

Physical Modeling and Hybrid Synthesis for the Gyl African Xylophone

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ABSTRACT

We propose a physical model for the *Gyl*, an African pentatonic idiophone with wooden bars that have similar sonic characteristics to the western marimba. The primary focus is modeling the gourds that are suspended beneath each bar and have a similar role to the tuned tubes below the bars in western mallet instruments. The prominent effect of these resonators is the added buzz that results when the bar is struck. This type of intentional sympathetic distortion is inherent to African instrument design as it helps unamplified instruments be heard above crowds of people dancing and singing. The *Gyl's* distortion is created by drilling holes on the sides of each gourd and covering them with membranes traditionally made from the silk of spider egg casings stretched across the opening. By analyzing the sonic characteristics of this distortion we have found that the physical mechanisms that create it are highly non-linear and we have attempted to model them computationally. In addition to the fully synthetic model we consider a hybrid version where the acoustic sound captured by contact microphones on the wooden bars is fed into a virtual model of the gourd resonators. This hybrid approach simplifies significantly the logistic of traveling with the instrument as the gourds are bulky, fragile and hard to pack. We propose several variants of the model, and discuss the feedback we received from expert musicians.

1. INTRODUCTION

In this paper we introduce a physical model for the *Gyl*, an African mallet instrument with a unique system of resonator-gourds mounted below wooden bars. These gourds are unique in that they have holes drilled in them, which are covered over with membranes. These membranes react to sound pressure in a highly non-linear fashion and produce a buzzing sound when the bars are played with force.

Physical modeling efforts have typically focused on modeling stringed instruments, struck bars, and membrane models usually in the context of western classical music instruments. To the best of our knowledge, the *Gyl*, and the nonlinear processes which are the cause of its characteristic sound, have not been studied before in the context of physical modeling synthesis.

One objective behind creating the model is to provide performers and composers an audio effect that can be applied to the signal of any mallet percussion instrument. This enables the use of techniques associated with the *Gyl* without having to include the actual gourds and membranes. The gourds are cumbersome, fragile, difficult to construct, and can not be added to conventional pitched percussion instruments. Electro-acoustic mallet percussionists have little choice but to apply filters and audio effects that are designed for other instruments such as guitar pedals. In contrast, our model and associated audio effect are idiomatic to pitched percussion instruments.

The *Gyl* is an ancestor of the marimba, and originates in western Africa the region defined by the political borders of northwest Ghana, northeast Ivory Coast, and southwest Burkina Faso. It has strong roots in the region near Wa, Ghana, on the Black Volta where it forms a key part of the Lobi and Dagara cultures. The *Gyl* is a pentatonic instrument with between 11 and 18 keys played with rubber tipped wooden mallets that are held between the index and middle fingers and about the size of a nickel in diameter. The keys are carved from a local hardwood called Legaa, and are mounted to a wooden frame with leather strips [1]. A dried calabash gourd is hung below each bar. These gourds have irregularly spaced holes drilled in them, which are covered over with spider silk egg casings. These egg casings form membranes which produce a buzzing sound when the bars are played with enough force. This buzzing sound distinguishes the *Gyl* and it is this aspect of the instrument that we focus our modeling efforts on. Figure 1 shows photos of a *Gyl* and the associated gourds.

The *Gyl* occupies a central place in the Lobi and Dagara culture, with *Gyl* performances accompanying major ceremonies and festivals [2]. There is a special variety of *Gyl* for solo performances at funerals and it is believed



Figure 1. bass gourd shown (14” deep, 10” dia.- body, and 4” dia.- mouth) and frame construction.

that the sound emitted from the instrument escorts the deceased soul into the next world. The sound-design of the buzzing is motivated by the belief that the vibrations it produces balance the water in the human body and have physiological healing qualities. There is no traditional written notation for the *Gyil*, and the repertoire and technique is passed on orally. Players typically perform in groups solo or in duo, accompanied by a bell, a calabash resonator drum with animal skin stretched over an opening played by hands, and a double pitched log drum played by sticks. The music combines pre-written melodies with improvisation comprised of bass ostinatos using the left hand and lead solos using the right hand, similar to jazz arrangements [1]. The repertoire is made up of pieces that are time, season, and context appropriate- funeral songs for men vs. women, wedding songs, recreation songs, etc.

2. RELATED WORK

Physical modeling is an audio synthesis technique in which the sound of an instrument or circuit is emulated by numerically solving the differential equations that describe the physics of the system [3]. In contrast to other synthesis techniques the parameters of physical models have a direct correlation to the properties of the sound generating object being modeled. For example, in a model of a vibrating string the length, linear density, and stiffness can be directly controlled with parameters [4]. Most research on physical models has focused on modern Western European instruments. Even for instruments that have been intensely studied, such as the violin, the resulting sound is still quite distinct from the original acoustic instrument [5–7]. At the same time physical models provide a realism and physicality to the generated sound that is impossible to achieve with techniques such as waveform sampling.

In early work, physical modeling was based on linear approximations of non-linear phenomena, such as the behavior of percussive surfaces [8, 9]. Non-linear models can provide a more realistic sonic experience [10], however are considerably more complex to understand [11]. This difficulty has motivated the development of different exploratory interfaces for the parameters of these models [12] as well as learning models that can automatically obtain

Parameter	Typical values
Gourd width	5 cm to 25 cm
Gourd height	5 cm to 40 cm
Mouth radius	1 cm to 5 cm
Membrane radius	0.5 cm to 1 cm
Number of membranes	2 to 5

Table 1. Measurements on the gourds.

interesting non-linear mappings for sound synthesis [13]. Another idea is to combine or manipulate the audio signal acquired from an acoustic instrument with digital processing as a form of hybrid synthesis [14, 15]. There are some existing efforts to obtain physical models for non-western-european instruments, like the ancient greek *auloi* [16] as well as pitched percussive instruments [17, 18]. However, there are many instruments which have not been physically modeled, including the *Gyil*.

In previous work we have shown how each wooden bar of the *Gyil* can be retrofitted with contact microphones providing clean audio signals for each bar that can be used for sound enhancement, synthesis and transcription [19]. An early version of the physical model of the gourds described in this paper was also used. In this paper we improve the physical model, explain in more detail how it was designed, explore various configurations, and report on feedback we received from a group of expert musicians that have intimate knowledge of the instrument.

3. PHYSICAL MEASUREMENTS

Each individual *Gyil* is unique, as it is constructed using natural materials and is tuned by ear by its builder. We present physical measurements made using a specific *Gyil* with the goal of obtaining reasonable ranges for the parameters of the proposed model. The synthesis of the wooden bar sound can be performed using standard modal synthesis techniques [20] and therefore the focus of the measurements was to obtain information about the prepared gourds. The resonant characteristics of each gourd depend on its geometry, so we measured the width, the height, and the radius of the mouth of all the gourds for the specific instrument considered. The buzzy sound that is a characteristic of the *Gyil* is created by several membranes that are attached to the gourd so their number and radius were also measured. The measurements are shown in Table 1.

The gourds are natural objects and therefore there is no consistency in their exact shape. As seen in Figure 1, their shapes can be very different making it practically impossible to model them in detail. The same holds for the spider silk egg casings used in the membrane. For that reason, the sonic characteristics of the gourd were evaluated by comparing two different recordings: one of a note of the *Gyil* without the gourds (that is, a sound similar to the one of a xylophone) and the other one of the same note of the same *Gyil*, with the gourds reattached. The Discrete Fourier Transform of the first 300 ms after the attach was calculated and is shown in Figure 2. The energy present

below the fundamental is likely to be caused by intermodulation distortion.

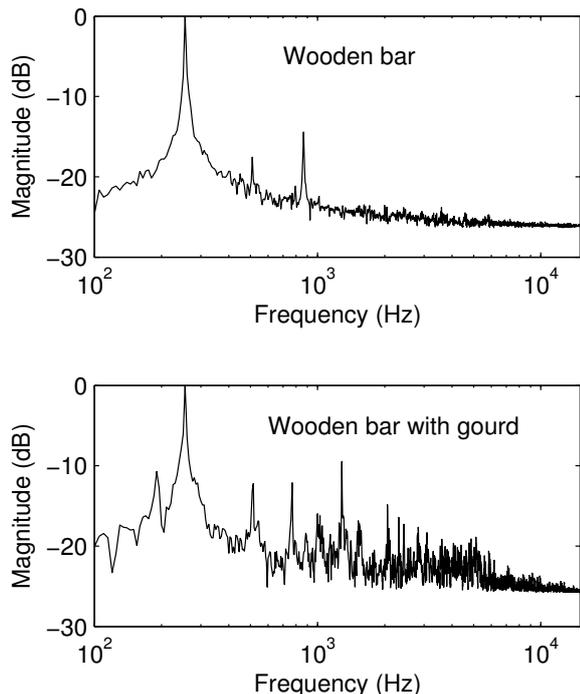


Figure 2. DFT of the recordings of a resonating wooden bar and a wooden bar with attached gourds.

As can be seen, attaching the gourds to the *Gyil* introduces non-harmonic frequency components around 1.2 kHz and 1.8 kHz that indicate non-linear behavior. These frequency components cause the characteristic buzzy sound of the *Gyil*. In the next section we propose a technique for obtaining this type of distortion.

The instruments used were built in 2002 for one of the authors while on a six-month research visit to Ghana. They were crafted by the late master builder/performer Kakraba Lobi. The two instruments were built as a pair and tuned to a western G major pentatonic scale. This is unorthodox, as the instruments are usually tuned by ear. The one *Gyil* was kept intact, while the gourds were removed from the other one for hybrid synthesis.

4. MODEL DESCRIPTION

We present a model of the *Gyil* gourds that produce the characteristic buzzing sound of the instrument. We treat the gourds in isolation from the wooden bars. This is justified by the fact that the ratio of the mass of the bars to the sound pressure levels produced is large and the gourds are not precisely tuned to resonate at the frequency of the bars so we can assume there is no feedback of acoustic energy from the resonators to the bars. Consequently, we treat the *Gyil* as a source-filter system, and focus our modeling efforts on the gourds, and in particular aim to simulate the non-linear response of the vibrating membranes as well as the filtering characteristics of the gourd.

In constructing a mathematical description of the *Gyil*, two options present themselves: a model can be built that is

a direct representation of our understanding of the physics of the system, or we can abstract and idealize the processes at work, representing them by algorithms which perform a similar function to the various components of the instrument. The first option has the advantage of the ultimate degree of realism available to us, however it can lead to highly complex numerical models which are unusable in real time. In particular, even a simplified mathematical description of the physics of the membranes would require a high degree of complexity due to the irregular shapes of the membranes, the unique material properties of the egg casing, and the coupling between the egg casings and the resonating surface of the gourd, which is itself highly irregular. The second option is to represent the processes we have observed using signal processors which replicate the effect of the process, and it is this option that we will take. In addition to the inherent nonlinearity of the system, each *Gyil* is built by hand, using the available materials (*e.g.* wood, gourd shells, and spider silk), that the builder judges to be most suitable. In the course of construction, the instrument is tuned by ear by the craftsman. Under these circumstances, it makes little sense to attempt to create an exact model of a particular *Gyil*. Instead, we seek to emulate the sonic features that we have identified as characteristic of the instrument. The proposed model is based on a general structure with adjustable parameters that are set by the user for fine tuning; we propose that this process is analogous to the decisions made by the craftsman when building the physical instrument.

The proposed system consists of a model for the gourd itself which is excited with either a signal generated by a modal model [20] of the wooden bar, or by audio acquired from the wooden bars using either a microphone or contact microphones [19]. The modal model used in this study was created in the Reaktor programming language, and was tuned to the sound of the xylophone recordings by ear and by comparison with spectral plots of the recordings. The modal model used 6 partials above the fundamental, and was excited with a filtered impulse mixed with an enveloped burst of white noise, in order to simulate the sound of the mallet strike on the bars.

The gourd is modeled as a resonant filter [4] and the membranes are modeled as a non-linear function that yields the *Gyil*'s buzzing sound. The output of the membranes is heard both directly and after being filtered again by the gourd. This leads to the model structure seen in Figure 3.

The center frequency f_c of the resonant filter model associated with a gourd is inversely proportional to the volume of the gourd. For that reason, larger gourds are chosen to be associated with the lower pitched notes. The filter's Q-factor Q is inversely proportional to the size of the opening at the top. Due to the natural shape of the gourds used, the resonators hung below the higher bars tend to have wider apertures, and the model can be tuned to reflect this.

4.1 Modeling the Membranes

The membranes present a non-linear behavior that is difficult to quantify, as there are no precise measurements for the characteristics of the specific spider silk used in the pa-

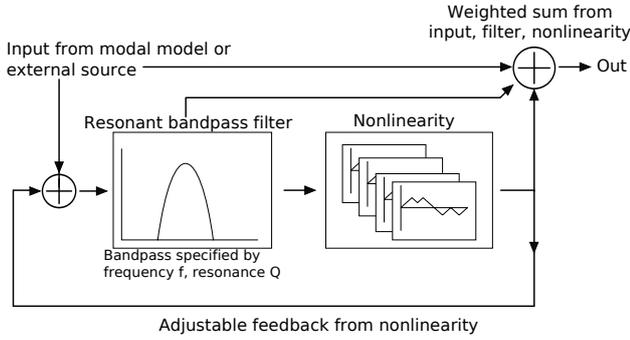


Figure 3. Diagram of signal flow for one gourd.

pering of the gourd holes. While some *Gyil* makers use varieties of paper as a replacement for the silk, the rheology of paper membranes is an unexplored field, and there are few physical results on which to base our investigation. It is reasonable to assume that the membranes respond linearly to low-intensity acoustic signals, but are only able to vibrate within a certain range of amplitudes, hence clipping the input signal in levels A_+ and A_- as in:

$$x_{out} = \begin{cases} x_{in} & A_- < x_{in} < A_+ \\ A_+ & x > A_+ \\ A_- & x_{in} < A_- \end{cases} \quad (1)$$

We also believe that uneven tension on the membrane, coupled with the material properties can lead it to fold back on itself (crinkle) when forced above a certain amplitude A . We have decided to represent this behavior in our model using a wave folder nonlinearity. Other options which we have considered and tested are a cubic nonlinearity, and a sine waveshaper. Preliminary testing showed that the cubic waveshaper did not generate sufficient harmonic content to begin to emulate the behaviour of the membranes, and the sine shaper performed similarly to the wave folder, but with a higher computational cost. Due to the position of the membrane on the outside of the gourd, its motion may be impeded (Fig. 4) when the pressure inside the gourd is drawing it inward. We can include this behavior by making the wave folder asymmetric.

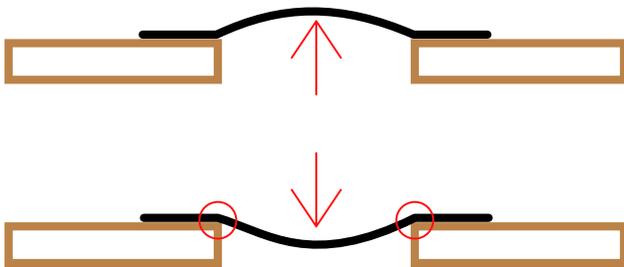


Figure 4. Asymmetric motion of the membrane as its travel is impeded by the presence of the gourd.

The output signal from our wavefolder may be expressed

in terms of the input signal as:

$$x_{out} = \begin{cases} x_{in} & -A_- < x_{in} < A_+ \\ x_{in} - A_+ & x > A_+ \\ A_- - x_{in} & x_{in} < -A_- \end{cases} \quad (2)$$

where x_{out} is the output, x_{in} is the input, and A_+ (A_-) is the amplitude at which the wave is folded over for positive(negative) amplitudes. The wavefolder produces a signal with more high-frequency energy than a simple clipper due to a higher level of inter-modulation distortion.

To implement asymmetric behavior in the model, we can also use a symmetric wavefolder with parameter $A = A_+ = A_-$ and add an offset c to the input signal prior to applying the non-linear function. Adding an offset will change the energy of the harmonics added to the output. The two parameters, A and c , that define the behavior of the membrane model are respectively connected to the age of the membranes, as old membranes tend to require more energy to trigger the non-linear behavior, and to the asymmetry of the membranes construction, which is determined manually by the craftsman. Since there is a great deal of variability between individual membranes, both in material properties, size, and position, the level of asymmetry in the wavefolding is varied between them. In order to explore a range of possible parameterizations of the behavior of the membranes, we tested three different algorithms: a simple clipper, a simple wave folder, and a series association in which the output of a wave folder is clipped. These algorithms are compared in Section 5.

As typically there are several membranes (between 3 and 5) attached to each gourd we run several membrane models (with N being the number of them) in parallel. To mimic the different sizes of the membranes, and variations in material, the non-linearities must have different parameter settings for A and c . Although these differences could be set manually for each membrane, that would imply adjusting $2N$ parameters. To simplify this tuning process, an adjustable scaling parameter $0 < s_w < 1$ is specified so that, for a model with N membranes, the level A related to the non-linearity in the n^{th} membrane is given by $s_w^n A$, and the offset level c is proportionally adjusted so as to keep the asymmetry constant, thus reducing the number of adjustable parameters for the wave folders from $2N$ to 3.

4.2 Signal Flow

Using a resonant filter to model the gourd, and clipping and wavefolding to model the behavior of the membranes, we have the building blocks of the *Gyil* gourd model. To complete our gourd-membrane model, we couple the output of the membrane models to the gourd by summing the membrane outputs and feeding them back into the resonant filter with a controllable gain g . We must now determine the optimal signal flow for the whole instrument. In the physical instrument, sound energy created by striking a bar excites the gourds, with the strongest excitation in the gourds immediately proximal to the bar. The sound heard by listeners is a mixture of the direct sound from the bar, the sound from the mouths of the gourds, and the sound from the membranes (an example of the signal flow is shown in

Figure 5). In order to explore the relative importance of these sources, a number of signal path structures can be implemented.

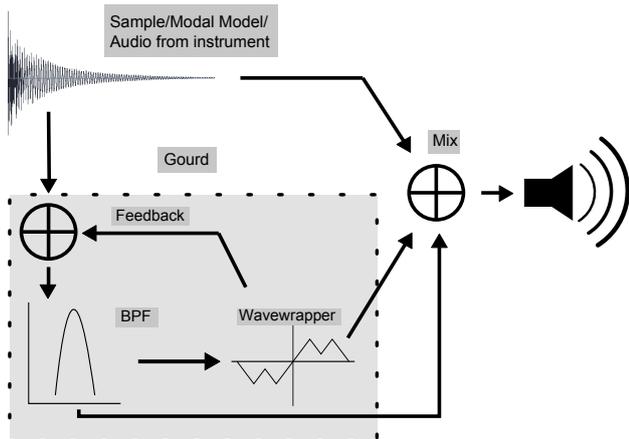


Figure 5. Example signal flow for a one-gourd one-membrane variant of the model, with a source that can be a sample, modal model, or input from an acoustic or electric instrument

The question of the importance of the excitation of more than one gourd by the striking of a bar can be addressed by comparing the performance of a model in which there is a one-to-one connection between the bars and the resonant filters to one in which the signal generated by the bar is fed into a number of parallel gourd models, with signal weightings given by an array of values B . In a system with p bars, and p gourds, the amplitude of the signal from bar i is $b_i(t)$, the level of the signal reaching gourd j is $B_{ij}b_i(t)$, where $0 \leq B_{ij} \leq 1$, and we assume that the bar and gourd indices are such that $B_{ii} > B_{ij}, \forall j \neq i$, so that the gourd directly below the bar receives the strongest signal. We may write the attenuation matrix as the product of a scalar b_{lev} and a matrix B that is normalized so that the largest element is equal to 1. By doing so, we can adjust the global level of the signal that reaches the gourds with a single parameter. When signal level from the bars to the gourds not immediately underneath them is negligible (*i.e.*, $B_{ij} = \delta_{ij}$) we can simplify the model structure by reducing it to a bar-gourd signal flow. For any situation where the off-diagonal elements of B are non-zero, we must feed the signal from the bar into a number of parallel gourd algorithms, and sum the result. Irregardless of the configuration of the bar-gourd system, we must sum the signal from the bar, and the signals from both the gourd and the membranes. To obtain these signals, we take two output taps in the gourd algorithm, one immediately after the resonant filter, and one immediately after the non-linearity. By adjusting the relative levels of these taps we may fine-tune the output of the gourd model to best emulate the behavior of the physical *Gyil*.

In the following section we present a user survey investigating the algorithms which we have discussed. The performance of the three different forms of the non-linearity have been evaluated by a trained *Gyil* player, as is the cou-

Parameter	Range	Meaning
f_c	20 to 10^4	The volume of the gourd
Q	0 to 10	Size of the mouth of the gourd
A	0 to 1	Age of the membranes
c	0 to 1	Asymmetry of the membranes
N	> 0	Number of membranes
S_w	0 to 1	Similarity of the membranes
g	0 to 1	Membrane feedback gain
k	0 to 1	Membrane direct gain

Table 2. Range and meaning of the model parameters.

pling of the bars to the gourds. In addition, we compare the performance of a physical model which uses a modal algorithm to simulate the bars to the data produced by a hybrid synthesis method in which the acoustic signal of the bars captured by contact microphones is used as input to the gourd and membrane model. Although the model proposed in this paper relies on a number of parameters that must be manually set, all of them are meaningful and correlated to actual characteristics of the *Gyil*. The correspondence between the model parameters and physical properties, is shown in Table 2.

5. RESULTS

The proposed model was evaluated in two different ways. The first was through a comparative analysis, in which the output of the implemented models was compared to the audio signal recorded using a real *Gyil*. In the second, the model was applied as a digital effect and fed with the audio signal acquired from a the wooden bars without attached gourds using contact sensors as well as the output of the modal synthesis model. By means of a survey we solicited feedback from expert musicians about the different configurations of the model and we report on the findings.

5.1 Comparative analysis

The experiments in this section were performed by one of the authors who is a percussionist with experience playing the *Gyil*. The parameters of the model were changed until the maximum auditory similarity, in the perception of the user, was obtained. The timbre of the model is greatly improved when a wave folder is used for the nonlinearity. The sound is further improved by adding clipping in series with the wave folder. This process corresponds to the expected behaviour of the membrane. The final timbre lacks some of the brightness of the sound of the real instrument, but does sound like a *Gyil*. The magnitude spectra of the signals yielded by each model, considering the first 0.3 s after the onset, were calculated are shown in Figure 6).

Comparing these results to the spectrum of the real *Gyil* in Figure 2, it can be seen that the digital models produce more energy below 1 kHz. Conversely, the physical *Gyil* has more high-frequency energy that is only present in the models that include clipping. The real sound has significant energy between 1.2 kHz and 1.8 kHz which was not produced by any of the models. These harmonics may play

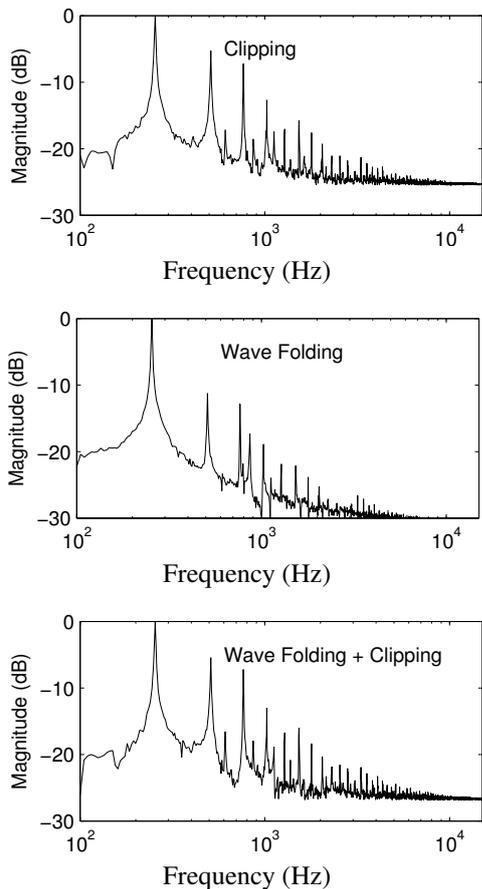


Figure 6. DFT of the outcome of different non-linearities: clipping, wave folding and wave folding followed by clipping.

a role in defining the timbre of the real instrument. The energy of the harmonic content in the model follows the general rule $1/f$, whereas that rule is clearly not applicable for the spectra of the sound of the real *Gyil*. The $1/f$ behaviour is common to most non-linear mathematical functions, which means the behaviour of the membrane can not be modelled as a simple non-linear function. Despite the limitations of the model, the obtained timbre is considerably similar to the one of the real instrument. Interestingly, although waveshaping synthesis is known to shorten the decay envelope of sounds [21], signals processed by our model had greater sustain than their acoustic counterparts. The attenuation of the decays of the *gyil* sounds is likely due to coupling between the bars and gourds, and remains a matter for future investigation.

5.2 Qualitative analysis

A qualitative assessment was also conducted to deal with aspects hard to identify with the spectral analysis method used in Section 5.1. This assessment was based on short recordings of a physical *Gyil* as well as synthesized clips. A phrase was played on a xylophone retrofitted with contact microphones [19] for multi-channel recording. Using a simple thresholding process, symbolic data was extracted from this recording [19] and used to render an audio file

with the modal model described in Section 4 that simulates vibrating wooden bars [20].

In total, four sound configurations were considered: a real *Gyil* recording, a multi-channel hybrid synthesis model in which each bar of the prepared xylophone was used to drive a different instance of the gourd model, a single-channel hybrid synthesis model in which the signal of the prepared xylophone was mixed to mono and then driven into a single instance of the model, and a single-channel fully synthesized version in which the audio signal obtained from modal synthesis was used to drive the model. The audio files obtained were analyzed by experienced *Gyil* players, who kindly provided feedback regarding the usability of the sounds in real performances and the similarity of the modelled distortion to the buzzy sound of the real instrument. Our goal was not a quantitative user study where findings are aggregated but rather to solicit feedback about our choices from musicians and scholars with significant experience with the *Gyil*. The names and affiliations of the experts are provided in Table 3. The samples used for the survey are available at: <http://gyil.sness.net/survey.html> and can also give readers a sense of the quality of the different model configurations.

While the evaluators could identify the model output as having some characteristics of the *Gyil* sound, many of them commented that the synthesized samples do not fully capture the richness and life of the sound of a *Gyil*. Despite this shortcoming, the samples obtained by hybrid synthesis were generally considered to be usable for performance. Of all of the model variants, the one that was preferred by most of the specialists was the gourd model with one channel, which is surprising given that it should be equivalent as having a physical instrument with one single gourd. The synthesis of the sound using the modal model was considered the least realistic and, in general, not sounding like a *Gyil*.

The detailed comments from the evaluators suggested that the buzz sound of synthesized samples was too dark, mellow and predictable, whereas the buzz characteristic from a real *Gyil* is more inconsistent, in the sense that it does not present the same response at every stroke of the mallet. It was observed that the samples recorded from a real *Gyil* lacked some desirable sonic characteristics, like a deeper bass resonance and a correct timbre of the buzz. This is partly due to the particular physical instrument that the digital model was based on that has aged membranes.

6. CONCLUSIONS

We have analyzed the physical and sonic characteristics of the *Gyil* and developed a physical model of the gourds which produce its characteristic sound. We have investigated the performance of several different variants of the model using both comparative analysis and through listening tests with experts. The creation of a physical model of the gourds presents immediate applications for performers. The gourd model which we have developed can be used in real time with any audio input as an effect. In particular, it can be used to process audio produced by other members of the idiophone family, in effect ‘*Gyil-izing*’ them. Given

Name	Info
Greg Harris	Professional vibist, world music specialist, music producer, Gyil researcher
Birdooh 'SK' Kakraba	Professional Gyil performer, composer, instructor- Hewale Sounds Ensemble, Ghana
Dr. Payton MacDonald	Chair of percussion studies at William Patterson University, master marimbist, composer
Valerie Naranjo	Professional percussionist, clinician, Gyil expert, West African mallet percussion pioneer
Dr. Karolyn Stonefelt	Chair of percussion studies, State Univeristy of New York Fredonia, Gyil scholar
Aaron Bebe Sukura	Professional Gyil performer, composer, instructor at the ICAMD, University of Ghana
Dorawana Edmund Tijan	Master Gyil performer, composer, teacher and builder from Saru, Ghana
Dr. Michael B. Vercelli	Director of the World Music Performance Center, West Virginia University, Gyil scholar
Bernard Woma	Master Gyil Performer, teacher, and founder of the Dagara Music Center in Accra, Ghana

Table 3. Gyil Experts used for feedback

the relative rarity of the *Gyil* outside of western Africa, our model presents performers with a means to access the characteristic *Gyil* sound without requiring the sourcing or construction of a *Gyil*. It also enables efficient traveling as packing the wooden bars is easy and the gourds which are fragile and cumbersome can be emulated digitally.

Because the physical model uses control parameters which are clearly linked to the physical properties of the gourds on which they are modelled, users have an intuitive way to modify the sound of the model to suit their own purposes. The parameters and parameter ranges of the model have been specifically selected for use with mallet instruments (particularly idiophones), based on the pitch range and timbre produced by the *Gyil*, which makes them a uniquely useful tool for musicians and composers working with these instruments.

While we have created a good model of the *Gyil* gourds, there are improvements which we plan to implement in future developments of the model. The primary difference remaining between the model and the physical instrument is the spectral characteristics of the distortion produced by the gourd. As was demonstrated in the comparative and qualitative listening tests, the *Gyil* model produces output with less high-frequency energy than the physical instrument. In future work we will introduce a more detailed model of the physics of the spider-silk membranes to address this. While we have discussed the complexity of the physics of the membranes makes them a difficult object to model, this does not mean that efforts in this area will be fruitless. We plan to experiment in future with a nonlinear waveguide mesh.

Furthermore, comments from the expert listening tests suggested that the buzz produced by the physical *Gyil* is much less predictable than the buzz produced by our model. In future work, we plan to explore this aspect of modelling the *Gyil* using stochastic methods in order to introduce random variation.

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