World Conference on
Timber Engineering
Oslo 2023

INVESTIGATION OF LONG-TERM MODAL PROPERTIES OF A TALL GLUE-LAMINATED TIMBER FRAME BUILDING UNDER ENVIRONMENTAL VARIATIONS

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ABSTRACT: Evaluation of long-term modal properties, such as natural frequencies and damping ratios, is important for tall timber buildings, which can be prone to environmental variations. However, in long-term operational modal analysis, the estimation of modal properties, especially damping ratios can be subject to significant uncertainty due to requirement of stationarity of the input data. Therefore, a combined variational mode analysis and data-driven stochastic subspace identification method was used for modal identification to reduce the potential errors related to the input data. The method was employed to investigate the long-term modal properties of an 18-story glulam frame building using ambient vibration data of 18 months. The observed natural frequencies exhibit seasonal behaviour with an average variation of ±0.02 Hz. Damping ratios do not show a seasonal relationship as opposed to the natural frequencies. The identified natural frequencies tend to have an inverse relationship with the mean temperature, while a positive correlation between the natural frequencies and the relative humidity is observed.

KEYWORDS: dynamic identification, ambient vibrations, tall timber building, VMD, SSI, modal properties.

1 INTRODUCTION

Tall timber buildings are relatively new in the construction industry, and as a result, there is still much research being conducted to understand their dynamic response under different loads, including service loads [1]. In general, tall timber buildings tend to have a lower natural frequency compared to traditional steel and concrete buildings due to inherently low stiffness and mass properties. This means that they are more susceptible to vibrations caused by external forces such as wind or human activities, and this can affect their performance and occupant comfort [2]. Excessive vibrations during strong winds might lead to discomfort for building occupants, particularly on the higher floors, if the design is incorrect.

Modal identification is a process used to determine the natural frequencies, damping ratios, and mode shapes of a structure. It is an important step in evaluating the dynamic response of a structure, as it provides information about the behaviour of the structure under different loading conditions.

Different techniques and methods can be used for modal identification of structures. For example, the operational modal analysis (OMA) method, which relies on ambient vibrations induced by natural events, can be used to identify the dynamic properties of the structure under real-life operating conditions. Other techniques such as impact testing or shaking table tests can also be used to identify the dynamic properties, but they require significant planning and labour and can be quite costly. In comparison to other techniques, OMA is a cost-effective and relatively easy method, which is suitable for long-term measurements.

Data-driven stochastic subspace identification (SSI-DATA) is an OMA technique used to extract dynamic models from ambient vibration data. SSI techniques involve constructing a mathematical model of the structure using the measured response data. This model can then be used to estimate the properties of the structural system. One of the limitations of ambient vibration techniques for modal identification, such as SSI, is the assumption of stationarity. This assumption requires that the ambient vibration signals remain constant over time, which is not always the case in practice. Non-stationarity can occur due to changes in the ambient conditions, such as wind or temperature, or due to changes in the dynamic behaviour of the structure itself. To overcome this issue, the variational mode decomposition (VMD) can be used, which decomposes the initial signal into a set of oscillatory components containing the modes of the structure.

The modal identification of timber buildings presents some additional challenges that are unique to this type of construction. For example, timber structures are more susceptible to environmental factors such as temperature

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https://doi.org/10.52202/069179-0385

and humidity, which can cause changes in their material properties over time. In addition, timber buildings tend to have a more complex and variable behaviour compared to traditional steel and concrete structures, which can make their modal identification more challenging.

Several studies investigating the effects of environmental variations on the dynamic properties of timber buildings are available [3,4]. However, no previous studies on the relation between the environmental factors and the dynamic response of tall glulam frame building were conducted.

Considering these challenges, this paper investigates the modal properties of a tall glue-laminated timber (glulam) frame building under long-term ambient and operational variations using combined VMD/SSI technique. The effect of the variational environmental conditions on the identified dynamic properties is investigated using the meteorological data from the nearby weather station.

2 FIELD MEASUREMENTS SETUP

2.1 BUILDING DESCRIPTION

Mjøstårnet is an 18-storey tall glulam (glue-laminated timber) frame building located in Brumunddal, Norway (Fig.1). As of March 2023, Mjøstårnet is considered the tallest residential timber building in the world [5]. The load-bearing system of the building consists entirely of structural timber elements. The building height is 88.8 meters and the structural system consists of glulam trusses connected with slotted-in steel plates [6]. Cross-laminated timber (CLT) is used in the elevator and staircase shafts and the floors are made of prefabricated timber decks (floors 1-10) and concrete decks (floors 11-18). The concrete decks are added purely as additional mass due to occupational serviceability requirements. The pergola truss is mounted at the top of the building for architectural appearance.

(a) Building location (b) The Mjøstårnet building view

Fig.1. The Mjøstårnet building

2.2 EXPERIMENTAL SETUP

A long-term ambient vibration monitoring system was installed inside the building (Figs.2-4). The hardware in the system consists of three Kistler K-Beam® accelerometers, model 8395A2D0 [7], one CompactRIO controller by National Instruments, and connecting wires and cables. The accelerometers have sensitivity of 2000 mV/g and the sampling rate for data was 400 Hz. The building has been in full operational condition, therefore, the placement options for the long-term monitoring setup were quite limited. After the discussion with the building manager, the setup was installed in the emergency staircase shaft. This staircase could only be accessed in emergency cases only, therefore, it was not obstructing the normal operations of the building. Prior to the current accelerometer setup, the accelerometers were installed at the roof of the building. Therefore, to ensure that the captured modes from the current setup were representative of the global structural behaviour, the identified modes were compared against their counterparts from the setup on the roof. More details regarding the comparison of the two setups can be found in [8].

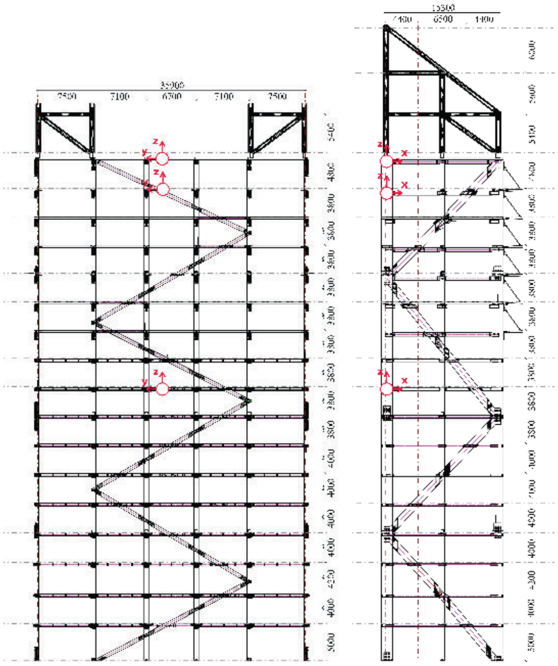

Fig.2. Accelerometer setup inside the building.

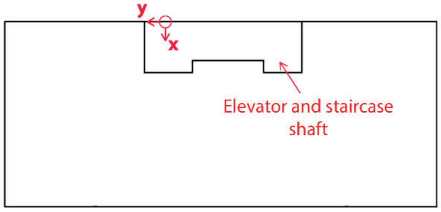

Fig.3. Plan view of accelerometer setup.

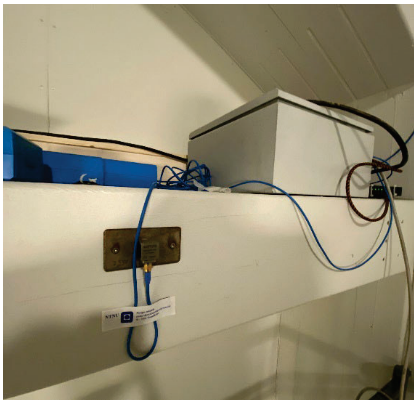

Fig.4. Long-term monitoring setup with the control box.

3 METHODOLOGY

The combined VMD and SSI-DATA methodology is outlined in the Fig.5. First, the initial ambient vibration data is decomposed into a set of modal components using the VMD technique. These identified modal components are then evaluated using the spectral analysis and the modes containing the structural behaviour are selected for further analysis. Then, the SSI-DATA technique is applied separately on each structural mode and the corresponding natural frequencies and damping ratios are identified. The following sections present the methodology in more detail.

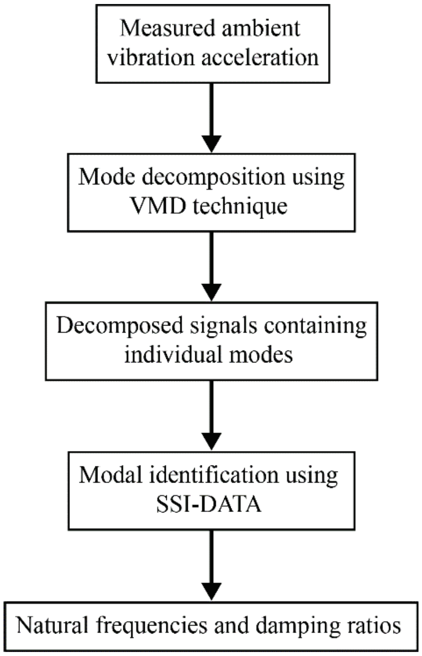

Fig.5. Combined VMD/SSI-DATA methodology.

3.1 VARIATIONAL MODE DECOMPOSITION (VMD)

VMD is a signal decomposition method that aims to decompose a complex signal into a set of intrinsic mode functions (IMFs) or oscillatory components [9]. Each IMF represents a distinct oscillation mode in the signal, which is characterized by a particular frequency and amplitude modulation. The VMD algorithm is based on an optimization problem that seeks to minimize the total power of the signal subject to a set of constraints. The constraints ensure that the extracted IMFs are spatially and temporally localized and are well-separated in the frequency domain. A more detailed description of the technique can be found in [9]. The VMD algorithm can be briefly described as follows:

- Obtain frequency spectrum of each mode by applying the Hilbert transform.
- Shift the frequency spectrum of the mode to the estimated centre frequency using the exponential tune.
- Solve the following minimisation problem to estimate the bandwidth of each mode using the Gaussian smoothness of the demodulated signal:

$$\min_{\{u_k\},\{\omega_k\}} = \left\{ \sum_k \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * u_k(t) \right] e^{-j\omega_k t} \right\|_2^2 \right\}$$

$$s.t. \quad x(t) = \sum_{k=1}^{K} u_k(t)$$

where $u_k(t)$ are the decomposed modes, ω_k are the corresponding central frequencies, $\|.\|_2$ is the L2 norm, ∂_t is the derivative with respect to time, $\delta(t)$ is the Dirac delta function, $x(t)$ is the original signal.

After application of the VMD the initial signal is decomposed into a set of modes compacted around the central frequency. The signals containing structural modes are then selected for further analysis.

3.2 STOCHASTIC SUBSPACE IDENTIFICATION (SSI)

Once the signals containing structural modes were identified, thee data-driven stochastic subspace identification (SSI-DATA) technique is applied on each signal separately. The procedure for the SSI-DATA method is explained in detail in [10-12], and a brief description of the method is presented here. In SSI-DATA, the dynamic system is assumed to be described by the discrete state-space model:

$$\mathbf{x}_{k+1} = \mathbf{A}\mathbf{x}_k + \mathbf{w}_k \qquad (1)$$

$$\mathbf{y}_k = \mathbf{C}\mathbf{x}_k + \mathbf{v}_k \qquad (2)$$

where x is a state space vector, which holds the current state of the system at time instant t, y is a measured output at a specified sampling rate, w and v are system noise and measurement noise, respectively, A is a state matrix, and C is an output matrix.

The state-space model of order i is used to identify the eigenvalue μ_i, from which the corresponding pole λ_i can be obtained at a sampling period t_s. Then, the frequency and damping values, ω_i and ξ_i, can be calculated for each pole. The expressions for the calculation process of the values mentioned above are as follows:

$$\lambda_i = \ln(\mu_i)/t_s \qquad (3)$$

$$\omega_i = Im(|\lambda_i|) \qquad (4)$$

$$\xi_i = -Re(\lambda_i)/|\lambda_i| \qquad (5)$$

Stabilization diagram is then plotted with the stability criteria for natural frequency and damping ratio of 1% and 5% respectively, and the vertically aligned poles on the stabilization diagram indicate a stable frequency.

4 RESULTS

4.1 MODAL DECOMPOSITION

The acceleration time series were processed separately in the x- and y-direction (see Fig.3 for coordinate reference). Acceleration time series were resampled to 8 Hz sampling rate and the band-pass filter between 0.2 Hz - 1.0 Hz was applied to remove the noise and response outside the range of interest. In total three fundamental frequencies were identified: mode 1 at 0.5 Hz (first bending in the x-direction), mode 2 at 0.54 Hz (first bending in the y-direction), and mode 3 at 0.84 Hz (torsion). Fig.6(top) shows the original acceleration time series containing noisy data in the x-direction with the corresponding Fourier spectrum, where the peaks at 0.5 Hz (mode 1, bending) and 0.84 Hz (mode 3, torsion) can be seen.

Below the original data series are the two decomposed signals, which are called the intrinsic mode functions (IMFs) using VMD method, which show only one peak at their respective frequencies, indicating that the signals containing fundamental modes have been successfully separated. Similarly, Fig.7 shows the original acceleration time series containing noisy data in the y-direction (top) and its decomposed IMFs containing the fundamental modes along with the Fourier spectra indicating the fundamental frequencies in y-direction: mode 2 (bending) and mode 3 (torsion). These intrinsic mode functions containing the modes of interest were further processed using the SSI-DATA technique to identify the natural frequencies, damping ratios and mode shapes. Each mode-containing signal was processed separately. The methodology was applied continuously over the entire monitoring period (Jan.2021-Jun.2022) on 1-hr data segments to investigate the variation of the identified modal properties with time.

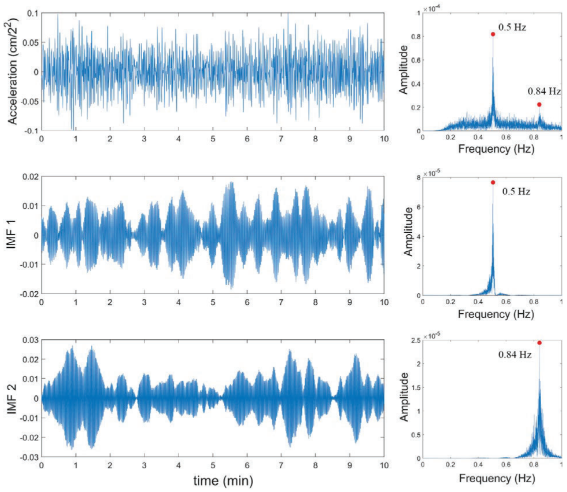

Fig.6. Input signal in x-direction (top) and its decomposed intrinsic mode functions (IMFs) with the corresponding Fourier spectra.

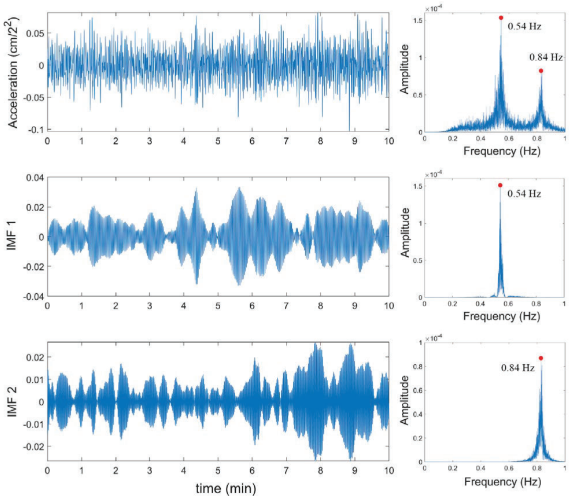

Fig.7. Input signal in y-direction (top) and its decomposed intrinsic mode functions (IMFs) with the corresponding Fourier spectra.

4.2 LONG-TERM MODAL PROPERTIES

The long-term monitoring records of the total of 18 months (Jan.2021-Jun.2022) were processed using the combined VMD/SSI-DATA methodology. Fig.8 shows the variation of the identified natural frequencies with time and the corresponding statistical distributions using 1-hour increments of the acceleration response for the first three modes of vibration. The torsional mode is plotted in both x- and y-direction. From observation, a seasonal pattern of natural frequencies can be observed. The highest values for natural frequencies are observed in the late winter (January-March), while the lowest values are observed in the late summer (July-September). The total natural frequency variation is ±0.015 Hz for mode 1, ±0.02 Hz for mode 2, ±0.03 Hz for mode 3. A larger scatter of identified values can be observed for mode 3 in the x-direction compared to the y-direction which might be due to the accelerometer placement: location of accelerometers close to the centreline might not allow for a proper identification of the torsional mode in the x-direction.

Fig.9 shows the variation of the identified damping ratios with time and the corresponding statistical distribution using 1-hour increments of the acceleration response for the first 3 modes. Similarly, a larger scatter is observed for mode 3 in the x-direction compared to the y-direction. Unlike natural frequencies, no seasonal variation of damping ratios can be observed. The mean values for the identified damping ratios seem to be quite stable at values around 1% except for mode 3 in the x-direction, where a larger variation is observed.

From Figs.8 and 9, it can be seen that the natural frequencies and damping ratios can be identified quite stably indicating the effectiveness of the combined VMD/SSI-DATA technique for extraction of long-term modal properties from ambient vibration data.

4.3 EFFECT OF ENVIRONMENTAL CONDITIONS

The meteorological data from the closest weather station was used to investigate the effect of the environmental conditions on the identified dynamic properties. The location of the weather station is approximately 10 km away from the building and the weather statistics for the monitoring period was obtained from the Norwegian Climate Service Centre [13]. The following environmental properties were selected for further analysis: mean air temperature (°C) and mean relative humidity (%).

The building in this study is located in a region with humid continental climate with cold and dry winters and comfortably warm summers. The warmest month of the year is July with mean daily temperature of 17°C and the coldest month of the year is December with daily mean temperature of -4.5°C.

Fig.10 shows the mean daily natural frequencies for the first 3 modes plotted together with the mean daily air temperature. The smoothed variations using 1-month averaging window are plotted to represent the trend of the parameters with time. From observation, for all natural frequencies the variation occurs in a similar seasonal manner. The highest frequencies are observed in the late winter and the lowest frequencies are observed in the late summer, with an exception of the first frequency, where the additional peak can be observed in the early summer period. For modes 2 and 3 (x- and y-direction) an inverse relationship is observed between the natural frequencies and the air temperature. The inverse relationship might be caused by the delay between the variational changes and the structural response. For mode 1, the inverse seasonal relationship can be observed in the winter, however, in summer the frequencies seem to have an increasing trend with increase of temperature.

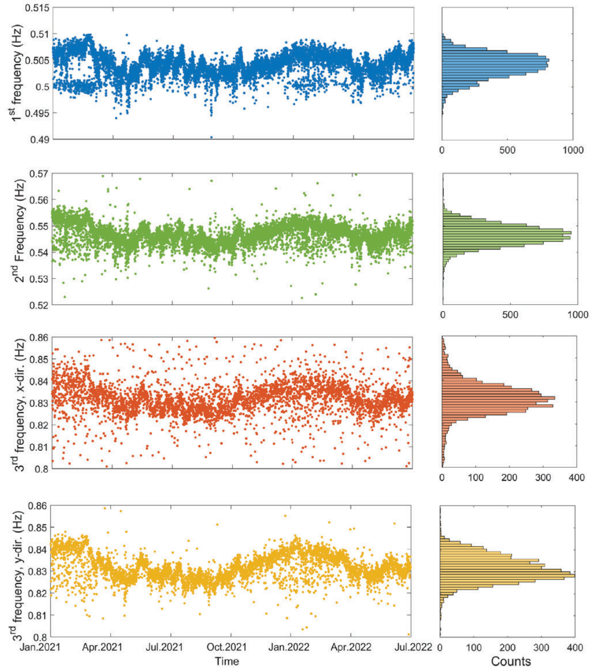

Fig.8. Variation of identified frequencies from 1-hour data segments over time (left) and the corresponding statistical distributions (right) for the first 3 modes of vibration.

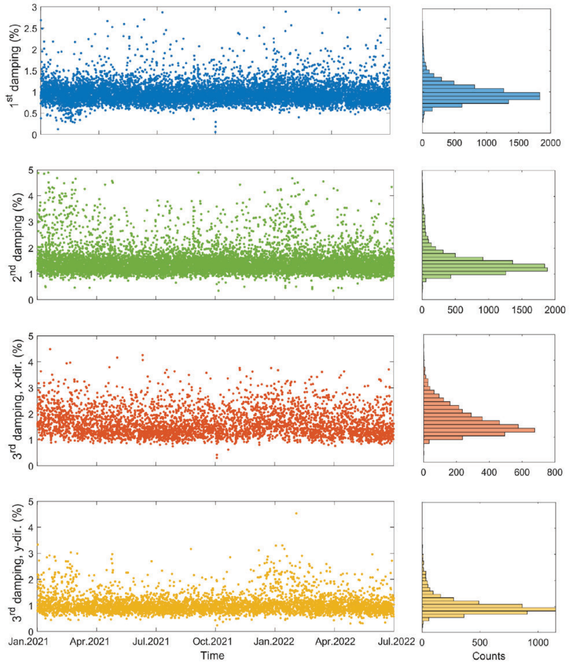

Fig.9. Variation of identified damping ratios from 1-hour data segments over time (left) and the corresponding statistical distributions (right) for the first 3 modes of vibration.

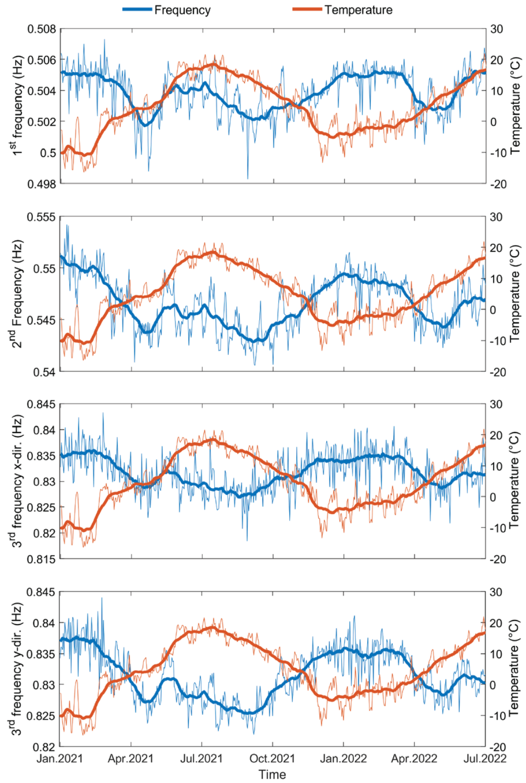

Fig.10. Variation of identified frequencies (1-day mean) and temperature.

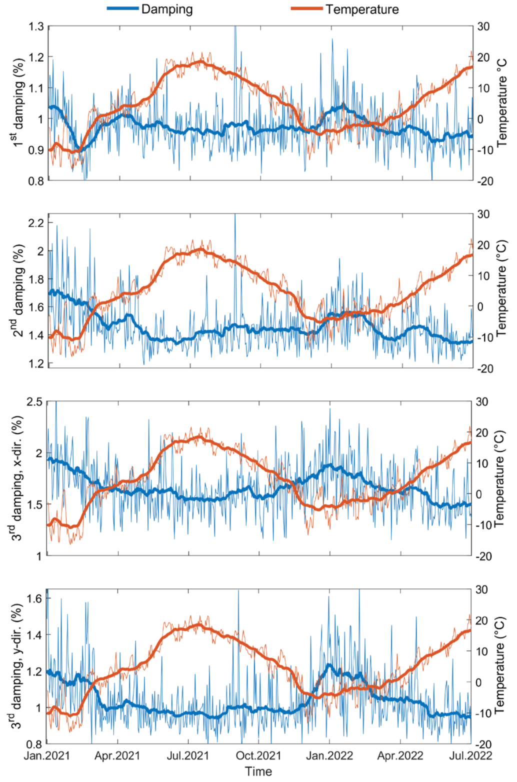

Fig.11. Variation of identified damping ratios (1-day mean) and temperature.

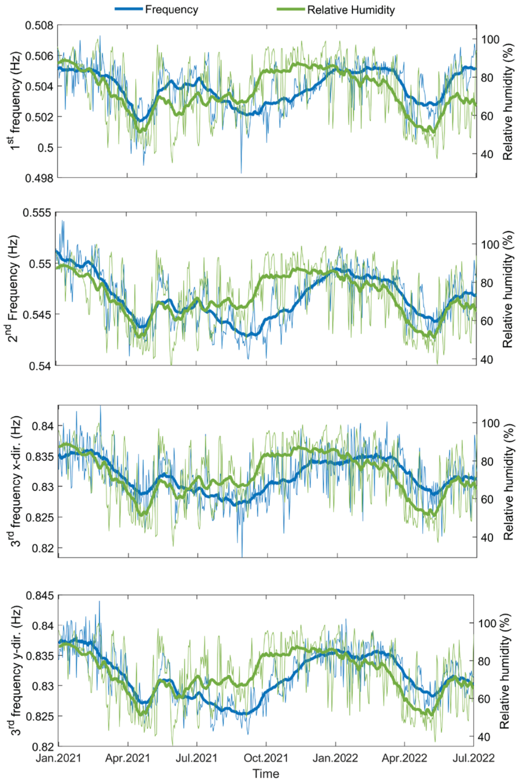

Fig.12. Variation of identified frequencies (1-day mean) and relative humidity.

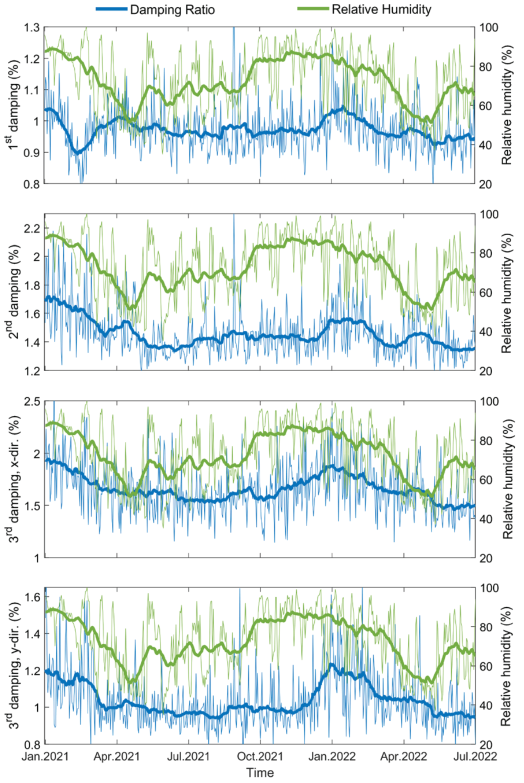

Fig.12. Variation of identified frequencies (1-day mean) and relative humidity.

https://doi.org/10.52202/069179-0385

The variation of mean daily damping ratios is plotted together with the mean daily air temperature as shown in Fig.11. The 1-month smoothed plots are plotted on top of the variations to indicate the trend of parameters with time. No clear relationship is observed between the damping ratios and the seasonal temperature for all three modes of vibration. However, it can be observed that damping ratios are higher in the January-February period compared to the other months for all modes.

Fig.12 shows the variation of the mean daily natural frequencies plotted together with the mean daily relative humidity. The thick smoothed plots (1- month averaging) indicate the trend of the parameters with time. All of the natural frequencies exhibit a positive trend with the relative humidity: with increase of mean relative humidity the natural frequencies increase as well. However, a small delay is observed, indicating that it takes time for the structural properties to respond to the change in relative humidity.

Mean daily damping ratios are co-plotted together with the mean daily relative humidity in Fig.12. From observation no evident effect of the relative humidity on the damping ratios is observed.

For a closer investigation of the effect of environmental conditions on the natural frequencies, 1-month variations of the parameters were co-plotted as shown in Fig.13 for July 2021. Each dot on the figure represents a 1-hour mean value of the parameter. From observation, the relationship between the natural frequency and temperature is not fully clear. A positive relationship between the natural frequency and the relative humidity is observed: increase in the relative humidity results in the gradual increase of the natural frequency with a delay. A similar positive trend between the 1st natural frequency and the relative humidity in Fig.13 was observed for the other two frequencies as well.

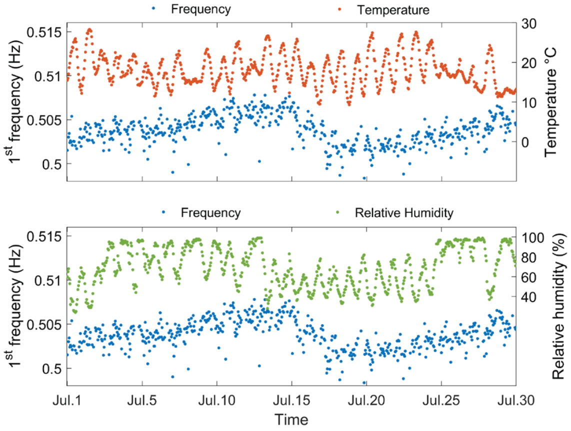

Fig.13. 1-month period (July 2021) variation of identified frequencies co-plotted with mean temperature and mean relative humidity (each dot represents 1-hr segment).

5 CONCLUSIONS

This paper investigated identification of the long-term modal properties under variable environmental conditions of an 18-story glulam frame building in Norway. The combined VMD/SSI-DATA scheme was applied to the measured ambient vibration response. First, the original signal was decomposed with VMD technique into intrinsic mode functions containing the modes; then, the SSI-DATA technique was applied separately on each mode-containing signal to obtain natural frequencies and damping ratios. The identified modal properties were quite stable indicating that the combined methodology can be effectively used for dynamic properties extraction from the ambient vibration data of the tall glulam frame building. The identified natural frequencies for most modes exhibit a similar seasonal behaviour, where highest values for natural frequency are observed in the late winter and the lowest values are observed in the late summer. The identified damping ratios for all modes did not exhibit seasonal variations and have quite stable mean values. From co-plotting the identified frequencies and mean air temperatures, the inverse relationship can be observed for most modes. From co-plotting the natural frequencies and mean relative humidity, a clear positive trend is observed, where the increase in the relative humidity is followed by the increase of the natural frequency for all modes. A delay in response might be caused by the time required for the structural properties of timber to be affected by the environmental conditions. Thus, both temperature and relative humidity impact the natural frequencies: high delay (around 6 months) is observed for temperature variations and a low delay (1-2 months) is observed for the relative humidity.

It is important to note, that in this study analysis of the effect of environmental conditions on the natural frequencies and damping ratios has certain limitations. A longer period of observation is needed to establish a clearer relationship between the seasonal variations and the natural frequencies. Additionally, an on-site weather station measuring both the indoor and outdoor environmental conditions should be installed for a more accurate investigation of the effect of environmental conditions on the dynamic properties of the building.

ACKNOWLEDGEMENT

The research in this paper has been conducted as part of the Dynamic Response of Tall Timber Buildings under Service Load project (DynaTTB). Norwegian Research Council was responsible for providing funding in Norway, grant no.297513.

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