Determining the dynamic characteristics of an existing timber belfry structure and impact on FEM modelling

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Abstract. The paper studies the assessment of the dynamic characteristics of an existing historic timber belfry structure using FEM modelling and dynamic identification tests performed on a structure. The analysed structure undergoes geometrically measurement, including elements inspection, and on this basis the corresponding initial FEM model was built. The initial model including actual dead loads was computed to achieve dynamical and static calculations results, including eigenmodes and modal masses. On the belfry structure, dynamic identification tests were performed using accelerometers arranged in places of expected maximum amplitudes for belfry parts. The same initial model was calibrated according to the data achieved from computing in-situ identification tests (FFT spectrum analysis) and recalculated for static and dynamic results. Computed results from the initial and calibrated models were compared, presented and discussed. Brief summary includes conclusions from analysis and contribution to researches on belfries dynamics.

Keywords: timber, belfry, belltower, dynamics, FEM, dynamic identification tests

1. Introduction

Timber belfries were frequently built in the southern part of Poland but also, along the Carpathian Mountains. This kind of belfries are still not well identified structures in the field of structural mechanics and FEM modelling. The main purpose of the article is to determine actual structure and dynamic characteristics of the belfry in a FEM model using the in-situ dynamic identification tests.

1.1. History and localization of the belfry

The church with a belfry tower is located near the town centre of Skrzydlna, on sloping terrain, which makes the level of the belfry’s tower foundation stand higher than the church’s structure. According to the known history of the building, the first belfry structure was annexed to an existing church structure in the late 16th century. The structure was probably built in later periods (exact history and dates are unknown). It is located in front of the church’s main front wall (a typical log timber construction) with main doors which creates an additional room – a vestibule in front of the building. Over the centuries, the belfry structure has undergone several renovations and rebuilding. Most of the modifications concerned its highest (bellroom with a turret) and lowest (ground beam, support) parts. The exact dates of the renovations and rebuilding are unknown [1][2].
1.2. The main belfry structure

The main structure of the belfry presented in Fig.1 is composed of 4 main columns with varying cross-sections (from 29x30 to 38x40). The columns are supported (with additional knee bracing) on the ground beam which nowadays is rested on RC foundations (original foundations were simple stone-built footings) and connected with struts and beams along the height of the main structure. Those struts are crossing each other with lap jointing. At first sight, the main structure looks like a truss, but because the elements are not symmetrically connected, it works similarly to a frame – providing also bending moment. Originally, the analysed structure had both axis of symmetry, but due to progressive damages of the belfry’s back wall, currently it has only one axis (symmetry of the side walls). This situation is caused by irregular subsidence of the whole structure in the past and wood rooting due to leakings, and this in time lead to disconnection of a strut and destruction of another one in the back wall. The elements are connected with each other with traditional, typical historical joints described in [3], which in some aspects are rigid types, but with limited work angle (dependent on connection loose) and limited resistance to tension. It needs to be mentioned, that the belfry has got 2 platform levels – the first above the vestibule creating ceiling and the second one creating a kind of a technical platform. Main dimensions of the structure are given in Fig.2, where H1 is height of the main structure.

1.3. The bell room and the turret

The bell room is built as independent space, supported on the main structure’s columns by capping beams along the structure contour, however, the bell room is not the original one and it was built in the later periods (the exact dates are unknown). The bell room structure is composed of 8 posts (3 per each side) connecting two capping beams: upper (supporting the turret) and lower (rested on the main structure’s columns). The structure is braced by knee braces arranged to connect upper and lower capping beams with posts. An additional king post was added in the centre of the structure, supported on purlins with knee bracing.
The turret is built as another structure composed of 8 posts each located on circumference, radial symmetry, placed on 8-star beam base forming the shape of a turret. Every two opposite posts and a single beam base are connected by a long strut forming a braced structure for each direction. Additionally, the posts were braced along the circle line with the horizontal elements in the connection levels. Tops of posts are connected with themselves with another horizontal bracing, also forming the structure of the king post. The explanation of the structure and localisations of the elements are given in Fig. 4. Additionally Fig. 3 and Fig. 5 present an overview of the belfry structure and the bell room.

1.4. Use of the belfry
Nowadays, the bells are dismantled, and the belfry serves as a historical attraction creating on the ground level a vestibule as the first room in the church.

2. FEM model building and assumptions
The whole structure of the building was measured including cross sections of elements, points of connections between the belfry elements, estimated characteristics of those connections, and claddings with their thickness (forming dead loads of the building, such as planks, roof steel panels and timber structure, according to [6]). Based on the measurements, the FEM model was built for a given structure. Belfry geometry, nodes (representing joints), and the relevance of the elements were converted to a 3D model which is the basis for the FEM calculation. In the first attempt, some assumptions were simplified (nodes were considered as pinned connection, pinned support on ground beam, excluding rigidity of a cladding). Tab. 1 shows the layout of characteristic fragments of the analysed belfry structure, including characteristic joints and problems specific for this structure according to the in-situ structural health check. Many aspects identified in this existing structure need to be validated in the model, as presented in Tab. 2.
Table 1. Joints – nodes. Presented the following structural specification of the existing belfry

| Joints – nodes                                                                 | Description                                                                 |
|--------------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| Overlapping joint between struts (Tab.2)                                      | Disconnection of the elements in pos. B (Tab.2)                              |
| Damage of the main column pos. B (Tab.2)                                       | Knee braces and upper caping beam – corner of the bell room (Tab.3)         |
|                                                                                | Turret structure (posts and struts), view from 8-star beam level (Tab.3)     |
|                                                                                | Replaced destroyed fragment of the main column with a joint pos. A (tab.2) and knee bracing |

Table 2. Modelled characteristics of each the main structure and the bell room structure sides

| East side (nave entrance) | West side (church entrance) | North side (almost symmetrical to south side) |
|---------------------------|-----------------------------|-----------------------------------------------|
| A                         | A                           | A                                             |
| B                         |                              |                                               |
The structural layout of each wall presented in Tab. 2 consists of the main structure and the bell room structure. It is worth to pay attention to modelled deformation visible on each wall, which was mostly caused by uneven subsidence of the structure and rooting of the lower parts of the structure (modelled inclination of each wall on the basis of geodetic measurement). The destroyed lowest segments of the main columns together with the ground beams were already replaced with new ones which resulted in the creation of additional joints in the main columns (A). The present technical conditions of elements were considered in the model as a narrowing with eccentricity of a damaged main column (north-east one) (B). Tab. 3 shows the structural layout of the bell room and the turret with an 8-star beam. Red and green nodes above the caping beams and below 8-star beam base present connection between the bell room and the turret. According to [4] in the case of small displacements under actual dead loads, the connections between the elements are modelled as pinned connections because the static scheme are more common (most of connections are not tightly fitted and there are some significant imperfections). Tab. 2 and Tab. 3 segregate the belfry according to relations between elements and structures, for example, in terms of support, the turret structure is freely supported on the bell room structure, and the bell room is freely supported by caping beams on main columns (the bell room and the turret as separate structures consistently rest on each other). The representation of the existing structure principles in one calculation model is presented in Fig.6. The completed model underwent discretisation presented in Fig. 7. The materials’ elastic modulus was generally assumed as for the timber strength class C20 (on the basis of structure’s general visual wood characteristics).
3. Initial FEM model analysis

An initial (with pinned connections) built-up model (Fig. 6) including dead loads (structure load, cladding load) was calculated to disclose belfry eigenmodes. Masses were distributed to nodes (Fig. 7), model computed and first 5 eigenmodes are presented in Tab. 4. The selected eigenmodes were chosen from a set containing over 50 eigenmodes based on the modal mass impact (5 with greatest modal masses).

Table 4. Computed belfry Eigenmodes

| eigenmode 1 | eigenmode 2 | eigenmode 3 | eigenmode 4 | eigenmode 5 |
|-------------|-------------|-------------|-------------|-------------|
| ![eigenmode 1](image1) | ![eigenmode 2](image2) | ![eigenmode 3](image3) | ![eigenmode 4](image4) | ![eigenmode 5](image5) |
Table 5. Natural frequencies and oscillating masses (related to axis)

| Eigenmode | Frequency [Hz] | Oscillating part of the structure                          | Contribution of oscillating mass | Related mass on axis X [%] | Related mass on axis Y [%] |
|-----------|----------------|------------------------------------------------------------|---------------------------------|---------------------------|---------------------------|
| 1         | 2.8            | Turret, very limited oscillation of the capping beam       | 33                              | 0.2                       |                           |
| 2         | 3.1            | Turret (local character)                                   | 0.7                             |                           | 15                        |
| 3         | 3.8            | Turret, bell room, main structure                           | 43                              | 0.2                       |                           |
| 4         | 6.3            | Side walls (local character)                               | 0.1                             | 10                        |                           |
| 5         | 7.0            | Turret, bell room, side walls (limited)                    | 0.4                             | 14                        |                           |

Eigenmode 3 received from the FEM model is related with a general structure response, while the 1, 2, 4 eigenfrequencies are related mostly with local responses. Eigenmode 5 may have impact on the upper parts of the structure (bell room structure, the turret and limited impact on side walls) and limited on the main structure (oscillation of struts). The way to describe the character of eigenmodes and their impact on the structure is to analyse oscillating masses related to each axis. After the analysis of the masses of each selected eigenmode, one may deduce that eigenmodes 1 and 3 have the greatest impact on the structure. Eigenmode 3, which has strictly global character, affects the whole structure. Eigenmodes 1 and 2 are characteristic for the turret structure (oscillation of the turret mass) of which eigenmode 1 shape is characteristic for cantilever vibration and have impact on the turret stability. Despite some asymmetry between opposite walls, specified eigenmodes have in this case directed character. For most important eigenmodes (no. 1, 3) vibration is strictly along the “x” axis. According to the initial FEM model, eigenfrequencies 1 and 3 would be suspected as potentially dangerous while using the bell and, for the safety purposes, those natural frequencies shouldn’t be inducted during the usage of the belfry. The rest of the non-presented calculated eigenfrequencies have little impact on the structure (referring to the whole structure or its parts), impacting only individual elements, not considered in this article. For such a described model of the belfry structure, static calculation was conducted, and Tab. 6 presents the results which are characteristic values of internal forces caused by dead loads of the structure and cladding.

Table 6. Results of static calculations. Characteristic value of internal forces.

Main belfry structure

Axial force

Bending moment (to the local “Y” axis)
Bending moment (to the local “Z” axis)

Bell room

Axial force (view from below)

Bending moment (to the local “Y” axis)

Bending moment (to the local “Z” axis)

Turret
The irregular distribution of the internal forces as presented in the Tab. 6, is a predictable behavior due to some imperfections between the walls of the main structure, monosymmetric character and reduction of the main column’s cross-section (corrosion). The same situation was discovered in the elements of the bell room and turret, which was mostly caused by inclination of those structures and trapezoidal projection of the bell room (inclination and proportions obtained from geodetic measurements).

4. Dynamic identification tests
The author performed the dynamic identification tests using accelerometers for the main belfry structure, the bell room and also the turret (but the highest parts were inaccessible, so the measurement is not fully reliable for the turret). The first stage of testing includes inducting impulsive force to the structure and recording dynamical response (acceleration, Fig. 9) of the analysed structure with performing the FFT (Fast Fourier Tranformation) analysis. In the second stage, (if it was possible) frequencies received from the FFT analysis were inducted to confirm those results.
As shown in Fig. 8, the test was performed for the turret structure (pos. A), the second for the bell room at the level of capping beams (pos. B), and the third for the main belfry structure near the level of lower capping beams (pos. C). Those positions were determined by achieving possibly maximum amplitudes as well as the accessibility of those parts (that is why pos. A is not on the top of the turret).
Figure 11. Example FFT spectrum analysis of a dynamical response of the main structure to impulses – natural vibration frequencies of the structure in pos. C. No.1 natural frequency 2.9 Hz, no.2 natural frequency 4.5 Hz specific for the main structure

Table 7. Dynamic identification tests results – natural frequencies

| Position | Frequency No. [Hz] | Characteristic of the frequency |
|----------|--------------------|-------------------------------|
| A (No.1) | 2.6                | Main oscillation on the “x” axis, limited oscillation recorded on the “y” axis |
| B (No.1) | 2.7                | Main oscillation on the “x” axis, limited oscillation recorded on the “y” axis |
|          | (No.2, but limited amplitude) 4.5 |                                |
| C (No.1) | 2.9                | One direction of the oscillating. The “x” axis |
|          | (No.2) 4.5         |                                |

Computed FFT presented in Fig.10 and Fig.11 shows disclosed natural frequency no.1 and no.2. Disclosed natural frequencies for positions A, B and C according to Tab.7 show convergence of the received natural frequencies for each tested position. This convergence suggests one eigenmode type, which is expected to be a fundamental eigenmode for the estimated cantilever scheme of this belfry structure. According to the results of the tests performed on different levels and parts of the structure, natural frequency fluctuates between 2.6 and 2.9 Hz. For pos. C (the main structure) the tests revealed another significant response of the structure with frequency about 4.5 Hz (No.2), and the amplitudes almost as high as 2.9 Hz.

5. Comparison of the computed eigenfrequencies with the dynamic identification tests results
By comparing the results of tests in Tab. 7 with the computed results from the FEM model in Tab. 5, one may find potential paired eigenfrequencies. Such comparison is shown in Tab.8, below

Table 8. Comparison of eigenfrequencies

| Eigenmode | Frequency [Hz], Axis | Oscillating part of the structure | Identification tests [Hz] |
|-----------|----------------------|----------------------------------|---------------------------|
| 1         | 2.8, X               | Turret, limited capping beam oscillation | 2.6, Turret, bell room, main structure |
| 2         | 3.1, y               | Turret, locally                  | No match, bell room, main structure |
|           |                      |                                  |                           |
The comparison of the computed results with the in-situ test results demonstrates very high convergence between modelled and the turret natural frequencies for the eigenmode 1. However, considering behaviour of the computed bell room structure’s eigenmode 1, the oscillation is very limited, whereas the same structure in the in-situ excitation tests (pos. B, Fig. 8) reaches similar amplitudes as the turret (pos. A). A comparison of the computed results for eigenmode 2 with the identification test results has no match - computed oscillation has only local impact on certain turret’s elements which was not recorded during the tests. The analysis of the eigenmode 3 shows convergence with the recorded second natural frequency of the main structure which amounts to 4.5 Hz (Fig.11, no.2) and it may explain the second recorded significant frequency. Eigenmodes 4 and 5 will not be considered due to the lack of equivalence in records and insufficient convergence. The presented comparison shows that only the modelled turret structure converges towards the actual structure, whereas the bell room and the main structure should be modified.

6. Results of the model calibrations
The FEM model of the belfry structure was calibrated in accordance with the test results. Calibration was implemented by elastic releases of nodes positioned in joints. The main purpose of calibration was to achieve convergence between natural frequencies received during the in-situ tests and in FEM eigenmodes with simultaneous analysis of the eigenfrequency form. Best possible matching between the model and test results was achieved by calibration of bracing elements in the bell room and main structure’s struts. The results of matching are shown in Tab 9.

| Eigenmode | Frequency [Hz], Axis | Oscillating part of the structure | Computed results | Accelerometer tests [Hz] | Convergence of frequencies [%] |
|-----------|----------------------|----------------------------------|-----------------|--------------------------|-------------------------------|
|           |                      | Turret, Bell room’s capping beam, main structure | 2.6 | 2.7 | 2.9 | 93 | 96 | 97 |
| 1         | 2.8, x               | Turret, Bell room, main structure  | 2.6 | 2.7 | 2.9 | 93 | 96 | 97 |
| 2         | 4.4, x               | Main structure, highest part of the turret | -   | -   | 4.5 | -  | -  | 98 |
### Table 10. Comparison between matching eigenmodes of FEM model

| Eigenmode | Calibrated FEM model | Initial FEM model |
|-----------|----------------------|-------------------|
| 1         | ![Calibrated Eigenmode 1](image1) | ![Initial Eigenmode 1](image2) |
| 2         | ![Calibrated Eigenmode 2](image3) | ![Initial Eigenmode 2](image4) |

The comparison between the initial and calibrated models in Tab. 10 shows changes of eigenmodes’ shapes. For eigenmode 1, the initial model shape shows oscillation only within the range of the turret structure, while the calibrated model oscillates within the range of the turret, the bell room and the main structure (oscillating part of the main structure has lower amplitude). In the case of eigenmode 1, both models give the same resultant frequency (2.8 Hz). Comparing the frequency results for eigenmode 2, there is a divergence between models. Calibrated model is much closer to No.2 natural frequency received in the dynamic identification test than initial one. For eigenmode 2, the initial model shows the same oscillations of the main structure and the bell room, while for the one calibrated oscillation of the bell room’s capping beam is limited. Calibrated model shows that the turret’s braced post oscillation is nearly zero (the same post where testing position A is set according to Fig.8). The calibrated model was calculated in terms of the impact of modal masses, and the results are presented in Tab. 11. Those results are compared to the initial model.
By analysing the difference in modal masses in Tab.11, one may conclude that calibration has an impact on dynamic characteristics by changing proportions of modal masses associated with eigenmodes. The analysis results show that the calibrated model in comparison with the initial one is more vulnerable to resonance in the case of eigenfrequency 1 due to higher modal mass than in the case of eigenfrequency 2. The situation for the eigenmode 2 is opposite, modal masses are greater in the case of the initial model. Comparing the character of both eigenmodes (according to Tab.10) it is visible that the results from both models differ within the range of the upper parts of the structure such as bell room and the main structure. It should be mentioned that the bell is located classically in the bell room or just below, inducing vibrations (energy) in a critical position, where high amplitudes are expected. In this case, calibration should not be skipped during the examination of the structure due to the ULS criteria according to [7]. It is worth to mention that resonance may occur with swinging bell’s potential harmonic frequencies \( f_3 \) and \( f_5 \) [1], and those harmonics should be always checked while considering mantling a bell.

![Initial FEM model](image1)

\textbf{Figure 12.} Axial forces comparison, maximum absolute values [kN]

In general, axial forces are more redistributed among the elements of the structure. The function of the bell room’s bracing elements was reduced by given elastic releases, so forces (Fig.12) are very limited. In the initial model, some of the bell room posts’ segments were tensioned, in the calibrated one there is only compression.

![Initial FEM model](image2)

\textbf{Figure 13.} Bending moment, maximum absolute values, [kNm]

According to Fig. 12, there are no significant changes in momentum values except for the beam elements of the bell room and 8-star beam supporting the turret. In those elements, apart from the values, the distribution of moments has changed (mostly for the vertical bending). In general the
values of the presented internal forces (Fig.12 and Fig. 13) calculated from the initial model are usually greater and do not consider redistribution as in the case of calibrated FEM model.

7. Conclusions
Building the calibrated model of such belfry structure is a complex task. It requires carrying out dynamical identification tests for as many points of the structure as possible (at least those which are the most characteristic). These points are supposed to give an approximated shape of the fundamental frequencies to achieve best results in calibration (based on the comparison between each tested point of the structure). The results of the tests show, that non calibrated model in this case did not give rational, convergence results. This indicates that its stiffness does not correspond to the actual, old structure of this belfry (initial model is characterised by overestimated stiffness of the elements and joints). The analysis of the related modal masses, which were computed from both models, shows that in the initial model the related mass is underestimated in case of the fundamental mode. The mentioned modal masses have impact on the behaviour of the belfry structure (forces from mass oscillation) during the resonance and they should be considered if a bell is mantled again. Static calculations for both models confirm the expected redistribution of forces among the structure elements. Currently, provided similar dynamic researches are mostly aimed at historical brick belfry towers [8,9] and modern reinforced concrete bell towers [10]. The results of the dynamic analysis presented in the this article can be used as a point of comparison with other types of belfries. The intention of the author is to provide further research to better recognize the dynamic of timber belfries based on the results from wide range of belfries. Such analysis is important to preserve the structure of historical timber belfries and to create a possibility for safe bell mantling/reinstalling.

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