Surrogate Modelling Based Optimization In Horology

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Abstract

This paper focuses on the acoustic modeling and simulation of a simplified minute repeater watch using the Boundary Element Method (BEM). The overarching objective is to optimize the hammer's impact location on the watch's gong (timbre) to enhance both the radiated acoustic intensity and the spectral content of the sound, while also addressing the computational efficiency of the simulations.

The minute repeater is a horological complication designed to chime the time on demand, similar in principle to grandfather clocks. Its acoustic signature is a key quality attribute, and optimizing its sound production process is critical for user satisfaction and product differentiation. Due to the complexity of acoustic propagation in small mechanical structures and the need for high-fidelity simulations, numerical modeling is used extensively in this study.

Initially, a detailed theoretical comparison between Finite Element Method (FEM) and Boundary Element Method (BEM) is conducted. FEM, commonly used for structural analysis, requires meshing both the solid and the surrounding air volume, which results in a high computational burden. BEM, in contrast, only requires meshing the boundaries, significantly reducing memory and time requirements in acoustics, especially in unbounded domains. A comparative study reveals that BEM provides similar acoustic results to FEM but with substantial savings in computation time and resources.

The core of the study lies in the parametric modeling of the hammer-gong interaction using COMSOL Multiphysics. A simplified 2D model of the mechanism is developed to reduce complexity and facilitate debugging. The mechanical domain is modeled using multi-body dynamics, including pivot joints and contact interactions, while the acoustic domain is treated using Helmholtz-based BEM. A weak one-way coupling is employed, wherein mechanical vibrations of the gong drive the acoustic radiation into the surrounding air.

To enable efficient optimization, surrogate models are introduced. These data-driven models approximate the behavior of the full BEM simulation, significantly reducing computation time during optimization. Parameters such as hammer impact velocity and angular position are varied systematically to generate training data for the surrogate model. Once trained, the surrogate enables rapid exploration of the design space, identifying hammer positions that yield optimal acoustic intensity and tonal quality.

The study concludes that BEM, combined with surrogate modeling, offers a powerful framework for the acoustic optimization of minute repeaters. While the simplified model and assumptions (e.g., absence of spring dynamics) limit direct application to commercial products, the methodology lays a solid foundation for more advanced modeling and optimization workflows in horological acoustics.

Reference

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Figures used in the abstract

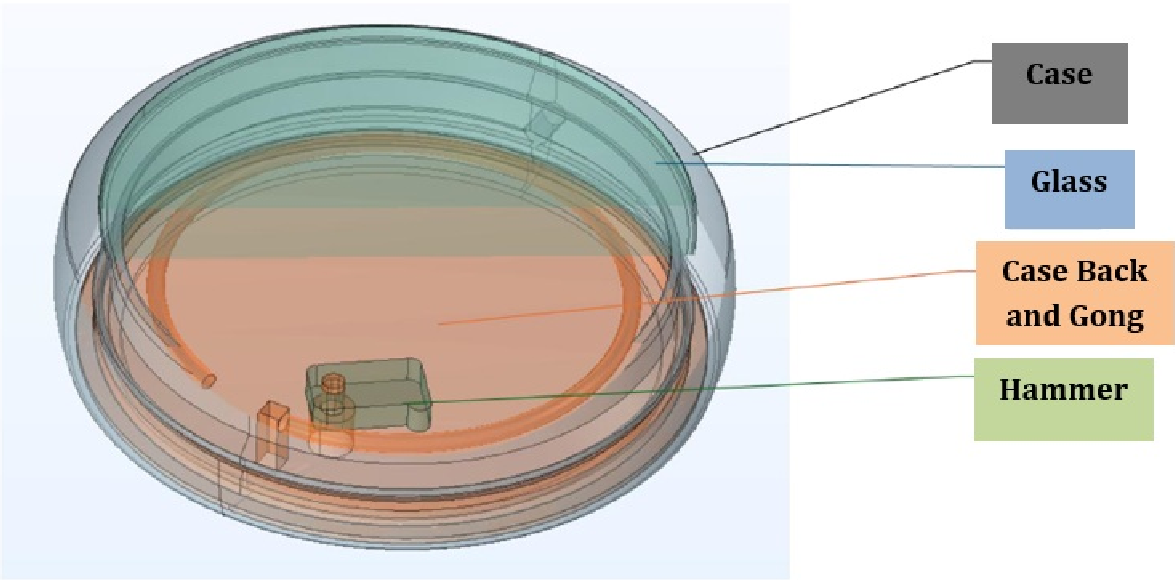

Figure 1 : The simplified minute repeater watch geometry