are characterized by having relatively small overlapping frequency responses. Two parallel comb filters were assigned to each channel, as shown in Figure 5, generating the digital filtered signals $D^f_1 \ldots D^f_6$. The digital signals are later converted to analog signals $V^p_1 \ldots V^p_6$ and routed to the electromagnets. Thus, each glass is excited by either a signal in its own pitch, or in the pitch of its paired glass. For each tone produced by the source instrument, two glass sounds are generated: a tuned response from the tuned glass, and a single untuned response from the paired glass. This scheme reduces the untuned responses to a barely audible level.

The various parameters of the comb filters can be set by the player via the software interface. In addition, the option of routing the attenuated unfiltered V^{aux} (dry) signal to the electromagnets, in parallel to the filtered signal, is available. While the unfiltered signal may be undesired from the point of view of noise suppression, it can be useful for other reasons. Primarily, some sound effects seem to be more pronounced when applied on the unfiltered signal, as explored in Section 5. In addition, some of the attack portion of the tones is attenuated by the comb filters. Thus, the unfiltered signal, still containing the attacks, is useful for emphasizing a sense of rhythm in the glass sounds. The final balance between the filtered and unfiltered signals is left to be set by the players.

3.2.2 Pitch modulation

Pitch modulation is proposed when the source instrument is played in a different octave than the tuned wine glasses. For example, this occurs when playing basic chord patterns in the 3rd octave on a guitar as a source instrument, while the wine glasses are tuned to the 4th octave. Such differences arise from the practical limitations in assembling a wine glass set, as described in Section 3.3. When the input pitch matches the glass pitch, the glass sound is optimal - bright and slowly fading. When an interval of one or more octaves between the input and the glass exists, a glass sound is still generated, but it is shorter and dimmer. Therefore, it is proposed to use existing pitch-shifting tools to shift the input tones to the glass set octave. The pitch modulation may be applied at any stage within the digital module (D^{smpl}, D_i^f), shown in Figure 5, using existing DSP tools.

3.3 Wine glass tuning and set assembly

Wine glasses are typically tuned by adding water. Based on most glasses we examined, filling a glass to the top tunes it down by up to 5-6 semitones. In addition to lowering the pitch, filling a glass with water tends to lower the response intensity and shorten the decay time. Thus, an ideal glass set would have natural frequencies as close to the desired tuned notes as possible, and would require little to no tuning with water. The desired tuned notes themselves are a matter of subjective preference. Technically, any selection of notes is possible, including micro-tonal tunings and ranges of over a single octave.

Practically, assembling a wine glass set is limited by the available selection. Of the numerous wine glasses we tested, most produced notes in the range of G_4-B_4, and only a few produced notes above C_5. Glasses naturally producing notes below G_4 were quite uncommon. Thus, even when tuning with water, our sets were limited to cover the 4th octave and the lower notes of the 5th octave. The 12 glasses of the Symbaline prototype were tuned to cover all notes from F_4 (349.23Hz) to E_5 (659.25Hz).

In addition to tuning aurally ('by ear') or using a tuner, the Symbaline's glasses can be tuned by a unique method: the glass is excited by a pure tone in the fundamental frequency of the desired note, via the electromagnet. Water is added to the glass, gradually lowering its resonance frequency, while the glass responds by radiating sounds. Once the glass resonance frequency coincides with the excitation frequency, an extremely loud glass sound is produced. This sound is accompanied by visible standing waves on the water surface, and sometimes even by water spouts, reminiscing of the Chinese Yu xi [20], providing clear visual and auditory indicators.

3.4 Future design considerations

The current prototype of the Symbaline was designed strictly with laboratory use in mind. It is envisioned that the Symbaline's future versions, currently under design, will incorporate many additional features and structural changes. Several such features are especially worth noting: primarily, the Symbaline design should permit musicians to play, tune and perform basic maintenance tasks by themselves. In addition, we desire to design at least one compact and easily portable version of the Symbaline, facilitating setting up in various locations. Finally, while musical instruments' primary figure of merit is their sound, visual aesthetics are also a desired trait [24]. No visual aesthetic elements were included in the design of the Symbaline prototype described in this paper, beyond the aesthetic value of the wine glasses themselves.

4 String instrument source

The first main configuration intended for the Symbaline is based on an amplified string instrument as a source instrument. This configuration produces sounds that best fulfill the original vision of a string instrument equipped with sympathetic wine glasses. Here, the source instrument both excites the Symbaline (R^{gls}) and generates stand-alone sounds (R^{src}). The output analog signal (V^{src}) of the source instrument may be further processed (V^{aux}), amplified and radiated through a speaker (R^{aux}). The sound of the entire system is then a blend of the source instrument's sound and the Symbaline responses. This setup is analogous to the sound of a sympathetic string instrument, which is a blend of the sound of the playing strings and the responses of the sympathetic strings.

4.1 Acoustic Characteristics – classical guitar source instrument

The Symbaline's acoustic response characteristics are dependent on the source instrument, the selection of glasses and the hardware properties of the system (electromagnets, magnets, amplifiers). Here, the Symbaline prototype was excited by a classical guitar as a source instrument, amplified using an external microphone. Figure 10 shows the waveforms and spectra of a classical guitar A4 tone (R^{src}) and the corresponding Symbaline response (R^{gls}). (See sound sample 3). Note the differences between the input and output tones: while the guitar spectrum is characterized by many harmonic overtones, the glass response's harmonics are barely visible above the 2nd harmonic. Furthermore,

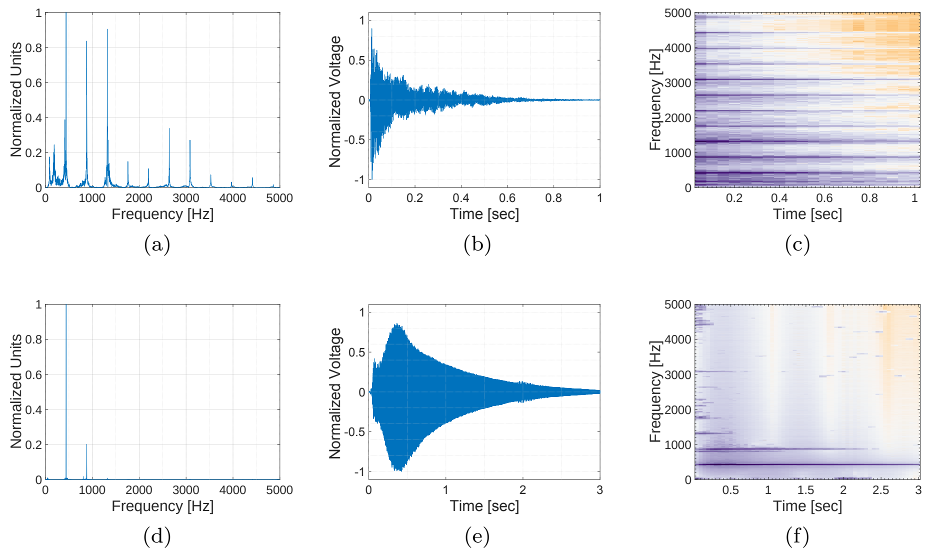


Figure 10: [a-c]: The spectrum, waveforms and spectrogram of a classical guitar A_4 tone (V^{src}). [d-f]: The corresponding Symbaline response (R^{gls}). Note the differences in spectrum and volume envelope between the excitation tone and the response.

while the guitar's attack tone is very short (about 10msec), the glass response attack is over 300msec.

5 Sound effects

Effect units and DSP tools can be used to process the various Symbaline signals, thus altering the produced wine glass sounds. The effects can be applied within the digital module, at any of the stages shown in Figure 5 (D^{smpl}, D_i^f). In addition, hardware effects may be applied on the analog signals, either before or after the audio interface (V^{src}, V_i^p) .

Here we present the use of two digital sound effects, applied within the digital module to D^{smpl}. The comb filters were bypassed, as the sound effects are more pronounced when applied on unfiltered signals. These effects were selected out of the large variety of effect units and DSP tools in wide use. It is envisioned that future musicians will experiment and create their own custom sounds using different effect units, as often done today with electric guitars.

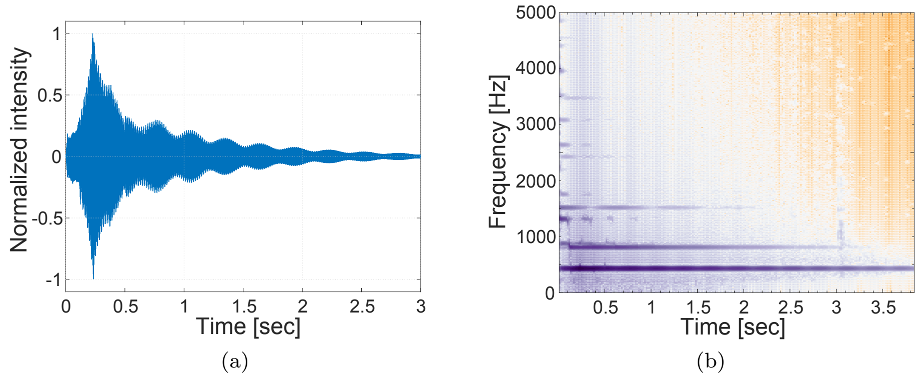


Figure 11: The output of the Symbaline (R^{gls}), excited by a classical guitar A_4 tone. The guitar signal is processed using a wah-wah effect. Note the observable amplitude modulation created by the wah-wah.

5.1 Wah-wah

The wine glasses selected for the Symbaline may or may not exhibit warble even after the magnets attachment, as described in Section 3.1.1. Thus, we propose using the wah-wah effect to artificially create a warble impression in the Symbaline's sound. The wah-wah introduces a band pass filter on the input signal, with a dynamically changing center frequency. The change is automatic or expression pedal controlled. Figure 11 shows the Symbaline response to a classical guitar tone processed by a wah-wah effect. Note the beat frequency of the volume envelope as well as the appearance of additional higher partials with longer decay times. (See sound samples 4a and 4b).

5.2 Chorus effect

The electronic chorus effect is typically implemented by mixing a signal and a periodically delayed copy of itself. When applied to D^{smpl}, the chorus creates an apparent beating effect in the Symbaline's reponse R^{gls}, much like the wah-wah. The chorus effect also adds many additional partials, apparent mostly in the first 500msec of the tone, as shown in Figure 12. (See sound sample 5).

6 MIDI source

The Symbaline can be played by a MIDI controller as the source instrument. In this configuration, the MIDI controller controls a virtual instrument or a sample library via the digital module. Figure 13 shows the entire system in MIDI configuration, while Figure 14 details the digital module. The MIDI controller sends a MIDI signal, D^{MIDI}, to the digital module. The digital module then generates

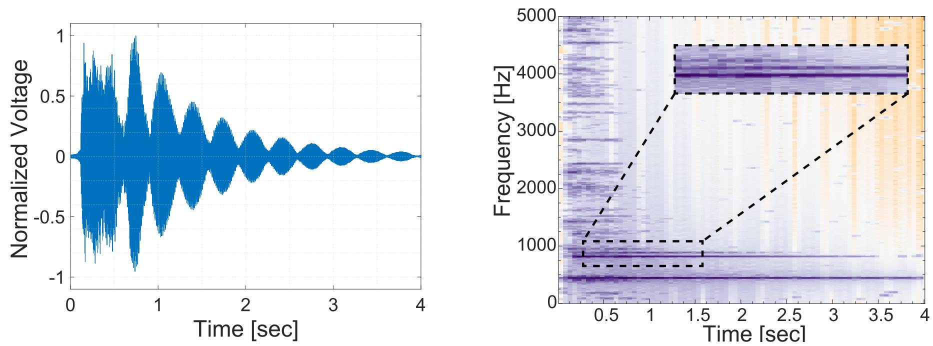


Figure 12: The output of the Symbaline (R^{gls}), excited by a classical guitar A_4 tone. The guitar signal is processed using a chorus effect. The 2nd harmonic doublet is magnified. Note the observable amplitude modulation as well as the addition of higher partials, created by the chorus.

digital audio signals, $D_1^m, D_2^m \dots$, using pre-recorded or pre-synthesized tones of virtual instruments and sample libraries $(T_1, T_2 \dots)$. The digital audio signals are then processed and converted to analog signals $V_1^p, V_2^p \dots$. The large existing variety of sample libraries provides a convenient means for exploring the Symbaline's response to various instruments. In addition to existing sampled and virtual instruments, new virtual instruments can be custom designed for playing the Symbaline.

The MIDI configuration shares two key characteristics with the string instrument configuration. First, the digital signals (D_i^m) can be further processed using DSP. Second, in addition to controlling the Symbaline, MIDI generated sounds can be routed via a parallel path (V^{aux}), and radiated using an auxiliary speaker (R^{MIDI}). The MIDI configuration offers an additional feature to the string configuration: the signals routed to the Symbaline (V_i^p) and the signal routed to the auxiliary speaker (V^{aux}) can be produced by entirely different virtual instruments (T_i). Therefore, the player can create complex sounds - for instance - playing a sampled marimba solo via the auxiliary speaker, accompanied by the Symbaline sounds driven by a virtual violin. Lastly, the MIDI configuration enables an additional approach for noise prevention. Using the DAW, the digital signals D_i^m may be mapped to different channels based on the pitch. When a signal of a specific note is produced, it can be sent only on the output channel routed to the glass tuned to the same note, rather than being sent to all glasses simultaneously. Thus, each pair of glasses will be excited by only its tuned pitches, and the untuned responses are avoided. In the current Symbaline prototype, C and $C\#$ are mapped to D_1^m, D and $D\#$ are mapped to D_2^m, and so forth. This approach obviates the need for comb filters, achieving a similar effect without processing or manipulating the signal itself.

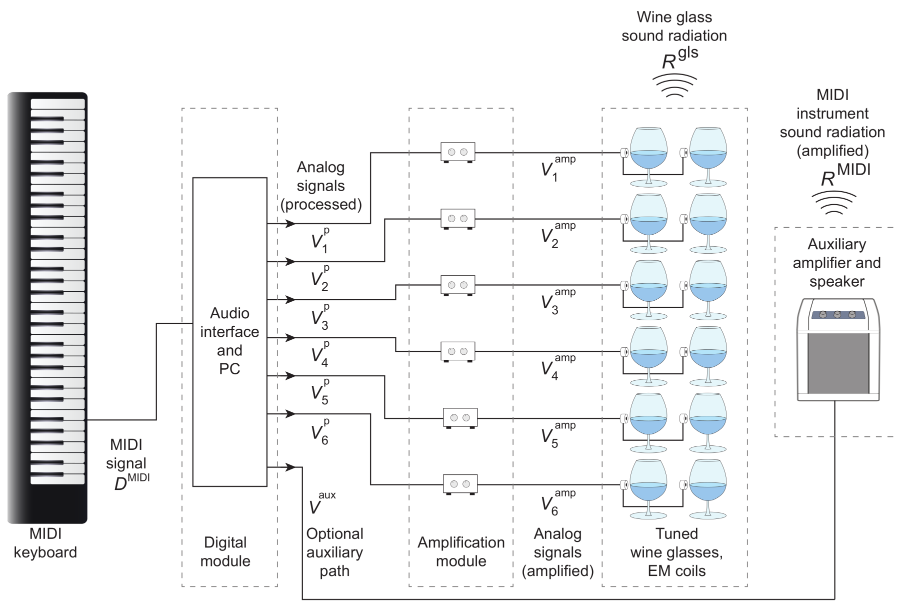


Figure 13: The Symbaline system in MIDI configuration. The MIDI controller sends a MIDI signal, D^{MIDI}, to the digital module (shown separately in Figure 14). The digital module generates audio signals $V_1^p \ldots V_6^p$ and V^{aux}, using sample libraries or virtual instrument tones. The signals are amplified by the amplification module ($V_1^{amp} \ldots V_6^{amp}$) and radiated by the wine glasses using electromagnetic coils. V^{aux} is routed to a standard amplifier and speaker.

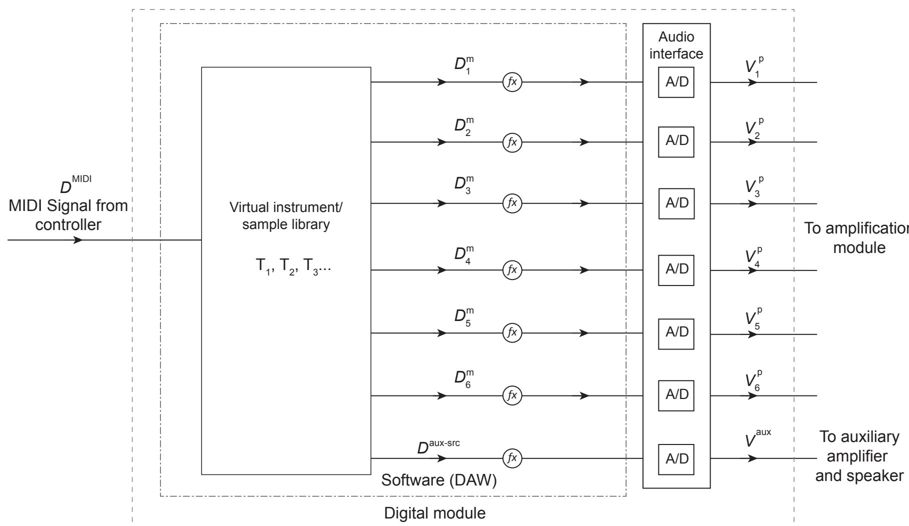


Figure 14: Block diagram of the digital module in MIDI source configuration. The MIDI signal from the controller, D^{MIDI}, is interpreted by the DAW. The DAW then generated audio signals $D_1^m \dots D_6^m$ and $D^{aux-src}$ using pre-recorded or pre-synthesized tones $T_1, T_2, T_3 \dots$. The audio signals are reconstructed $(V_1^p \dots V_6^p)$ and sent to the amplification module. $V^{aux-src}$ is reconstructed and sent to a standard amplifier and speaker. Additional digital effects may be applied to D_i^m and $D^{aux-src}$ at any stage marked by 'fx'.

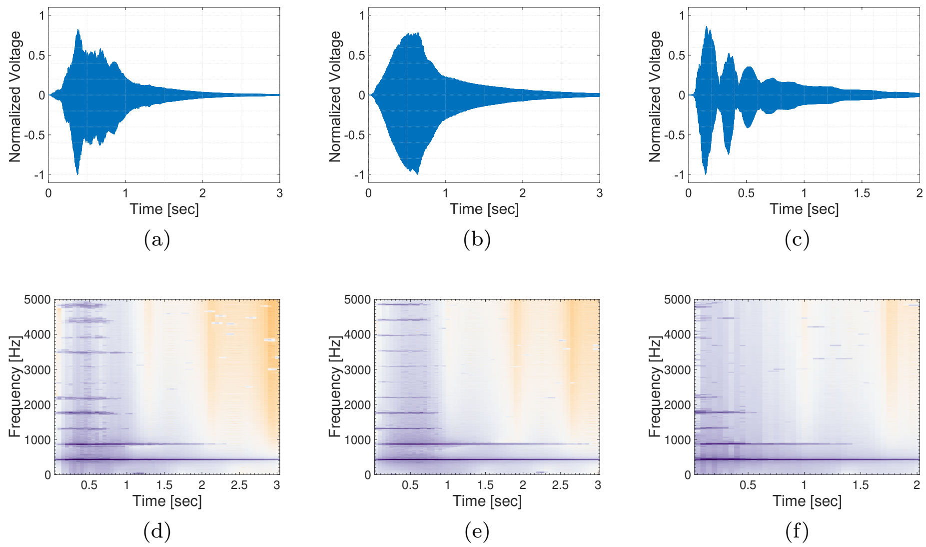


Figure 15: Symbaline responses (R^{gls}) to A_4 tones produced by a cello, a flute and a marimba ($T_1, T_2 \ldots$). Note the differences between volume envelopes and spectra of the different responses.

6.1 Excitation by sampled instruments

Many musical instruments are available as sample libraries. The prevalence of these libraries permitted us exciting the Symbaline using tones of various string, wind and percussion instruments.

Excitation by most sampled instrument tones ($T_1, T_2 \ldots$) create similar strong and slowly decaying Symbaline responses (R^{gls}) in the fundamental and 2nd harmonic. However, major differences are apparent in the higher harmonics of the different Symbaline responses. Excitation instruments having a relatively short sustain, e.g., percussion and plucked string instruments, produce fast decaying higher harmonics. Contrarily, excitation instruments having long sustained tones, e.g., wind instruments and bowed string instruments, manage to sustain the higher harmonics of the Symbaline response (R^{gls}) for as long as the input sound is present. Additional apparent differences exist in the attack times. When using plucked string or percussion instruments for excitation ($T_1, T_2 \ldots$), the resulting R^{gls} tend to have attack times of 100-300msec. When wind and bowed string excitation instruments are used, R^{gls} attack times are 500msec or higher. Figure 15 demonstrates both differences, showing Symbaline responses to cello, flute and marimba inputs. (See sound samples 6a, 6b, 6c).

6.2 Custom designed virtual instruments

While the available selection of sample libraries is very wide, they are all intended to be played through a standard loudspeaker, characterized by a relatively flat frequency response. Using these virtual instruments as excitation instruments for the Symbaline may produce pleasing results by chance, rather than design. It is thus sensible to design custom virtual instruments for exciting the Symbaline, while considering wine glass acoustic properties.

Several variations of a virtual instrument were generated by additive synthesis. The virtual instrument's tones contained a varying number of harmonic or inharmonic partials, shaped by programmable Attack-Decay-Sustain-Release envelopes. The tones were further modulated using low frequency oscillators. Out of the many variations explored, two are presented here.

The first virtual instrument excitation is suggested here as a lead-melody instrument. The virtual instrument tones ($T_1, T_2 \ldots$) are shaped by a volume envelope with a rapid 50msec attack, followed by a 400msec decay and a 3sec slowly fading release. The envelope is multiplied by a 3.3Hz tremolo sine. The tones consist of only two partials: the fundamental and the first harmonic, corresponding to the wine glasses' especially strong frequency responses at these frequencies. The instrument thus generates clear Symbaline responses (R^{gls}), having a distinct rhythmic emphasis. Figure 16 shows a sample waveform and spectrogram along the Symbaline's response. (See sound sample 7a).

A second instrument, consisting of significantly different tones, was envisioned as useful for ambient music, harmonies and slow passages. The tones ($T_1, T_2 \ldots$) are characterized by a long 550msec attack time, followed by a 800msec decay and a slowly fading release. The amplitude envelope is multiplied by a small 2Hz tremolo sine. The tones contain a full harmonic series, up to 20Khz, subtly modulated by a 2Hz sine. This variation and the corresponding Symbaline response (R^{gls}) are shown in Figure 17. (See sound sample 7b).

7 Preliminary evaluation

The Symbaline was presented to six amateur musicians for hands-on experimentation. The evaluators were selected due to their interest and experience in audio technologies. The evaluators were presented with the Symbaline and given a brief technical overview of both configurations. The evaluators were then given the opportunity to freely play the Symbaline as they wished.

The evaluators expressed two main views regarding the possible role of the Symbaline in music. One view favored using the Symbaline as an instrument in and of itself, played without amplifying the source instrument in a parallel path. The opposing view saw the Symbaline as an accompanying effect for a standard instrument.

The MIDI configuration was met with mixed views. Most evaluators enjoyed experimenting with both sample libraries and customized virtual instruments.

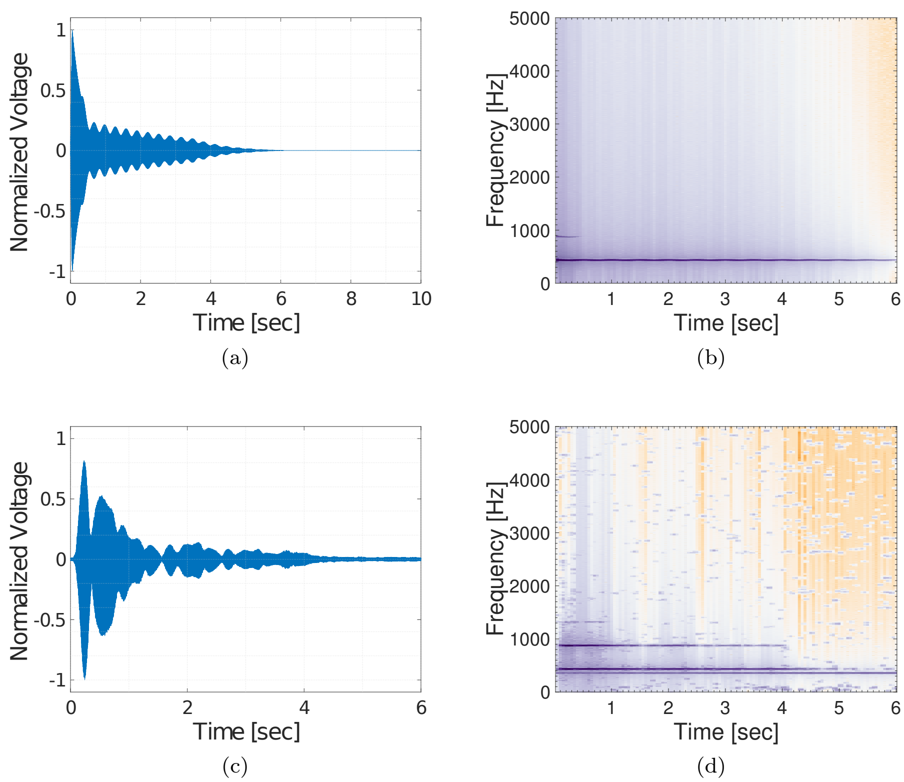
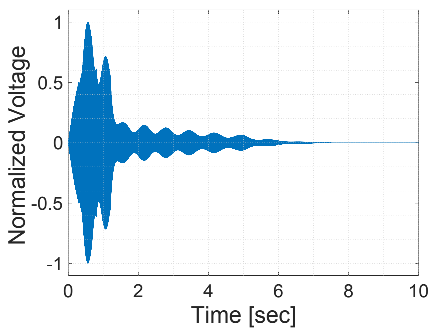
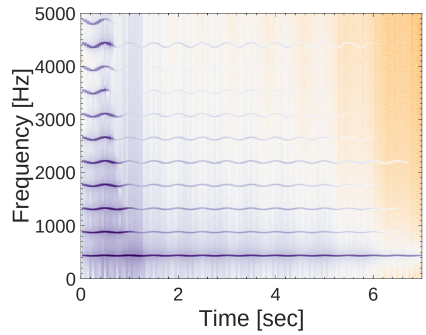


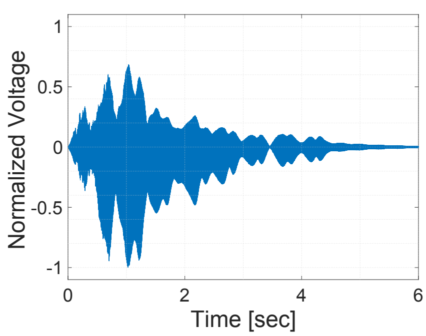
Figure 16: [a-b] Waveform and spectrogram of a virtual instrument tone (T_1). This instrument is characterized by a short attack and only 2 partials, with a rapidly decaying volume envelope shaped by a tremolo. It is suggested as a lead instrument. [c-d] The Symbaline's response (R^{gls}).



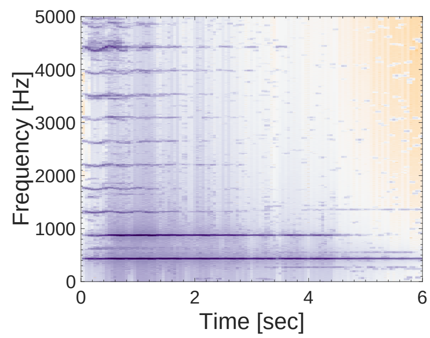
(a)



(b)



(c)



(d)

Figure 17: [a-b] Waveform and spectrogram of a virtual instrument tone (T_1). This instrument is characterized by a long attack, strong higher harmonics and heavy frequency modulation. It is suggested for ambient music. [c-d]: The Symbaline's response (R^{gls}).

However, one evaluator, trained as a classical pianist, had a negative opinion about exciting the Symbaline with samples of existing instruments, while favoring the use of custom virtual instruments. In the former case, the evaluator felt that the Symbaline spoils the already perfected sounds of the existing instruments. All evaluators requested MIDI controls for controlling additional parameters such as tone lengths, individual glass volume, timbres etc.

All evaluators stressed the need to make the Symbaline compact, portable and aesthetic, if ever intended to be used as part of their everyday music making. Some evaluators suggested fitting the Symbaline with audio controlled lightning effects. They expressed their wish of using these effects for performance purposes. One evaluator requested specialized audio effects, custom designed for the Symbaline string configuration, instead of using off-the-shelf effects designed for general audio usage.

8 Conclusion and outlook

This paper presents the Symbaline, a musical instrument based on electromagnetically actuated wine glasses. The guiding vision is to enhance the sound of a string instrument using wine glasses, in a similar fashion to sympathetic strings. The Symbaline allows players to produce wine glass sounds using familiar existing instruments, thus significantly shortening the learning curve. Two distinct configurations were explored, as well as the incorporation of audio effects and customized virtual instruments. It is envisioned that musicians will use the instrument for performance and music production, while crafting their own unique sounds, by effect chains and customized wine glass sets.

The presented prototype has been mostly designed for characterization and experimentation purposes. Further development is required to create a version more suitable for everyday music-making. Primarily, the instrument's portability, ease-of-use and aesthetics should be improved. The Symbaline design shown in Figure 1 may serve as the basis for the future versions. Furthermore, a suitable user interface should be developed, obviating direct interaction with the overcomplex DAW. Because the number of customizable features and possible digital module configurations is vast, additional research should be conducted to determine which features and configurations will be accessible to the players. Finally, as the current research only included a brief preliminary evaluation, an extensive evaluation process should be carried out. The evaluation should include many listeners and musicians of various genres, instruments and skill levels. Different possible usages of the Symbaline should be explored in all configurations. Complementary perception and listening tests should be conducted to evaluate the aesthetics of the Symbaline's various sounds and to investigate the various characteristics of the sound space.

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