Individual Fabrication of Cymbals using Incremental Robotic Sheet Forming

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ABSTRACT

Incremental robotic sheet forming is used to fabricate a novel cymbal shape based on models of geometric chaos for stadium shaped boundaries. This provides a proof-of-concept that this robotic fabrication technique might be a candidate method for creating novel metallic ideophones that are based on sheet deformations. Given that the technique does not require molding, it is well suited for both rapid and iterative prototyping and the fabrication of individual pieces. With advances in miniaturization, this approach may also be suitable for personal fabrication. In this paper we discuss this technique as well as aspects of the geometry of stadium cymbals and their impact on the resulting instrument.

Author Keywords

Incremental Robotic Sheet Forming, Cymbals, Chaos, Stadium Boundary

CCS Concepts

•Applied computing → Sound and music computing; •Computer systems organization → Robotics; •Computing methodologies → Physical simulation;

1. INTRODUCTION

The purpose of this paper is two-fold. First, it introduces incremental robotic sheet forming as a candidate for individual fabrication of deformed plate ideophones such as cymbals. Second, it suggests boundary geometry as an additional or alternative source for chaotic dynamics in cymbal construction. These two purposes are combined by fabricating a first version of such an "alternative chaotic cymbal," and we discuss the dynamical background of the chaotic properties using geometric wave propagation modeling.

This work can be considered a proof-of-concept contribution to the field of personal fabrication [4]. The goal of personal fabrication is to find fabrication approaches that can be deployed to allow individual fabrication for personal needs. Musically speaking, personal fabrication is the ability to craft one's own musical instrument including all of its physical aspects.

Cymbals and gongs are thin, deformed 3-dimensional shell structures [2, 14, 20, 31] that are characterized by their non-linear dynamics. This means that they are not fully described by linear eigen-mode behavior charactersistic of physical situations that are well-modeled by linear systems. Furthermore, they are usually made of metal. The material and fabrication have to withstand substantial impact in performance due to typical percussive performance styles. This aspect makes cymbals an interesting case for personal fabrication, as they pose a range of specific challenges.

NIME'18, June 3-6, 2018, Blacksburg, Virginia, USA.

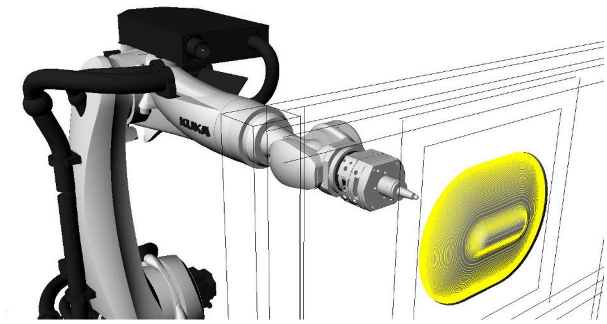


Figure 1: Digital robotic setup loaded with the geometry of the desired prototype.

Our interest is to expand and enable the notion of cymbals for individual differentiation and experimentation. Traditional gongs and cymbals are predominantly produced with a circular boundary. There are rare exceptions such as the Rocktagon cymbal series by Sabian, which has an octagon linear outer boundary or the linear cymbal by Wuhan which has a pentagon-shaped boundary. Another somewhat more popular recent trend is the presence of off-center holes in circular cymbals [39].

Expanding on the notion of guided experimentation in cymbal design, in this paper we document the construction of a prototype version of a stadium-shaped cymbal. The reason for this is based on the dynamic properties of that geometric shape, which is known to exhibit deterministic chaos under reflection [7, 12]. From a practical perspective, this form of chaos refers to the speed of divergence of localized energy on the cymbal surface. Energy does not remain localized, which leads to a kind of diffusion outcome. Hence a cymbal of this kind should exhibit a sharper drop-off than other shapes, making it a possible candidate for a splash or effect type cymbal.

2. RELATED WORK

Most closely related recent work investigates personal fabrication of ideophones. Umetani et al. discuss the design of bar percussion instruments with custom shapes [46]. This approach uses FEM-based spectral modeling to predict the sound of cut shapes of planar plate segments. The fabrication technique is based on wire electrical discharge ma-

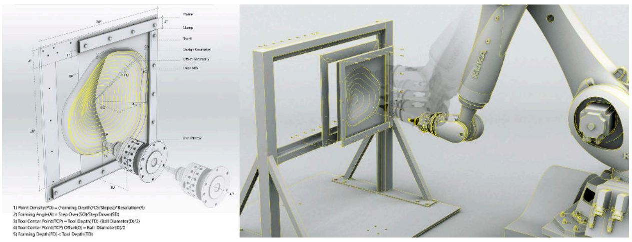


Figure 2: Diagram of Single Point Incremental Forming (SPIF) robotic setup.

chining. This approach was expanded to include aspects of impact and support as well as surfaces of revolution [8] using water jet cutting for flat structures and 3D printing for the surfaces of revolution. Custom construction of bells from simulation modeling was proposed using 3D printing for creating a positive that then is used to create a mold shape for a traditional molten tin bell casting process [23].

Our work uses a novel fabrication technique and a class of instruments with different geometries. Cymbals tend to be shallow-domed shell structures as opposed to severely domed structures like bells. Furthermore, rather than emphasizing modal properties, we are interested in non-modal properties of ideophones.

More broadly, personal fabrication has been used in a wider range of instrument designs. 3D printing is the dominant form [6, 32, 36, 37, 47, 50] of fabrication in most cases. There has also been substantial interest in using fabrics for making instruments [22, 49].

Our work uses a fabrication robot arm. While very different in purpose, these kinds of robot arms have been proposed to be used as musical performers [43]. This work is in line with longstanding efforts to explore robotics as the basis for musical performance [10, 11, 28]. Specifically, robots have been extensively explored in the context of percussive performance [5, 33, 40].

In this paper we will leverage simulation methods to justify our choice of prototype shape. We employ wave propagation modeling. Wave propagation underlies all waveguide synthesis techniques [42] and has been expanded to two-dimensional domains [18].

The dynamics of shells has been extensively studied for decades [2]. Recent progress improved our understanding of non-linear aspects of shell vibration. Geometry and boundary conditions as well as material imperfections are all sources of non-linear effects in shell vibrations [2]. Vibrations and associated non-linear effects are a desirable consequence in the construction of cymbals and gongs [14]. The study of harmonic forcing on circular plates with and without imperfections showed transitions into chaotic regimes [45]. This is particularly relevant as circular boundaries are classically known to be integrable [7] and therefore are not chaotic. The geometric deformation of a shell itself leads to non-linear effects [44]. Non-linearities can also arise as a consequence of friction-based interaction such as dry-friction [19]. The detailed understanding and modeling vibrations of shells further leads to potential applications for sound synthesis [9], graphical simulation [13] and structural control [21].

2.1 Incremental Robotic Sheet Forming

Incremental sheet forming (ISF) is a fabrication process that involves turning flat sheets of metal into three dimensional shapes using a CNC machine [30]. In this process, the stock is locally stretched using a custom tool running along a pre-programmed toolpath. The forming stylus could be mounted on any CNC machine with enough strength to overcome thin gauge metal forming forces. However, mounting it as an end-effector on an industrial robotic arm allows for more degrees of freedom, and a more versatile workflow.

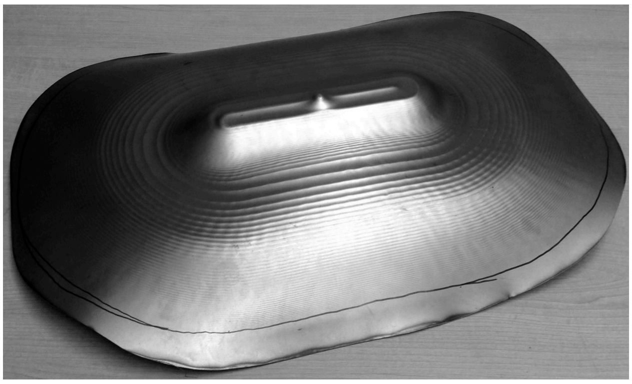


Figure 3: Stadium-shaped cymbal produced by incremental robotic sheet forming.

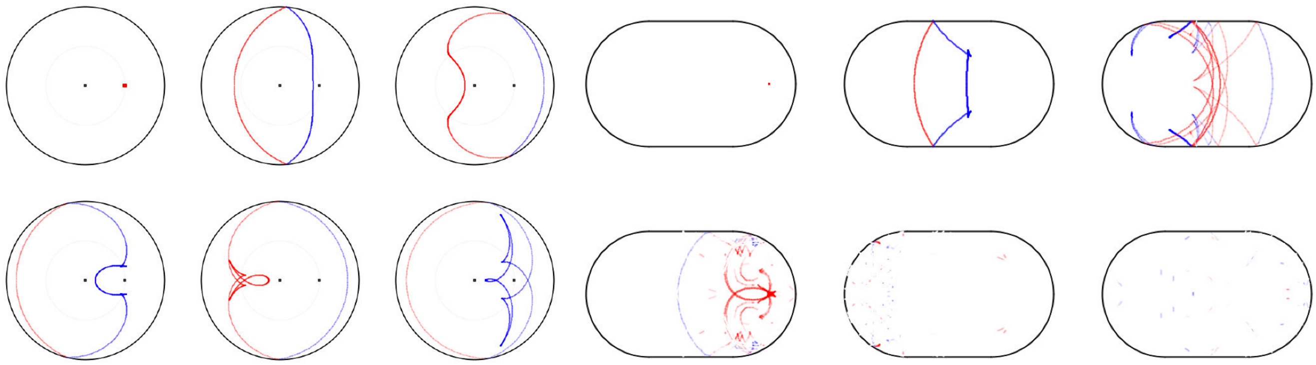
The advantage of using ISF as a fabrication method is its lack of reliance on dies or molds, which makes it more cost effective for prototyping and provides a more readily customizable workflow. Conventional forming processes such as hydraulic pressing or stamping require costly positive and negative molds, which are also time consuming to produce. While forming the same part in high volume batches is efficient, adding any variation to the stamped part requires redesigning the molds. Hence, employing ISF as a fabrication method allows quick and cost effective prototyping of custom and highly-varied designs. This in turn makes this fabrication approach particularly attractive as a candidate for individual and eventually personal fabrication.

Single Point Incremental Forming (SPIF) refers to a forming process relying on only one forming tool, while Dual Sided Incremental Forming (DSIF) employs two forming tools, one on each side of the material stock. There are a few variations on these methods which involve partial dies, or local support tools. These forming methods have been in development since the early 1990's and have been continuously refined mechanically and computationally [3]. The advantage of using DSIF over SPIF is in the accuracy of the final formed parts since the metal is pinched from both sides during the course of the forming process [34]. However, DSIF requires synced motion coordination between the two robotic tools and involves some issues like loss of contact of the one of the forming tools, a problem which is being studied by various research groups [41].

ISF poses a number of challenges that including accuracy in forming, the response of the material to forming and cutting, and the variation induced by toolpathing. This work employs single point incremental forming (see Figure 2 for a schematic reflecting our setup). This approach requires less space but sacrifices local pressure accuracy. Given that space is likely an important concern in a personal fabrication setup, the single sided approach is likely to be favorable.

Incremental sheet forming has been explored in a wide range of applications in industries requiring specific metal formed sheets with desirable dynamic properties, such as car and aircraft manufacturers [48]. Thin metallic shell structures also have applications in architecture [26].

The desired outcome for musical instruments is specific sustained oscillatory and other sounding phenomena, unlike most industrial application, where oscillations are undesirable and hence need to be controlled or suppressed [38].



(a) Circular Domain

(b) Stadium Domain

Figure 4: Wave front propagation of identical point excitation on a circular domain and stadium. Orders of reflection from zero to 5 from left to right, top to bottom.

3. ROBOTIC FABRICATION OF CYMBALS

In order to establish the feasibility of the proposed approach, we conducted a preliminary study forming flat structures with robotics incremental sheet metal forming. It showed promise with regard to the speed and efficiency of producing working prototypes, as well as customizing the fabrication workflow.

The process starts with digital, three-dimensional models of the desired forms. These models are drawn in readily available CAD software such as McNeel Rhino. Once the modeling has been completed, the model is then processed by a custom toolpath generating script, which will inform the way in which these parts are formed. Forming tools mounted on the robotic arms follow the toolpaths extracted from the geometry. The forming passes depths, stepovers, and other important driving factors can be parametrically tweaked to fine tune the forming process. The time it takes to form a single panel varies depends on how fine or coarse the described toolpath is, which ultimately also affects the surface finish and appearance. The work also largely builds on previous efforts that focus on computer modeling methods, parametric toolpath generation, forming practices, material testing, part validation, and aggregation strategies [27]. Several materials were tested to find the limitations of the forming process and for viability. The sampling of sheet metal included cold rolled steel, aluminum, copper, and brass. Cold rolled steel was used in most of the forming tests because of its high ductility and strength, which allowed for forming deeper parts.

To work with the issues that arise from single point incremental forming, additional toolpaths and geometric modifications were tested. Initially, the same toolpath was run multiple times on the same part, a strategy that has been proven to increase forming accuracy and help to reduce the maximum deviations up to $-0.5\,\mathrm{mm}$ [35]. This increased the accuracy of the part everywhere except for the perimeter, because this region was drawn past the desired depth. Modifications to the position of the part proved to increase accuracy of the edges. Adding geometric 'skirts' to the parts' edges stiffens the geometry and provides a deeper forming condition, hence reducing the overall deviation at the edge [29].

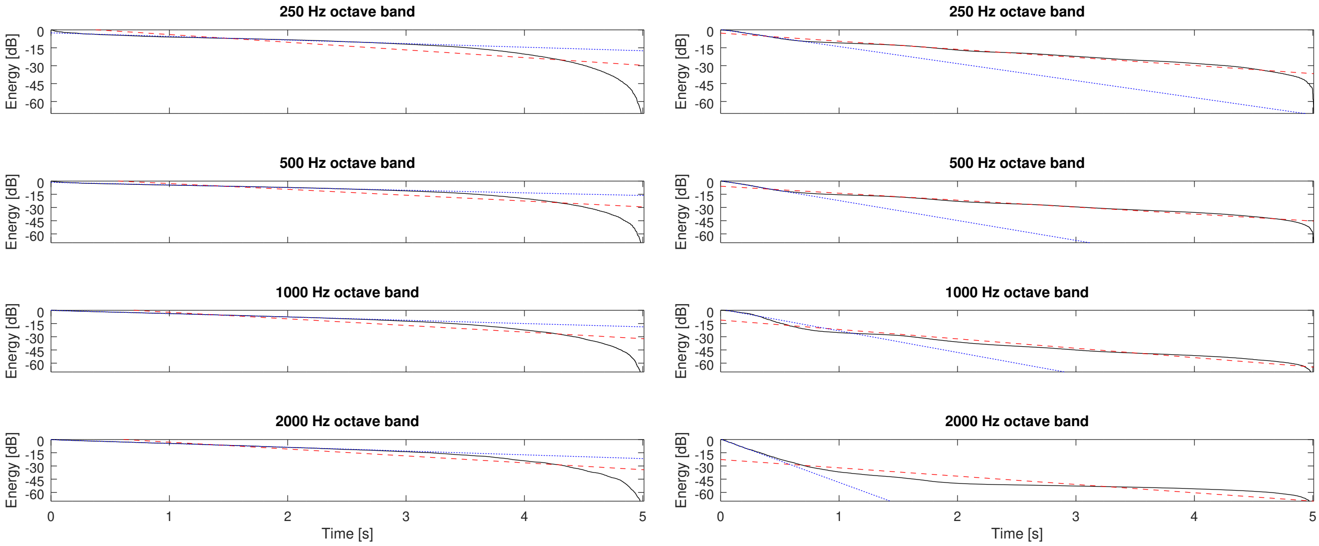
Once the study prototype was formed, its was trimmed out of the forming panel to the desired dimensions. Since this forming process induces a lot of stress in the material, trimming it releases some of that stress causing the material to deform, or springback. To combat that deformation, a sample part was placed in a kiln to anneal the metal and redistribute its molecules prior to trimming it. The preliminary results show promise as the annealed sample was trimmed and exhibited minimal deformation.

Results as such were validated using a handheld laser scanner, which was used to scan the material before and after trimming, and then comparing the two models. Digitally scanning prototypes also helped in identifying any major deviations from the computer model caused by inaccuracies in the forming process. The model produced by the scanning process is then used for additional processes after the primary forming for the next prototype. It accurately locates where detailed passes should be positioned. The model is also measured at the edge of the designed part to verify and reconstruct a toolpath for cutting the material from the stock sheet. The resulting prototype cymbal can be seen in Figure 3. The finished prototype cymbal is 55.5 cm long, 44 cm wide and has a shell height of 7.5 cm.

4. WHY A STADIUM CYMBAL?

We picked the stadium shape for our prototype specimen because it has unusual geometric properties. Traditional cymbals are characterized by non-linear effects that are related to geometric deformation and material thickness variation [2, 14, 20, 31]. While some degree of shape variation is present in cymbals, virtually all existing cymbals are either circular or exhibit circular symmetries. Examples are square, pentagon or octagon shapes, which are all symmetric under different angular rotations. It is well-established that the choice of boundary can have different consequences for wave phenomena on the interior. Circular and rectangular shapes are examples of a regular dynamical system where every traveling wave will close onto itself in closed periodic orbits. The resulting standing waves result in easily classified eigen-shapes: sums of sinusoids for rectangles, and sums of Bessel-functions for circles. It has been shown that ellipses are also regular in this sense and their eigen-shapes are Mathieu-functions [1]. They all have fixed spectra.

Due to their additional shell shape, cymbals already provide variation on this regular spectral behavior. The idea here is to provide a second source of chaos through boundary geometry. Bunimovich showed that Stadium-shaped boundaries do not only allow periodic orbits but also exhibit other kinds of orbits. Even initial paths that are close together will be geometrically dispersed quickly under reflection [7, 12]. In our case, we expect a stadium-shaped cymbal to more rapidly diffuse excitation energy than would a regular cymbal. Hence this will lead to a harsher tail sound suitable for a splash or effect style cymbal.



(a) Circle Domain

(b) Stadium Domain.

Figure 5: Comparison of frequency-band integrated intensity (black) reverberation time (RT) (red) and early decay time (EDT) (blue) between recordings of drumstick strikes on circle and stadium-shaped cymbals.

4.1 Wave Front Dynamics of Circular and Stadium Boundaries

To illustrate this geometric diffusion effect we follow the geometric wavefront modeling approach [17] to render repeat reflection of an initial local impact (such as a drum-stick strike) on two domain shapes: the circle and the stadium.

This methodology uses a ray-casting approach along with traveling distance information to compute the first arrival times of wave fronts. Connecting neighboring rays gives a local approximation of the wave front shape. In this simulation, additional functional content such as wake structures are neglected (see [18] for a treatment including wake information). Also shell deformations are also neglected in this rendering. The purpose of the simulation is to explain the effect of boundary effects on wave dynamics. This method is attractive for numerical simulation because it can be shown that the ray picture models critical structures of the solution such as the formation of sharp edges (singularities) in a robust fashion [16]. Furthermore, and critical for our purposes, chaos induced by boundaries are classically studied as billiard problems [12] which directly correspond to the ray casting and reflections modeled in this approach. In this sense ray-based wave front evolution methods for the wave equation can be considered to be *structure-preserving* with respect to the geometry of the wave front set, which is a desirable property for showing the decay of local energy.

Figures 4a and 4b show simulations of wave front propagation on circular and stadium domains. The traveled distance along the horizontal axis of symmetry is identical in both simulations. Color intensity reflects the distance between neighboring rays of the underlying billiard ray simulation. High intensity reflects closeness, while low or vanishing intensity reflects large distance between neighboring rays. Observe that the intensity of energy on a circular domain remains localized. The color of the wave front is strong through all five reflections. For the stadium domain however neighboring rays diverge quickly. Only after 4 reflection much of the local energy on the wave front is no longer locally focused. Both of these behaviors are well understood. The circle maintains local energy for reasons directly related to the whispering gallery effect [15]. Stadiums diffuse local energy because they exhibit deterministic chaos, which is characterized by the rapid increase of distance between initially close rays [7].

5. DECAY TIME MEASUREMENTS

In order to be able to compare the fabricated cymbal to our estimated decay behavior from simulation, we recorded strikes at the simulated strike position of Figure 4 on the stadium cymbal as well as a Sabian SBR1811 18 inch cymbal. This cymbal was chosen as its radius is close to the radial part of the stadium cymbal. We used an SX 2B drumstick to produce sensible impact conditions.

We used University of Surrey's IoSR Matlab Toolbox irStats Matlab function [24] for computing and plotting *reverberation time* (RT) defined as the decay timeto -60 dB and *early decay time* (EDT) using a method based on the ISO 3382-1:2009 standard [25]. We used GNU Octave for computing and rendering the figures[1]. While the standard is targeting room acoustic studies, the general approach is useful for any exponentially decaying sound in response to impulsive excitations.

Figures 5a and 5b show the decay curves as well as the linear decay estimates RT and EDT of the circular and stadium cymbals respectively. Computation of EDT and RT are closely related. RT computes the decay time until the original impact energy decayed to -60 dB. EDT does the same but only using the intial -5 dB drop. Hence EDT will estimate early energy drops, while RT is a good long-term decay descriptor. As decay can differ across frequencies we computed decay times over four frequency bands: 250, 500, 1000, and 2000 Hz.

For the circle (Figure 5a) we see that RT and EDT are very similar. However, for the stadium (Figure 5b) we see that RT and EDT substantially differ across all frequency bands. Numerically, the EDT of the circular domain range from 20.013 s in the 250 Hz band to 13.964 s in the 2000 Hz band. By comparison the stadium domain has an EDT of just 4.2113 s in the 250 Hz band which drops to 1.22 s in the 2000 Hz band. Interestingly RTs are rather comparable between the two domain shapes. RT for the circular

[1] `https://www.gnu.org/software/octave/`

cymbal in the 250 Hz and 2000 Hz bands are 9.3302 s and 7.6719 s. For the stadium cymbal in the same bands we get RTs of 8.8509 s and 6.3601 s. A possible explanation for this behavior is that in the general circular and long-term stadium cymbal, internal friction and radiation dissipation dominate, whereas the early decay for the stadium is dominated by the dissipation induced by the divergence of wave-front under early reflections which fits our hypothesis outlined in Section 4.1. A second round of recordings and computations was performed and showed the comparable qualitative differences between the cymbals with respect to decay time.

6. CONCLUSION AND FUTURE WORK

In this paper we presented a proof-of-concept fabrication of a stadium-shaped cymbal using incremental robotic sheet forming. This fabrication technique provides yet another way to fabricate prototypes or individual new instruments that complement other methods such as 3D printing. This is but a first step in the direction of making this approach viable for personal fabrication.

We picked a prototype shape on theorized dynamical decay properties and found evidence in measurements of the resulting fabricated cymbal that these properties appear. It is however important to note that this technique is flexible and can produce a wide range of not only cymbals but a range of instruments which contain deformed metals. With advances in miniaturized robotic arms this approach may offer a pathway for personal fabrication of deformed plate ideophones.

Much here is in its infancy. Optimization in toolpath tracing, advances in material that prevent stress buckling, and improvement in annealing are all important current research topics in advancing incremental robotic sheet forming. In this work we have used wave propagation simulation to hypothesize certain dynamic properties relating to chaos. However, full simulation and full predictive power will require further advances in simulation techniques.

Overall we believe that incremental robotic sheet forming is a promising candidate for individual fabrication of musical instruments.

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