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Original article

The sound of bronze: Virtual resurrection of a broken medieval bell

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ABSTRACT

The bell from the church of S. Pedro de Coruche is one rare surviving example of early bells, cast during the 13th century in Europe, which was exhumed from a crypt-ossuary in an archaeological excavation carried out near Lisbon in Portugal. Of particular significance, it is believed to belong to a time period during which bell's profile has evolved noticeably, leading to bells with fine musical qualities and a well-defined sense of pitch. If the bell from Coruche was a tangible piece of evidence for tracing the history of bell casting in Europe, it had however lost all trace of its original sound: indeed the bell was found broken and incomplete and even if it has undergone a restoration process since the archaeological discovery, the use of an adhesive during the reassembly has changed somehow the vibrational properties of the bell structure. To bring back to life the sound of this broken musical artefact, a methodology combining experimental and numerical techniques from materials science and music acoustics is described in this paper. The general approach comprises material characterisation, geometrical measurements, modal analysis and physics-based sound synthesis techniques. By coupling a physical dynamical model of a bell impacted by a clapper with the modal properties of the original bell computed by Finite Element Analysis, realistic time-domain simulations of the Coruche bell dynamics were performed and realistic synthetic sounds were produced. As the original clapper has not survived, parametric computations have been performed to illustrate the changes in bell sounds associated with clappers of different mechanical properties. The overall approach provides insight into the tuning of this medieval bell which can be compared to the modern-type tuning, and reproduce the sound that the bell from Coruche might have had. The strategy developed can be easily adapted to other musical instruments in poor/variable states of preservation, therefore benefiting the importance of such non-renewable cultural resources.

1. Research aims

As a rare example of early bells cast prior to the introduction of bell tuning techniques, the bell from the church of S. Pedro de Coruche is a valuable historical heritage object which deserves special scientific attention from archeologists and conservators. Discovered fragmented and incomplete, the bell has been partially reassembled, thus restoring its morphological aspect, but the use of an adhesive during the restoration process combined with the loss of a fragment of the original bell have eliminated any trace of its original sound. However, restoring its sound qualities is possible by exploiting the theoretical models and experimental methods used to investigate the acoustics of musical instruments. The main aim of the present work is then to bring back to life the sound of the bell from Coruche, by developing an instrumental strategy to assess the acoustical properties of bells that are no longer in condition to be played. The "virtual resurrection" is achieved through physical modelling sound synthesis techniques, guided by acoustical considerations based on measurements and simulations, as well as using the actual bronze material properties identified from elemental analysis and microstructural examinations.

2. Introduction

Musical instruments are fascinating objects which are an important part of every culture. They relate history, culture, art and science, and through the music they are intended to play, they embody spiritual values of cultural heritage. According to time and

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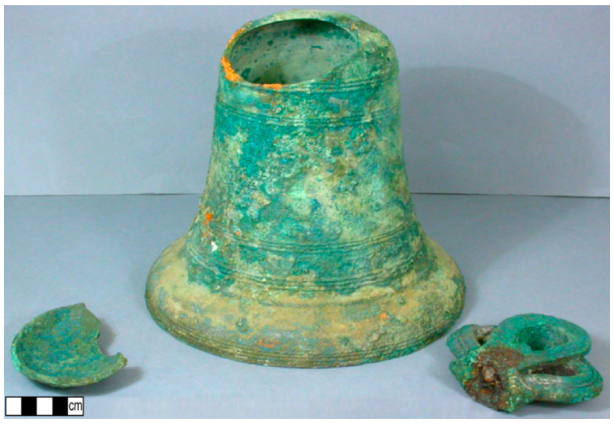

Fig. 1. The bell from the church of S. Pedro de Coruche, Portugal.

space, they have taken many forms and through the creative efforts of gifted crafters, primitive instruments became competent musical objects fulfilling cultural criteria for music performance.

Although bronze bells with remarkable musical qualities have been cast in China some 3000 years ago, it is only during the 17th century that the art of bell funding had reached its peak in Europe when the Hemony brothers successfully designed and cast the first precisely-tuned carrillon [1]. Improving on the basic search to relate simply the bell profile and the sounding frequencies, the Hemony brothers, with the collaboration of Jacob Van Eyck, discovered how to correctly shape the profile of bells so that the ratios of their vibrational frequencies fall into musical relationships. Besides giving strong tonal characteristics to their bells, this tuning notably enhanced their musical pitch so that both melodies and chords could be played from an ensemble of bells. Nevertheless, the so-called traditional *minor-third* bell has not emerged overnight and it is thought that the first experiments in bell casting in Europe go back to the 4th century. At that time, bells were certainly not intended to play polyphonic music. Instead, they were used to regulate the daily activities or to celebrate rituals for which the tuning qualities and musicality of bells were not of prime importance. Starting from the 12th century, a transition towards the design of new bells has occurred and the evolution of the bell's profile from conical to the actual curved shape has gradually provided bells with pleasant sounding characteristics [2].

Dated 1287, the bell from the church of S. Pedro de Coruche (Fig. 1) is therefore a rare surviving example of early bells belonging to that transition period. Of particular significance, it is the oldest recognised bell in Portugal and as such, its archaeological discovery in 2001 has raised many questions regarding the art of bell casting in the Iberian Peninsula. A first study focusing on historical and social aspects has been carried out by Sebastian [3] but while it also discusses aesthetical features of the bell, no information has been reported regarding its sound. The main reason for this comes from the poor state of preservation of the bell which was discovered broken and incomplete. Even if it has been reassembled since, a fragment of about 75 mm^2 is still missing near the head and the use of an adhesive during the reassembly process has modified somewhat the stiffness and damping properties of the overall structure, therefore preventing any reliable trace of its original sound.

To investigate the Coruche bell's acoustics, it is now possible to exploit the advances in computational modelling and simulations of musical instruments which have nowadays, in many respects, reached maturity. Crucial information about the important vibrational modes of the instrument components can be obtained from powerful computations and experimental techniques, while reliable and fast sound synthesis methods, based on the dynamical differential equations of the system, can be implemented for generating synthetic sounds. To revive the sound of the bell from Coruche, two common techniques of music acoustics are considered in this work:

- the Finite Elements Method (FEM) for assessing the vibrational properties of the bell structure;
- a modal synthesis technique which uses the FEM-computed modal data as inputs of the computational model for reproducing the bell's sound.

Even if this methodology appears straightforward and physically correct, the sound computed however crucially depends on the mechanical properties of the bell material, i.e. the Young's modulus, Poisson's ratio and density, which control the wave propagation within the structure. Knowing that bronze composition has changed over time, an elemental and microstructural analysis of the bell bronze material has also been performed in order to calculate and identify its mechanical properties, and thus bring back to life the original voice of this medieval bell as close as possible.

In this paper, the complete methodology developed to address the acoustical features of the bell from Coruche is described. As far as we know, such a multidisciplinary approach has never been attempted, at least for historical bells, and the method can be easily adapted to study other bells in a poor state of conservation, therefore contributing to the preservation of valuable cultural heritage. Of particular interest, the synthesis method, which is based on physical modelling techniques, allows many computations to be performed by simple changes of the model parameters. This study particularly benefits from this convenient feature of the computational approach, as it offers a way to counteract the unknown mechanical properties of the original clapper by performing parametric computations, therefore providing an overview of plausible sounds for this broken Medieval bell.

3. Material study of the Coruche bell

3.1. Background on bell material

Although there are examples of bells cast in different metals such as copper or iron, bells have been mostly produced in bronze (Cu-Sn alloy), to which superior sonorous qualities are generally attributed [4]. The bronze alloy used to cast a bell definitively influenced its acoustic features, its external appearance and durability. Compared to iron, bronze has a longer durability, especially when exposed to external atmospheric conditions. Compared to pure copper, the addition of tin allows an increase in hardness, preventing a deformation of the bell by the clamp which in turn would influence the tone. However, a compromise on the tin amount in the alloy had to be made, otherwise too much tin would turn the alloy too brittle, and thus easily breakable during striking. With respect to the sound, it has been found that by rising the tin content an increase in sound duration would be obtained, however, other elements that were commonly present in the alloy, such as lead, that was known to improve fluidity and thus casting properties, would produce a decrease in the sound duration [5]. Taking into account an optimum balance of the Cu-Sn alloy properties used to produce bells, a general bell bronze composition was early set up in the range of 20–25 wt.%Sn. Commonly described as four parts of copper to one of tin or three parts of copper to one of tin, the bell metal recipe can even be found in Theophilus's twelve-century treatise on bell casting. Nevertheless, analysis of bells from the Middle Ages until recent times have shown that Medieval bells did frequently have lower amounts of Sn (in the order of 10–15 wt.%Sn) and that Pb was frequently present in contents from 1 to 3 wt.% [4]. Due to