Dynamic loads produced by swinging bells – experimental and numerical investigation of the novel yoke-bell-clapper system with variable geometry

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Summary. Dynamics of the swinging bells is a timely problem considered when the bell's supporting structures are designed or monitored. The geometry of the yoke and the magnitude of excitation force are the crucial parameters determining the yok-bell-clapper system response for a given size and shape of the bell. In this paper we present novel yoke-bell-clapper system with variable geometry and adjustable excitation force. We introduce mathematical model based on the existing prototype. We validate the mathematical model and then assess the influence of the yoke geometry and excitation force on the system response. The simulations are done using sample-based approach. The system that undergoes investigation in the paper is non-linear, piecewise and discontinuous. Created numerical tool can reliably predict the ringing scheme of the bell and associated reaction forces in the supports.

Introduction

Dynamics of the swinging bells is a timely problem that is recently widely considered by scientific community. The phenomena that are the most widely investigated are the bell to the clapper impact modeling, different bell's working regimes, the dynamics of bell towers and the magnitudes of forces transferred between the bells and their supporting structures. The loads generated by swinging bells are in special interest because they may have severe consequences on the bell's supporting structure as recently reported by [1,2,3]. For a given size and shape of the bell, the crucial parameter that determines it's dynamics are the geometry of the yoke and magnitude of excitation force. In the existing studies, when modeling the dynamics of the bell supporting structure the loads generated by swinging bells are either measured by accelerometers placed on the existing constructions or estimated according to some semi-empirical formulas [4].

In this paper we present novel yoke-bell-clapper system with variable geometry and adjustable excitation force. We introduce the mathematical model of the system that is based on the existing prototype and validate it. Our goal is to assess the influence of the yoke's geometry and the excitation force on the bell's and clapper's oscillations amplitude and associated reaction forces in the supports. The simulations are done using sample-based approach, values of system parameters are randomly sampled from the analyzed set of parameter values. As a result we obtain an effective and robust numerical tool that can trustworthy predict the bell's ringing scheme and produced loads.

Experimental stand and mathematical model validation

Figure 1 presents the experimental rig based on the project and patent of the Lodz University of Technology. The rig consists of the yoke, the bell, the clapper, the moving beam and the supporting frame. The idea behind the moving beam is that we can alter the geometry of the yoke, therefore reproduce different bell mounting types and analyze the influence of the parameters describing the yoke's geometry on the system response. The rig is equipped with sensors that measure the kinematics and the dynamics of the system.

The mathematical model representing the yoke-bell-clapper system is build based on the physical model that is also schematically presented in the figure 1. It is a four degree of freedom (DoF) system accommodating the yoke with the bell, the clapper and the yoke's supports. The clapper to the bell collisions are described using a discrete mathematical model based on the coefficient of restitution. The analyzed yoke-bell-clapper system is propelled with a linear motor activated when the bell goes through its stable equilibrium position. The excitation mathematical model is therefore piece-wise and depends on the period of the system.

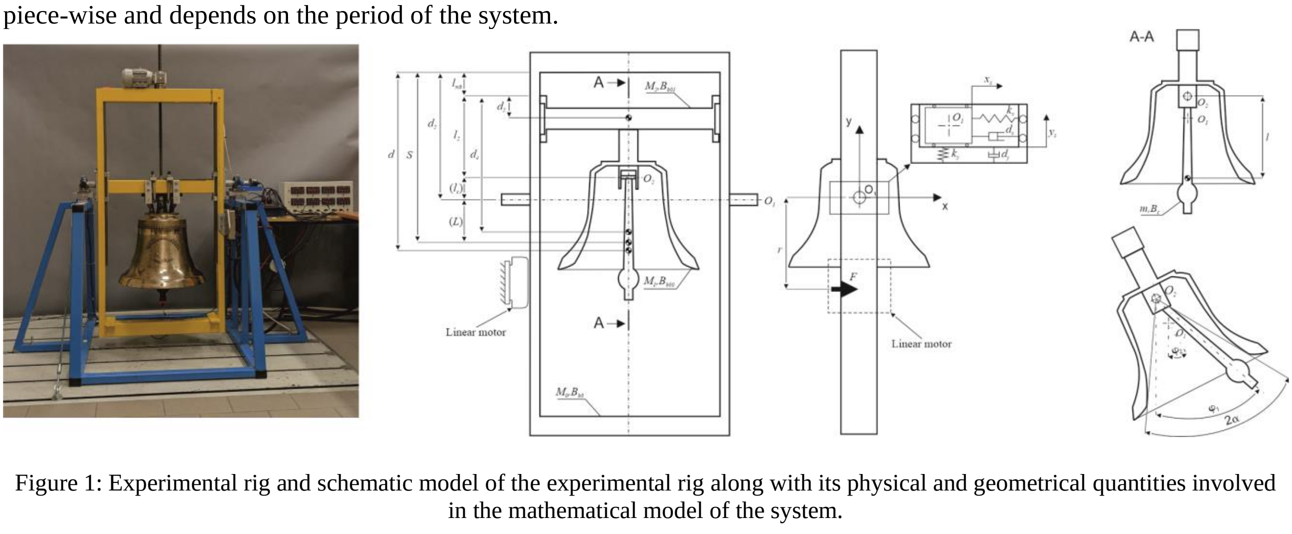

Figure 1: Experimental rig and schematic model of the experimental rig along with its physical and geometrical quantities involved in the mathematical model of the system.

The mathematical model is validated by performing the series of simulations for chosen yokes' geometries. Each time numerical results were compared with data obtained experimentally. Good matching between experimental data and numerical results is achieved in all scenarios. It shows that our model can accurately represents reality regardless of the yoke's geometry. Important aspects from engineering point of view including: The period of the system, its dynamics, reaction forces, and ringing scheme of the bell are reliably determined.

The influence of the yoke geometry and excitation on the system response

Using validated mathematical model we investigate the influence of the yoke geometry and the excitation force magnitude on the system response. In the analysis we focus on the aspects crucial from practical point of view namely: working regime, amplitude of the bell and clapper motion and dynamical loads acting on the supporting structure. We perform a series of 100,000 simulations using sample-based approach. The results are presented in a form of two parameters color maps. In each map on the horizontal axis there is a parameter determining the yoke's geometry and on the vertical axis the excitation force amplitude. Figure 2(a) shows the variety of ringing schemes that can be obtained depending on the geometry and excitation. Figures 2(b) and 2(c) present the amplitudes of dynamic reaction forces in the yoke supports in the horizontal and vertical direction consecutively.

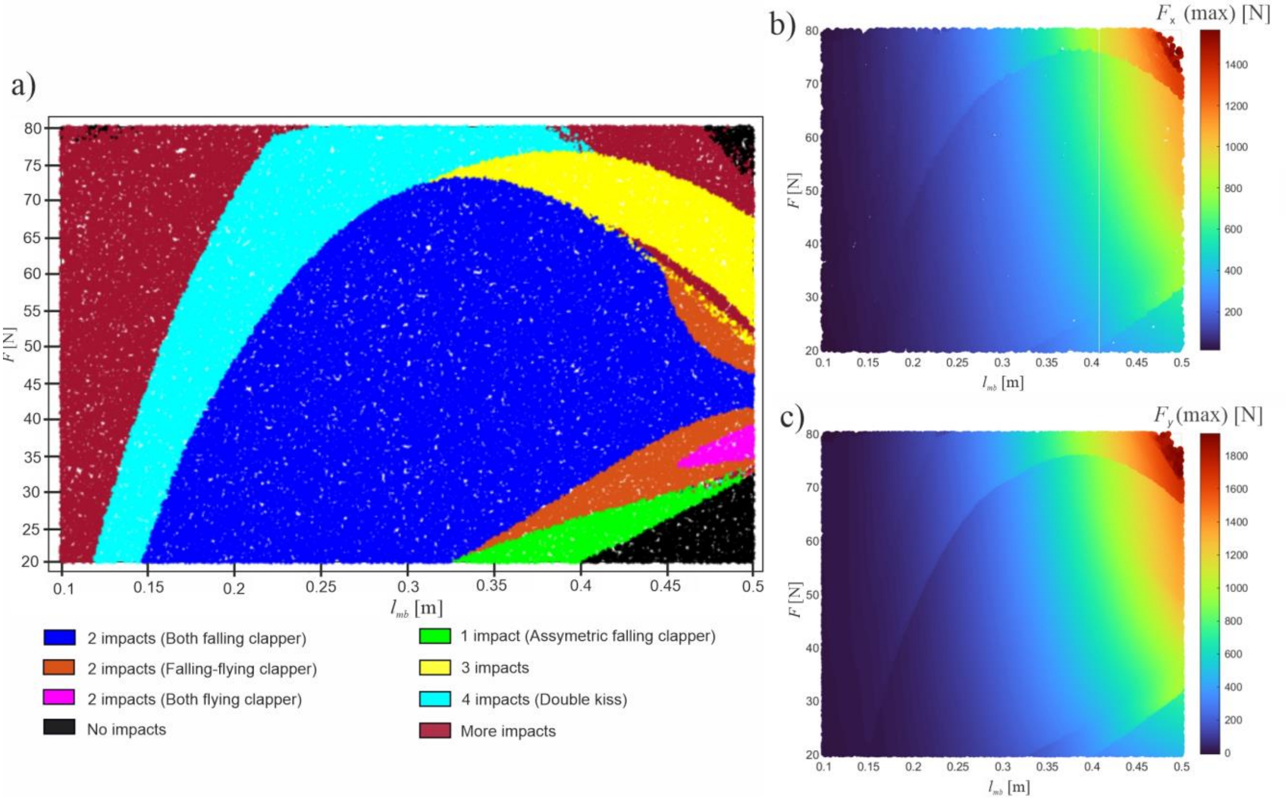

Figure 2: Two parameters colormaps showing a) the behavior of the system after reaching its attractor, amplitude of the reaction force in the supports in the a) horizontal and b) vertical direction.

Conclusions

We present that transition from one ringing scheme to another is usually associated with a step change of produced reaction forces and oscillations amplitude. We also show that for a given yoke's geometry different ringing schemes are possible depending on the excitation force.

Developed numerical algorithm can serve as a reliable tool for engineers during the design phase of the bells, yokes and their supporting structures.

References

[1] Ivorra, S., Palomo, M., Verdú, G. and Zasso, G. (2006) Dynamics forces produced by swinging bells. *Mechanica*, 41:47-62.

[2] Pallarés, F., Betti, M., Bartoli, G. and Pallarés, L. (2021) Structural health monitoring (shm) and non-destructive testing (ndt) of slender masonry structures: A practical review. *Construction and Building Materials*, 297:123768.

[3] McCombie, P. F. (2019) Rocking of a bell tower – investigation by non-contact video measurement. *Engineering Structures*, 193:271-280.

[4] Ivorra, S., Foti, D., Diaferio, M., Vacca, V. and Bru, D. (2018) Resonance detected on a historical tower under bell's forced vibrations. *Frattura ed Integrita Strutturale*, 12:203-215.

[5] Brzeski, P., Kapitaniak, T. and Perlikowski, P. (2015) Experimental verification of a hybrid dynamical model of the church bell. *International Journal of Impact Engineering*, 80:177-184.