MENDING BELLS AND CLOSING BELFRIES WITH FAUST

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ABSTRACT

Finite Element Analyses (FEA) was used to predict the resonant modes of the Tsar Kolokol, a 200 ton fractured bell that sits outside the Kremlin in Moscow. Frequency and displacement data informed a physical model implemented in the Faust programming language (Functional Audio Stream). The authors hosted a concert for Tsar bell and Carillon with the generous support of Meyer Sound and a University of Michigan bicentennial grant. In the concert, the simulated Tsar bell was triggered by the keyboard and perceptually fused with the bourdon of the Baird Carillon on the University of Michigan campus in Ann Arbor.

1. INTRODUCTION

In 1735 Empress Anna Ivanovna commissioned the giant Tsar Kolokol bell. The bell was cast in an excavated pit then raised into scaffolding for the cooling and engraving process. When the supporting wooden structure caught fire, the bell was doused with water causing the metal to crack. An eleven ton section parted from the sound bow and the bell plummeted back into its pit. A century later, the broken bell was raised to ground level where it now lays silent in front of the Kremlin. Having never rung, the bell persists as a prominent icon of imagined sound.

In 2015, Greg Niemeyer at UC Berkeley gathered a team to re-synthesize the Tsar bell through modern simulation methods and invited composers to write pieces for this virtual Tsar bell and Carillon. This research gave rise to a concert and symposium at UC Berkeley in April, 2016 where researchers, performers and composers discussed the challenges of the endeavor. In this paper we report on the process of analyzing the bell using data from Solidworks proprietary simulation [1], re-synthesizing the bell with the Faust programming language [3], as well integrating our re-synthesis into the Baird Carillon in Ann Arbor.

2. CASTING THE MESH

Solidworks Professional CAD software was used to both draw the bell (a swept extrusion around its profile) as well as conduct the simulation of its modal frequencies . The first step was to create a mesh corresponding to the dimensions of the bell. The bell's profile was drawn from reported dimensions in the literature, and traces from existing photographs. The fracture itself is revealing in this regard as it exposes the cross section from the sound bow to just above the bead line. Figure 2 shows the profile we used with the relative thickness variations between the inner and outer surface.

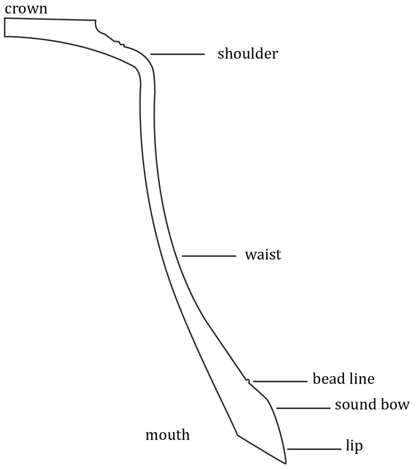


Figure 1: *Tsar Kolokol profile.*

Once drawn, the profile was swept as an extrusion around the z axis to create a symmetrical solid model (Figure 2). Bronze, the principle metal used in the bell, was selected from the materials list in the software to set the physical properties that are critical to effective analyses such as Young's modulus (100 GPa), Poisson's ratio (0.34) and density (8000 kgm^3).

FEA reduces the partial differential equation required to calculate wave propagation through materials into smaller tractable sub-elements and then combines these elements for a global approximation of the solution. Although efficient on modern processors, the simulation can still take hours depending on the size of the mesh, the geometrical complexity of the object and computational resources. Solidworks automates the mesh preparation where a balance is desired between resolution of the geometrical features and uniformity of constituent triangles. The simulation for the Tsar Bell mesh took approximately 2 hours on an Intel Core i7-7700 4.2 GHz processor accessed in the CAEN cluster in the School of Engineering at the University of Michigan.

Although there are software suites more suited to near field acoustics, Solidworks was available to us and produced reasonable

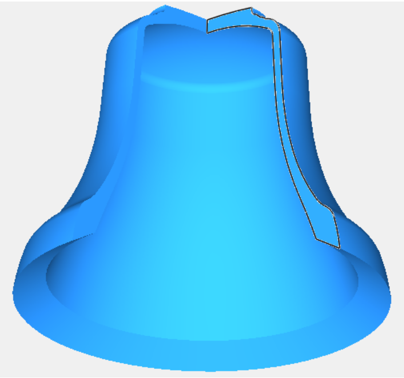


Figure 2: *Tsar Kolokol profile swept around the z axis.*

results with an estimated fundamental frequency of 43 HZ. Due to the size of the Tsar Bell combined with bandwidth limitations of the analyses in Solidworks (limited to 1000 modes), our results did not contain partials over 10,000 HZ.

Another limitation is that FEA does not give us the critical decay rates of the modes (T60s). Therefore, we predicted the prominent modes by observing the variation in mass displacement amplitudes; the modes from the analyses that exhibited prominent mass displacements were selected for modal re-synthesis[2]. Mode doublets were retained and contributed to wobbling and beating within the bell's sound. This FEA analyses via Solidworks simulation was conducted before the recent development of the *mesh2faust* tool that provides a workflow from FEA to FAUST using meshes from open source softwares such as openScad [4], [5]. Comparisons have not yet been made between the present work and the results we would get from *mesh2faust*, a clear next step in this research.

3. FAUST IMPLEMENTATION

Using Romain Michon's Modal Bar STK [6], Chris Chafe implemented a bank of biquad filters in Faust tuned to 50 of the most prominent partials from our simulation. The parameters of the biquad filter used for this task were formatted to control its center frequency (`resonance`) and its damping (`radius`) such as:

```
bandPassH(resonance,radius) = fi.TF2(b0,b1,
    b2,a1,a2)
with {
  a2 = pow(radius,2);
  a1 =
    -2*radius*cos(ma.PI*2*resonance/ma.SR);
  b0 = 1; b1 = 0; b2 = 0;
};
```

In the implementation the Tsar bell model is excited by a white noise generator with a sharp envelope which is triggered when the input of the system exceeds a certain threshold:

```
  process = an.amp_follower_ar(attDur,
      attDur)>triggerThresh : no.noise*en.ar
      (0.005,0.02) : *(gain) <:
((biquadBankX, biquadBankZ):>_),
((biquadBankY, biquadBankZ1):>_),
((biquadBankZ, biquadBankX1):>_)
;
```

The input to the the model was an audio signal sensed through a transducer attached to the bar of the 300kg clapper on the bourdon of the Baird Carillon. From this highly damped clapper bar we could detect a very short acoustic impulse synchronous with the attack of the bell, yet without sustained vibrations that would produce multiple triggers and false positives (i.e., as would be the case if we attached the transducer to the bell itself).

4. A CONCERT FOR THE CHARLES BAIRD CARILLON AND TSAR BELL

A concert was organized with the support of a Michigan Bicentennial Grant and the generous donation of full-range opera house speakers from Meyer Sound (Figure 3).

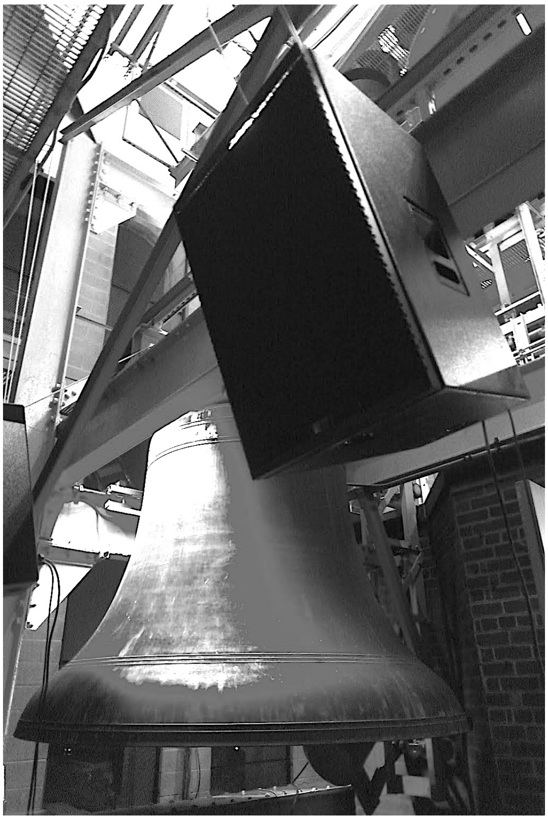
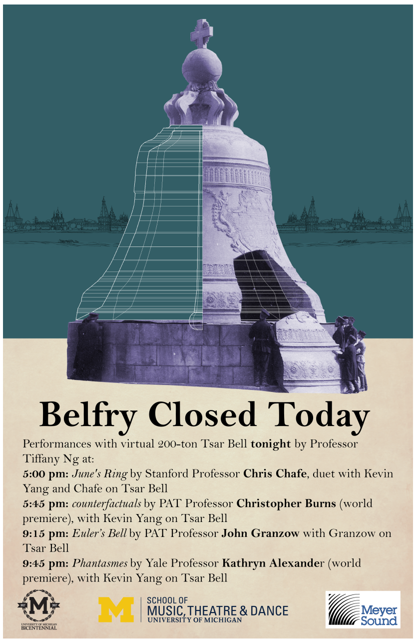


Figure 3: *Meyer full range speaker and bell*

Four new pieces were composed and played for our concert in conjunction with the Michigan Hailstorm which was the culmination of the bicentennial fall festival on Ingalls Mall in Ann Arbor. The pieces were performed by professor of Carillon Tiffany Ng. For Chris Chafe's piece, *June's Ring*, Kevin Yang played the second part.

The program included two world premieres: Christopher Burns' *Counterfactuals* and Kathy Alexander's *Phantasmes*. In all the works, the FAUST model of the Tsar bell was triggered by high amplitude transients in the clapper bar of the Baird bell, sensed through an attached transducer. In this configuration the two lowest bells (the natural bourdon of the instrument and the Tsar bell re-synthesis) always played synchronously and the attack of the real bell metal bonded aurally to the low modes of its coded counterpart. This hybrid bell allowed for the simulated spectra to be fully integrated into the existing keyboard of the carillon.

Our poster for the event used the graphic design of Greg Niemeyer initially created for the first concert in Berkeley yet this time with the addition of the injunction, *Belfry Closed*, to evoke the issues of political subterfuge associated with the 2016 presidential election and the possibly of international meddling (Figure 4).


Belfry Closed Today

Performances with virtual 200-ton Tsar Bell **tonight** by Professor Tiffany Ng at:

5:00 pm: *June's Ring* by Stanford Professor **Chris Chafe**, duet with Kevin Yang and Chafe on Tsar Bell

5:45 pm: *counterfactuals* by PAT Professor **Christopher Burns** (world premiere), with Kevin Yang on Tsar Bell

9:15 pm: *Euler's Bell* by PAT Professor **John Granzow** with Granzow on Tsar Bell

9:45 pm: *Phantasmes* by Yale Professor **Kathryn Alexander** (world premiere), with Kevin Yang on Tsar Bell

Figure 4: *poster.*

Although our interest in the Tsar bell may arise from an apolitical curiosity about its acoustics, the attempt to resuscitate an object of such historical import must provoke the question: why would we endeavor to simulate this symbol of imperial power and project it from our campus tower? With the present political climate in mind, two pieces deal directly with the erosion of the public good. *Euler's Bell* references the historical pillaging of belfries in times of conflict and relates this to the present depletion of arts funding. The program note reads:

> As history tells, bells were shattered in their belfries for easy transport to military furnaces during times of war. If the bell withstands the concussion, it may rebound and spin on its mouth's edge wobbling like an Euler's Disk, a physics toy used to investigate this type of oscillation. Composer John Granzow's "Euler's Bell" integrates the sound of such a bell wobbling and forestalling, if briefly, this perennial transfer of metals from music to munitions.

Chris Burns' piece, *Counterfactuals* addresses our endeavor of simulating such a bell in this particular media climate of rampant simulacra. Burns' note on the score captures the intersection between the products of foundries and those of forgeries and the necessary errors that must accumulate in our simulation:

> In 1737, the mammoth Tsar Bell, created as an expression and symbol of Russian state and industrial power, was irreparably damaged in a fire before it was ever rung. While we now have the digital tools available to create virtual models of the bell's acoustics, our reconstructions necessarily involve speculation and imagination. In 2017, lies and falsehoods are a prominent part of our political discourse, often disseminated via data-driven digital advertising and social media. We are confronted with urgent questions about truth and falsehood, fact and fiction, journalism and propaganda.
>
> *Counterfactuals* pairs an imagined digital reconstruction of the Tsar Bell with a real, acoustic carillon in order to invite reflection about truth and falsehood in our present moment. The piece proposes a chain of musical "what-if" scenarios: melodies and textures are proposed, then repeated in dramatically different contexts. Contrapuntal layers proceed in independent tempi, unable to reconcile to a common pulse. Repeating patterns prove unstable, breaking and evolving into unfamiliar forms. The real and the virtual entangle, and fictions abound.

5. CONCLUSIONS

FEA was used to predict the prominent modes of the Tsar Kolokol bell. The predicted partials were used for Modal synthesis in FAUST and a trigger function was used to integrate the model into the Baird Carillon. A concert was held featuring new works for Carillon and electronics where composers grappled with both acoustical and political resonances of this project.

6. ACKNOWLEDGMENTS

Many thanks to Meyer Sound and the Michigan Bicentennial Committee.

7. REFERENCES

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[3] Yann Orlarey, Stéphane Letz, and Dominique Fober, *New Computational Paradigms for Computer Music*, chapter "Faust: an Efficient Functional Approach to DSP Programming", Delatour, Paris, France, 2009.

[4] Romain Michon, Sara Martin, and Julius O. Smith, "Mesh2faust: a modal physical model generator for the faust programming language application to bell modeling," in *Proceedings of the International Computer Music Conference (ICMC-17)*, Shanghai, China, October 2017.

[5] OpenScad, (accessed March 29, 2018), `http://www.openscad.org/`.

[6] Romain Michon, "The faust synthesis toolkit: A set of linear and nonlinear physical models for the faust programming language," *Journal of the Acoustical Society of America*, vol. 134, no. 5, 2013.