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ASSESSING THE DYNAMIC RESPONSE OF HISTORICAL MASONRY PINNACLES

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Abstract. *The dynamic evaluation of historical masonry structures is a crucial aspect of conservation engineering, particularly when slender architectural components experience vibration-induced distress. The Church of Our Lady of The Assumption and The English Martyrs in Cambridge, UK, is a Gothic Revival church from the late 19th century, including a 65-m-high spire on its western bell tower. The construction material is Combe Down stone, a fine-grained oolitic limestone favoured in Victorian construction for its workability and aesthetic appeal. However, this workability comes alongside reduced strength, relative to other stones used in construction. A monitoring campaign was undertaken to evaluate the dynamic behaviour of pinnacles on the bell tower, following observations of cracking damage affecting both the pinnacles and their connecting stone tie-beams to the tower. Specifically, accelerometers were used to measure the response of a subset of the pinnacles, under both hammer-generated impulse excitation and forced vibration during bell ringing. A non-contact video-based approach utilizing Motion Magnification and WaveCam was concurrently employed, in which high-resolution video recordings were processed to enhance the visibility of small-magnitude motions and analysed in comparison with the accelerometric data. Motion Magnification and WaveCam are effective techniques for analysing the structural dynamics of heritage buildings, including at the subpixel level. In combination with accelerometer analysis, this campaign enabled assessment of the liveliness of the pinnacles during both ambient conditions and bell ringing, as well as their typical dynamic response, natural frequency and sensitivity to past damage and recent restoration.*

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1 INTRODUCTION

The long-term conservation of historical masonry structures requires an accurate understanding of their response to dynamic actions that may act repeatedly during service life. Unlike extreme events such as earthquakes, operational and environmental excitations often induce low-to-moderate amplitude vibrations that can nonetheless lead to progressive damage mechanisms, including joint opening, loss of interlocking and local instability. For this reason, dynamic assessment has become an essential component in the structural evaluation of heritage masonry buildings and monuments, complementing traditional static approaches and allowing the identification of critical vibration-sensitive elements [1].

Slender architectural components, such as towers, spires and pinnacles, are particularly susceptible to dynamic excitation due to their geometry. Analytical investigations may model masonry pinnacles as slender cantilever beams and estimate their dynamic properties using classical beam theory, highlighting their low natural frequencies and susceptibility to vibration under lateral excitation. Among anthropogenic sources of dynamic loading, bell ringing represents a well-documented but still insufficiently addressed action in historical masonry structures. Early analytical work [2] quantified the inertia forces generated during bell ringing and demonstrated that the oscillatory motion of swinging bells can induce significant horizontal forces at the supports, which are then transmitted to the nearby masonry. This work clearly established that these forces are not negligible and may govern the dynamic response of slender masonry components located above or near bell chambers. More recent technical analyses have further highlighted that bell-induced forces act in a narrow frequency band and may repeatedly excite structural modes when unfavourable dynamic coupling occurs [3].

The dynamic behaviour of masonry spires and other slender vertical elements has been extensively investigated under seismic loading, providing valuable insight into their global and local response mechanisms. DeJong [4] developed an analytical framework to describe the rocking and collapse behaviour of stone masonry spires subjected to dynamic base excitation, demonstrating that spire response is strongly influenced by geometry, mass distribution and crack localization. This analytical work was subsequently complemented by computational and experimental investigations, in which specific historical spires were modelled and tested to assess collapse mechanisms, damage patterns and the role of block stereotomy [1].

Despite the extensive presence of slender elements within the historical built heritage, dedicated experimental and monitoring studies focusing specifically on masonry pinnacles subjected to operational dynamic actions remain limited [2]. The present study therefore aims to investigate how combined contact-based and non-contact monitoring techniques can be effectively applied in situ to characterize the dynamic behaviour of such elements under operational excitation. By investigating these aspects through an experimental campaign conducted on the bell tower of the Church of Our Lady of the Assumption and the English Martyrs (Cambridge, UK), this work seeks to contribute to filling the current gap in the literature regarding the dynamic response of masonry pinnacles subjected to bell-induced loading.

2 CASE STUDY

The Church of Our Lady of the Assumption and the English Martyrs (OLEM Church, Fig. 1) is a Roman Catholic parish church located in Cambridge, UK. Constructed between 1885 and 1890 on a traditional cruciform plan, the structure incorporates multiple types of limestone: Casterton stone for the foundation, Ancaster stone for the plinths and Combe Down stone for the main walling [5]. The church's vertical emphasis culminates in a central crossing tower and a prominent west bell tower, surmounted by a 65-m spire, which constitutes one of the tallest structures in Cambridge and a distinctive feature of the city's skyline.

The bell tower and spire of OLEM include ornate pinnacles and finials characteristic of the Gothic Revival style, situated at the corners of the tower and along the parapets. The tower constitutes one of the most prominent structural components of the church, both in terms of architectural expression and structural significance. Its considerable height, combined with the presence of oscillating bells, makes it a critical element, and recent investigations have highlighted significant deterioration in the high-level stonework of the bell tower. In the summer of 2023, specialist surveys identified potentially serious stability issues with some upper masonry elements, prompting emergency interventions to remove unsafe stonework and the development of longer-term restoration plans.



Figure 1: Church of Our Lady of the Assumption and the English Martyrs (Cambridge, UK).

The bell tower houses a traditional ring of bells that plays a significant role in the dynamic excitation of the masonry tower structure. The tower accommodates a set of eight primary bells arranged for full-circle change ringing, a practice typical of English church towers. A ninth bell is also present for the Angelus, although its contribution to dynamic loading is comparatively limited due to its secondary function and use. The bells vary significantly in size, with the tenor bell weighing approximately 15.72 kN and the remaining bells progressively lighter according to standard bellringing practice. Both the diversity of bell weights and their spatial arrangement within the belfry are important in assessing the dynamic forces transmitted to the supporting masonry.

3 METHODOLOGY

The experimental investigation was conducted while the bell tower was fully scaffolded as part of ongoing conservation works. This condition allowed the experimental campaign to focus specifically on the highest pinnacles of the bell tower, at approximately 45 m height, which are expected to be the most dynamically sensitive components. The experimental data were collected using a combination of contact-based measurements and non-contact video-based monitoring, during two distinct testing conditions: controlled hammer tests and operational bell ringing tests. This dual approach allowed the modal response of the pinnacle to be investigated, as well as the response under operational loading.

Contact measurements were performed using PCB Piezotronics Model 356A16 triaxial accelerometers. For each monitored pinnacle, two accelerometers were installed: one roving accelerometer positioned at points up the height of the pinnacle and one kept near its base (Fig. 2). The accelerometers were magnetically attached to small steel disks that had been temporarily bonded to the masonry, and signals were recorded using a National Instruments cDAQ-9174 and site laptop. In parallel, non-contact measurements were obtained through high-definition video recordings. Videos were acquired using a smartphone camera with a resolution of 1080 px at a frame rate of 60 frames per second (fps). To minimise camera-induced motion and ensure stable recordings, a DJI Osmo Mobile gimbal stabiliser was employed to connect the smartphone to a fixed camera tripod. At the base of the tripod, natural rubber isolators (100 mm × 100 mm, with a thickness of 15 mm) were installed to reduce the transmission of vibrations (Fig. 2). Nevertheless, the entire setup was positioned on the free-standing scaffolding surrounding the tower, meaning that it was not possible to remove the potential for ambient and operational vibrations. The recorded videos were analysed using two complementary methodologies: Motion Magnification (MM, [6]) and WaveCam-based analysis [7].



Figure 2: Measurement Setup

Magnified motion is a relatively new technique that amplifies subtle, otherwise imperceptible movements in digital video recordings, increasing pixel intensity to make very small displacements visible while preserving the image topology. This method enables accurate analysis of structural dynamic behaviour and is particularly relevant for monitoring artworks in museums, as it allows the identification of vulnerable areas potentially at risk of damage [8]. By analysing pre-recorded video data, the technique can detect regions sensitive to vibrations induced by environmental factors, seismic activity, or human interaction. A key advantage is that the signal-to-noise ratio remains unchanged after amplification, preserving the characteristics of the original video while significantly improving graph readability [9,10]. Its non-invasive nature makes it particularly suitable for cultural heritage preservation, minimizing physical interaction while providing high-resolution diagnostic insight [6]. While museums generally provide a more controlled environment for video-based monitoring, particularly in terms of stable

lighting conditions and limited background vibrations. By contrast, field monitoring presents additional challenges due to variable lighting, environmental disturbances, potential for tripod vibration, and constrained structural accessibility. In the context of the OLEM church, the high scaffolding exposes the camera setup to vibrations, both from ambient wind and from sway of the scaffold.

While both non-contact methods start from digital video recordings acquired with a camera, WaveCam enables quantitative vibration measurements by extracting dense time data through optical flow-based algorithms [7]. The software enables definition of a conversion factor between pixels and meters and enables spatial filtering to mask the structure of interest in the image. Deformations calculated from time waveforms can be analysed and visualized for isolated frequencies. The combined use of accelerometric data and video-based techniques provides a robust and complementary experimental framework for assessing the dynamic behaviour of masonry pinnacles under both controlled and operational excitation, allowing cross-validation between contact-based and non-contact measurements across different levels of the bell tower.

3.1 Limits of each technology

Within the monitoring campaign, the different sensing technologies exhibited specific operational and methodological limitations. Accelerometers provide highly reliable measurements, as they are directly attached to the surface and measure the local vibration of the monitored points. However, they require a specialized and costly data acquisition system, and physical access to the structure to fix the accelerometers in position. Such conditions are not always feasible due to accessibility constraints and conservation requirements. The spectral response of the accelerometers used in this study became progressively noisier below approximately 5 Hz and was not reliable below 0,5 Hz due to the direct current (DC) cutoff of the accelerometers.

Conversely, video-based techniques offer the significant advantage of being fully non-contact. The source data can be acquired not only with professional cameras but also with readily available devices such as smartphones, as adopted in this study. A major limitation of video-based approaches is that the camera itself is subject to environmental vibrations, which may influence the recorded signal. Although this effect is often negligible in controlled museum settings, the presence of scaffolding at the OLEM church in this study led to significant camera-induced vibrations above approximately 28 Hz. An important advantage of video-based analysis is the possibility of investigating the entire framed area rather than discrete measurement points, enabling both qualitative and quantitative comparisons across multiple regions of interest. In particular, the use of WaveCam demonstrated notable sensitivity of the surrounding structural elements at low frequencies, especially in the spire of the bell tower, which was successfully analysed from the recorded footage. Nevertheless, video-based methods are subject to the same intrinsic constraints as any dynamic measurements. The relationship between recording duration and frequency resolution ($\Delta f = 1 / \Delta T$) requires careful management, and the Nyquist limit imposes an upper bound on the detectable frequency content. With a sampling rate of 60 fps, the effective upper limit of 30 Hz proved restrictive, as it was ultimately found to lie close to the frequency range of interest for the pinnacle.

4 ANALYSIS RESULTS AND OBSERVATIONS

From a practical perspective, this study addresses how contact and non-contact monitoring techniques compare in capturing the dynamic response of masonry pinnacles and evaluates their respective strengths and limitations under field conditions. Fig. 3 shows the acceleration frequency-response function obtained from a hammer test, illustrating the dynamic response at the

top of the pinnacle in the three accelerometer directions. The acceleration frequency-response functions are computed as the single-sided FFT magnitude of the measured accelerations; for each direction, the results are obtained by averaging across three tests and normalising the acceleration with respect to the impact force. The figure provides a clear representation of the pinnacle's dynamic behaviour and indicates the frequency range in which its natural frequency is likely to be, based on the hammer test. As annotated in Fig. 3, the fundamental frequency of this pinnacle is believed to lie in the range 15-20 Hz. It is also observed that there is an unclear response below ~5 Hz, due to the noise in the accelerometer signals.

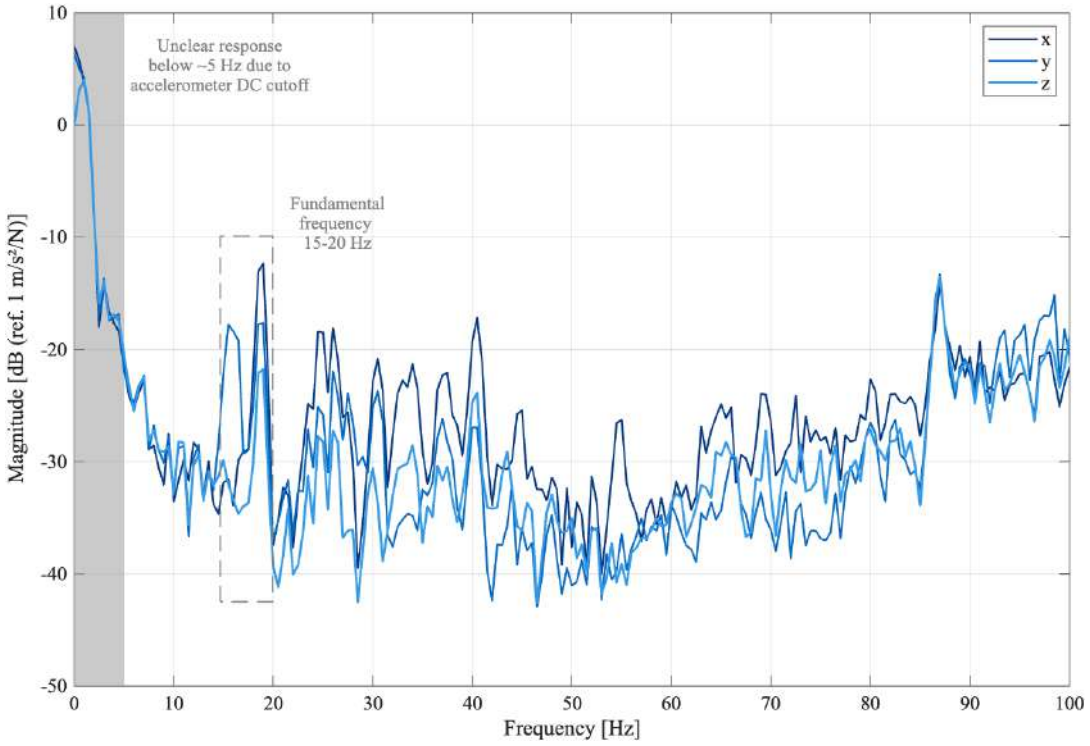


Figure 3: Acceleration frequency-response function at the tip of the pinnacle from the hammer test. The x and y curves represent the horizontal directions of the accelerometer, while z corresponds to the vertical direction.

Fig. 4 compares the displacement spectra obtained from the three monitoring approaches adopted in this study (accelerometers, Motion Magnification and WaveCam analysis) under bell ringing excitation. The curves represent the spectral response in the horizontal direction (y direction, corresponding to the horizontal direction shown in Fig. 5), with each curve corresponding to a different measurement technique and obtained by averaging the response along the height of the pinnacle. This corresponds to three measurements positions, with the video-based regions of interest selected to match the accelerometers locations. The results are plotted in normalised form to allow a direct qualitative comparison of the dominant dynamic features identified by the different measurement systems. For the accelerometer data, the spectra were converted from acceleration to displacement to ensure consistency with the displacement-related response extracted from the video data. Normalization between 0 and 1 was applied because the Motion Magnification approach, in the present implementation, operates directly on pixel intensity variations without geometric scaling of the image, meaning that the extracted signals reflect relative motion rather than physical displacement. Conversely, both the WaveCam analysis and the accelerometers provide displacement or acceleration measurements that can be expressed in physical units. For consistency in the comparison, the spectra obtained from all three techniques were therefore normalized considering the accelerometer response

only from 5 Hz upward, as its data below this threshold are affected by noise as already noted for Fig. 3.

The low-frequency range of the spectra shows several peaks that are likely associated with the global dynamic behaviour of the bell tower rather than the local vibration of the pinnacle. These frequencies may therefore correspond to large-scale structural motion of the tower itself, which can be transmitted to the monitored elements and detected by both contact-based and non-contact techniques. The three techniques show a broadly consistent spectral content, although with different signal-to-noise characteristics.

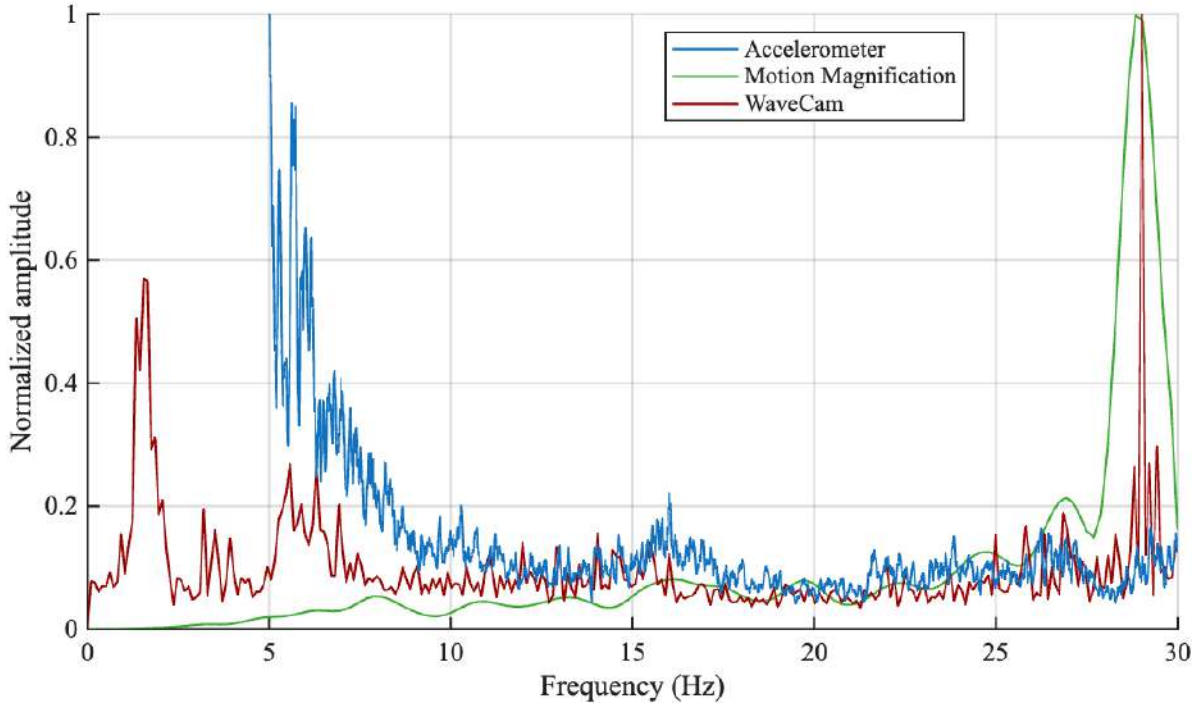


Figure 4: Comparison of normalized displacement spectra derived from accelerometer measurements, Motion Magnification (MM), and WaveCam analysis during an all bell ringing test.

A prominent peak appears close to 29 Hz in the Motion Magnification and WaveCam spectra (Fig. 4), which is only just within the Nyquist limit of 30 Hz imposed by the video acquisition rate (60 fps). The absence of a corresponding peak in the accelerometer spectrum suggests that this feature is not related to the structural response of the pinnacle. Instead, it is likely associated with residual motion of the camera system itself, potentially induced by small vibrations of the scaffolding on which the recording setup was installed.

Based on Heyman's formulation [11], assuming a conical model with a material density ranging between 1700 and 2500 kg/m³ and a Young's modulus of 2 GPa, the natural frequency of the pinnacle is estimated to lie between approximately 31 Hz and 27 Hz. The absence of significant peaks above 25 Hz in the accelerometer data recorded during bell ringing (Fig. 4) indicates that this frequency range is not excited by the bells. In the video-based data, this region is instead masked by the dominant peak at 29 Hz.

The WaveCam spectrum in Fig. 4 highlights the presence of two spectral peaks. Excluding the dominant peak around 29 Hz as due to the camera movement, a second peak is clearly visible at low frequencies, which can be reasonably associated with the global motion of the bell tower. This interpretation is supported by the spatial distribution of the response shown in Fig. 5a, which presents a heatmap extracted from a bell-ringing-test video analysed with WaveCam. At approximately 1.5 Hz (Fig. 5a), the motion appears spatially consistent and sim-

ultaneous between the pinnacle and the spire located behind it, indicating that the response is governed by the overall dynamic behaviour of the tower rather than by local vibration of the element. In contrast, the heatmap reported in Fig. 5b at 29 Hz does not exhibit a physically meaningful deformation pattern if interpreted as structural motion of the church or pinnacle; however, it can be plausibly explained by camera movement induced by vibrations of the scaffolding. This interpretation is based on the absence of a corresponding peak in the accelerometer data, the non-physical deformation pattern shown in Fig. 5b, and the inconsistency of the observed response with the expected dynamic behaviour of a slender masonry pinnacle, rather than on a direct measurement of the camera motion. The response is therefore likely not associated with actual structural motion of the pinnacle.

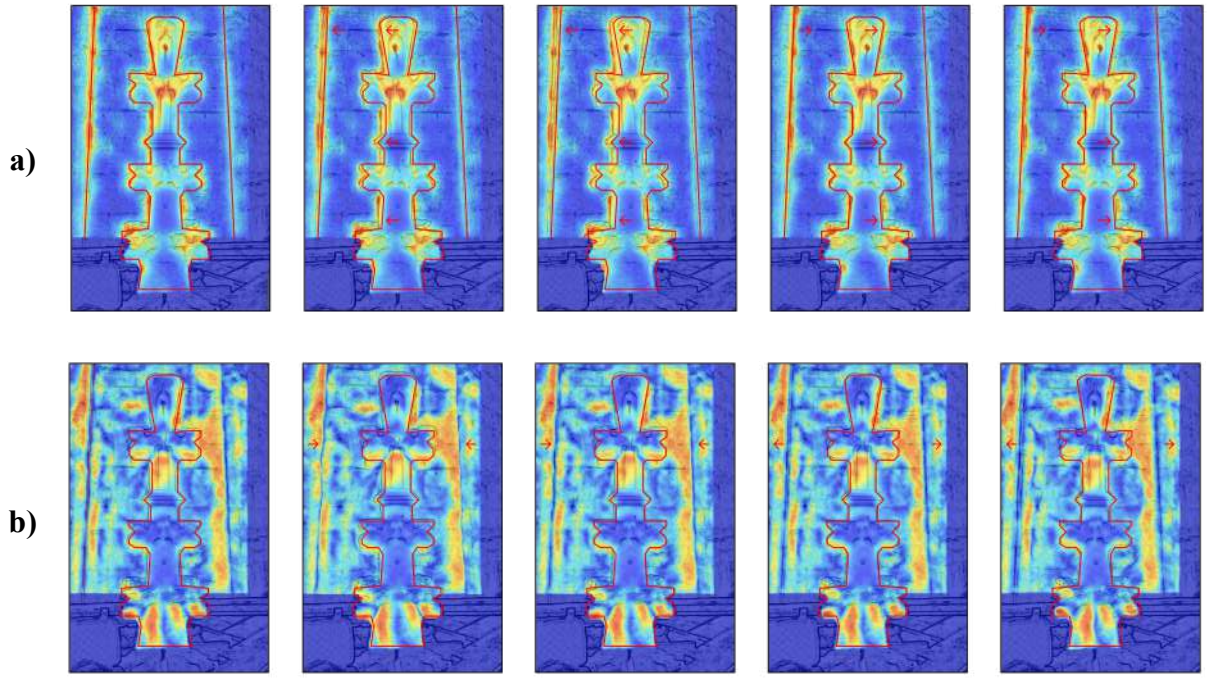


Figure 5: Frames extracted from a video recorded during a bell ringing test. Heatmaps obtained through WaveCam analysis illustrate the dynamic response of the pinnacle at: a) 1.5 Hz, b) 29 Hz.

Overall, the video-based analyses do not allow a clear identification of the natural frequency of the investigated pinnacle. This suggests that, under the examined conditions, the pinnacle response is dominated by the global motion of the bell tower, with no distinct local dynamic behaviour emerging within the reliably measurable frequency range, and that bell ringing does not excite frequencies close to the natural frequency of the pinnacle identified from the hammer tests. Moreover, the comparison highlights the complementary nature of contact-based and video-based monitoring techniques. While accelerometers provide more reliable measurements over a wide frequency range, video-based methods allow non-contact observation of structural motion and can capture consistent dynamic features within the frequency band of interest, particularly when appropriate care is taken to mitigate camera-induced disturbances. Furthermore, the increased reliability of the video-based methods at low frequencies enables the detection of the underlying tower response, which cannot be discerned in the accelerometer data.

5 CONCLUSIONS

This study investigated the dynamic response of masonry pinnacles on the bell tower of the Church of Our Lady of the Assumption and the English Martyrs (Cambridge, UK) under hammer testing and bell ringing excitation, using a combination of accelerometers and video-based techniques. The results show that the pinnacle response is governed by the global motion of the bell tower, with no clearly identifiable excitation of the local natural frequency within the reliable measurement range. Low-frequency components are associated with overall structural behaviour, while higher-frequency peaks observed in video-based analyses are attributed to environmentally-driven tripod vibration and exacerbated by technological measurement limitations. Overall, the findings suggest that bell ringing does not induce significant local dynamic amplification in the investigated pinnacle. The study also contributes to addressing the current lack of experimental data on their behaviour under operational loading. From a practical perspective, when direct contact with the structure is possible accelerometers provide reliable measurements. They are well suited to accurately measuring the absolute response of the pinnacle itself at a number of discrete locations. In contrast, video-based techniques enable non-contact measurements over the entire observed area, allowing the relative motion of the pinnacle and the bell tower to be assessed and providing a more comprehensive description of the structural behaviour. However, this comes at the expense of lower accuracy and increased sensitivity to environmental disturbances. The study confirms the complementarity of the adopted techniques, and their selection should be guided by the specific objectives of the investigation.

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REFERENCES

[1] DeJong MJ, Vibert C. Seismic response of stone masonry spires: Computational and experimental modeling. Eng Struct 2012;40. https://doi.org/10.1016/j.engstruct.2012.03.001.

[2] Heyman J, Threlfall BD. Inertia forces due to bell-ringing. Int J Mech Sci 1976;18. https://doi.org/10.1016/0020-7403(76)90020-5.

[3] EUPHONICS The science of musical instruments. The British Library's ISSN UK Centre 2023. https://euphonics.org (accessed March 19, 2026).

[4] DeJong MJ. Seismic response of stone masonry spires: Analytical modeling. Eng Struct 2012;40. https://doi.org/10.1016/j.engstruct.2012.03.010.

[5] OLEM Church, online URL: https://olem.org.uk/our-history, last visited on 02/2026.

[6] Chen JG, Wadhwa N, Cha Y-J, Durand F, Freeman WT, Buyukozturk O. Modal identification of simple structures with high-speed video using motion magnification. J Sound Vib 2015;345:58–71. https://doi.org/10.1016/j.jsv.2015.01.024.

[7] Vonrhein B, Höhna P. Vibration Analysis Based on Video Data for Buildings and Structures. INTER-NOISE and NOISE-CON Congress and Conference Proceedings 2023;268. https://doi.org/10.3397/in_2023_0492.
[8] Fioriti V, Occhipinti G, Roselli I, Cataldo A, Clemente P, Colucci A, et al. Dynamic Identification of the Sarcophagus of the Spouses by Means of Digital Video Analysis. Heritage 2025;8. https://doi.org/10.3390/heritage8040133.
[9] Fioriti V, Roselli I, Cataldo A, Forliti S, Colucci A, Baldini M, et al. Motion Magnification Applications for the Protection of Italian Cultural Heritage Assets. Sensors 2022;22:9988. https://doi.org/10.3390/s22249988.
[10] Wadhwa N, Rubinstein M, Durand F, Freeman WT. Phase-based video motion processing. ACM Trans Graph 2013;32:1–10. https://doi.org/10.1145/2461912.2461966.
[11] Heyman J. Vibration of masonry pinnacles. International Series on Advances in Architecture, vol. 3, 1997.