

Human Induced Vibrations on Cantilever Type Structures

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Abstract. Typical steel towers are usually subjected to wind loads. In the case of sightseeing towers with lattice steel structure core and low natural frequency of the structure, human and structure interaction could play role in the tower design. This paper analyses the response of the tower structure to the excitation caused by human movement to guarantee the acceptable levels of human comfort and safe operation of the tower. There are different adopted levels of the structure and human behaviour synchronization and its effect on the whole structure. This synchronization phenomenon should be taken into account, because people respond instinctively to oscillation of a structure at a frequency which is close to that of a man's natural movement. This paper provides the analysis of possible mode shapes of the existing 34 meter high steel core sightseeing tower structure. The paper gives recommendations for the maximum number of people allowed on the existing structure to ensure safe operation of the tower. The dynamic performance is established through the finite element modelling of the analysed structure.

Keywords: steel sightseeing tower, fundamental frequencies, human induced vibrations, live load, synchronization, human comfort criteria.

I. INTRODUCTION

Lattice steel structures are remarkably flexible, low in damping and light in weight. Traditionally, for such type of structures, the dynamic analysis is performed and dynamic parameters, such as fundamental frequencies, mode shapes and damping ratios, are found to evaluate the wind induced vibrations and effects on the structure. Even the most advanced and comprehensive codes, including the Eurocodes, focus mainly on these issues.

In the case of the steel lattice sightseeing towers with low natural frequency of the structure, human and structure interaction could play role in the tower design. Human walking induces dynamic and time varying forces. Those forces have components in vertical, lateral and longitudinal directions. The lateral forces are a consequence of the sideway oscillation of the gravity centre of a human body while stepping alternatively with the right or left foot forwards [1]. The published data on dynamic loads state that the fundamental frequency of the pedestrian vertical and longitudinal walking on stationary pavements is 2.0 Hz for normal walk, 1.7 Hz for slow walk and 2.3 for fast walk. The horizontal fundamental frequency is 1.0 Hz for normal walk, 0.85 Hz for slow walk and 1.15 for fast walk [2]. In the case of a tower structure, the horizontal and longitudinal components of the pacing frequency are of interest.

There has been the growing tendency observed to construct light weight foot bridges. Due to the problems with lateral vibrations experienced at some of these structures, studies on the phenomenon of synchronous lateral excitation have been performed. Humans are noted to be much more sensitive to the lateral vibration than the vertical one. Even when the horizontal vibration is only 2-3 millimetres, the lateral motion affects balance and pedestrians tend to walk with their feet further apart, which increases the lateral force imparted by individuals. In order to maintain the balance, pedestrians tend to synchronize their footsteps with the motion of the structure. This instinctive behaviour ensures that dynamic forces are applied at the resonant frequency of the structure and further increases the motion. With the increase of the motion, the synchronization between pedestrians increases as well. It does not go infinitely, but reaches a steady state with people stopping, when the motion becomes too uncomfortable [3]. The same processes are presumed to take place on the sightseeing towers. Wind forces will promote initiation of the lateral motion and, due the adaptive nature of human beings, the lateral vibration will have a self-excited nature until some point.

The expected vibrations of the lattice sightseeing tower require limitations to meet the human comfort criteria. The limit values for the acceleration in the international codes are directly related to the pedestrian comfort. International standards and sources in literature propose different acceleration limit values for different reasons, however most of these values coincide within a certain bandwidth. The guidelines [4] of the recommended bandwidth for different comfort levels are presented in Table I.

TABLE I
Acceleration Limits

Comfort Degree	Lateral Acceleration Limit
Maximum	<0.1 m/s ²
Medium	0.1-0.3 m/s ²
Minimum	0.3-0.8 m/s ²
Unacceptable discomfort	>0.8 m/s ²

II. MATERIALS AND METHODS

The present study focuses on the identification whether the particular structure – the sightseeing steel lattice tower is at the risk of the harmonic human induced excitation in resonance with the natural frequency of the structure. The study investigates the allowed static live load bandwidths to meet the acceleration limits and takes into account the possible human and structure synchronization. Possible mode shapes and the corresponding fundamental frequencies of the existing steel core sightseeing tower have been analysed.

The studied steel core sightseeing tower is located in Dzintari, Jurmala, Latvia. It has been open for public since 15 May 2010. The total height of the tower is 36.48 m. All its elements – the inner and outer core, platforms and stairs are made of steel, except for the wooden cladding on the facades of the steel cores. The structural configuration of the tower and its picture are provided in Figures 1 and 2.



Fig.1. Sightseeing tower in Dzintari

The structure consists of the braced inner core with the dimensions of 1500x1500 mm, made from tubes with cross section 200x200x8, and the outer core with the dimensions 4240x4240 mm, made from tubes with cross section 140x140x5. The outer core has no vertical bracing, as this was required by the architectural concept. The inner and outer cores are connected only by steel stairs.

Since the tower is opened for public, there have been complaints about the tower's excessive vibration. The human perception of vibration is very sensitive and the reaction is substantially psychological. Therefore, it should be analysed whether these vibrations are realistic or just perceived by the human visual stimuli.

The literature [4] provides a recommendation that, whenever fundamental frequencies are close to the critical range (from point of view of the pedestrian excitation), a more precise numerical model should be used, as the hand made formulas and simplified methods are not sufficient for the assessment of the fundamental frequencies. The finite element software is widely spread and accepted as a more precise numerical model. To evaluate the degree of vibration, the fundamental frequencies and the critical mode shapes of the existing tower have been established by using three dimensional finite element models created by the structural analysis software STRAP 12.5.

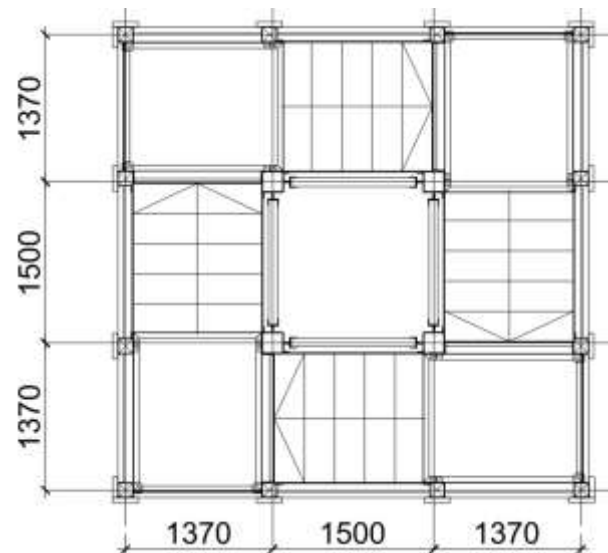


Fig.2. Plan of the Sightseeing Tower in Dzintari

The fundamental frequency and mode shapes of a structural system can be determined by solving the undamped free vibration equation (1) [5]:

$$K\phi = M\phi\Omega^2 \quad (1)$$

where :

K – stiffness matrix;

M – mass matrix;

Φ – corresponding eigenvector matrix;

Ω – eigenvalue matrix.

To extract the eigenvalues, the structural analysis software uses the subspace iteration technique. The created finite element (FE) model is presented in Figure 3 and the first three critical mode shapes for the structure are presented in Figure 4.

It is necessary to evaluate the influence of the mass of static sightseers on the tower's natural frequency, because natural frequencies of the structure decrease due to a live load and could shift into the critical frequency range or could leave it. It can be found in the literature [4] that the critical interval for the lateral vibrations is $0.5\text{Hz} \leq f_i \leq 1.2\text{Hz}$ and the critical range for longitudinal ones is $0.5\text{Hz} \leq f_i \leq 1.2\text{Hz}$, where f_i is the natural frequency of the structure.

In the case of the tower, the longitudinal component corresponds to the tower's torsional mode. The critical range of natural frequencies is based on empirical pedestrians on a flat surface. It is assumed in this paper that a similar range will be present for the pedestrian movement on the stairs. However, a more thorough investigation is required, as this matter has not been found in literature.

To evaluate acceleration of the tower, the recommended method found in literature [4] has been adapted and adjusted to suit for the tower case.

When the harmonic load ($F_0 \sin(2\pi f_0 t)$) is applied to a damped single degree of freedom system, the response of the system would be:

$$x(t) = \frac{F_0 / 4\pi^2 M}{\sqrt{(f^2 - f_0^2)^2 + 4\xi^2 f^2 f_0^2}} \sin(2\pi f_0 t - \varphi) \quad (1)$$

where:

F_0 – amplitude of the lateral load, N;

M – system mass, kg;

f – system natural frequency, Hz;

f_0 – load frequency, Hz;

ξ – structural damping ratio;

$$\varphi = \arctan\left(\frac{2\xi f f_0}{f^2 - f_0^2}\right)$$



Fig.3. FE model of the tower

Comparing the results obtained by Arup Partnership in the experiment with a shaking table [6] and the results given in [7], the amplitude of the lateral load is taken as a percentage of the vertical live load and depending on the lateral amplitude of the tower vibration (3). It is observed that the fundamental component of the lateral force increases with the platform's amplitude, but remains insensitive to the structure's lateral frequency.

$$H_0 = 0,2A + 4 \quad (3)$$

where:

H_0 – lateral force/vertical force, %;

A – tower vibration amplitude, mm.

Let us model a lattice tower as a cantilever with one degree of freedom and apply amplitude of the horizontal load at the cantilever tip. The equivalent mass applied at the cantilever tip from the tower mass and the pedestrian live load, which is uniformly distributed over the height of tower, can be obtained by taking approximately one fourth of the total mass of a beam at the free end [8]. Then by using the approximate methods, such as the Rayleigh's method or the Dunkerley's formula, the approximate equivalent mass of the cantilever is found by applying the formula:

$$m = \frac{33m_b}{140} \quad (4)$$

where m_b – uniformly distributed mass, kg.

In the analysis, the effect on the structure from the pedestrian synchronization has been considered for the first translational mode shape. A look is taken at one critical direction of the tower vibration and, therefore, the applied horizontal live load component is taken as a half of the total equivalent horizontal force, by considering the degree of the synchronization effect.

During the synchronization process, pedestrians adopt the same pacing frequency as the natural frequency of the tower. The response of the system (1) becomes:

$$x(t) = \frac{F_0}{8\pi^2 M \xi f^2} \sin(2\pi ft - \frac{\pi}{2}) \quad (5)$$

where:

F_0 – amplitude of the lateral load, N;
 M – system's mass, kg;
 f – system's natural frequency, Hz;
 ξ – structural damping ratio.

According to the Eurocode recommendations [9], the damping ratio ξ for a steel lattice tower with ordinary bolts is 0.05.

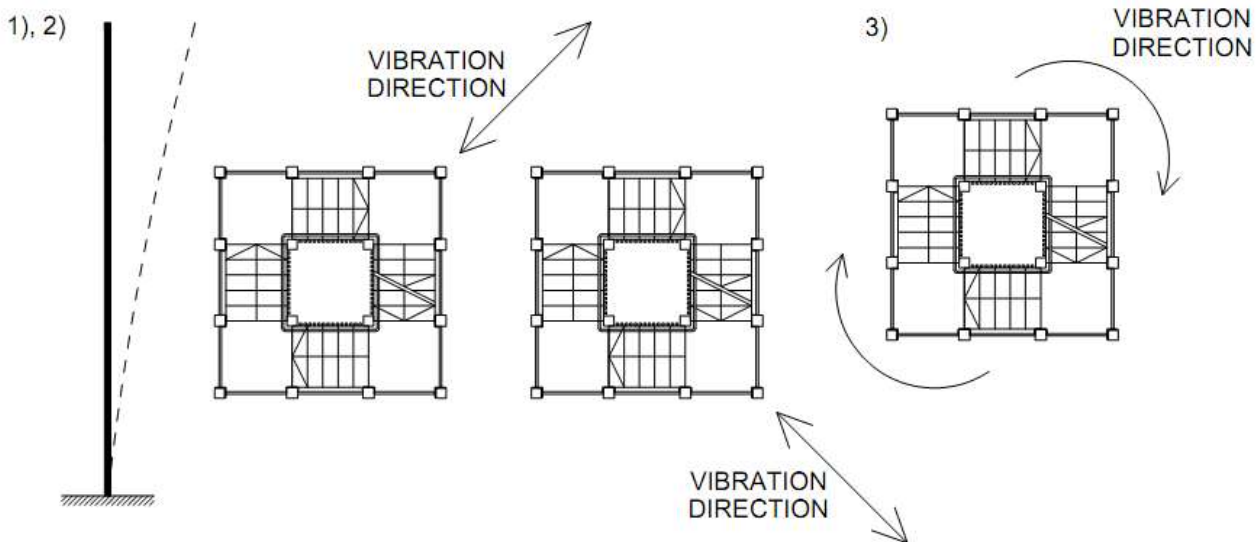


Fig.4. Mode shapes.
1), 2) first and second mode shape and vibration directions accordingly;
3) third mode shape vibration direction

Displacement of the tower tip can be found from the equation (5):

$$y(t) = x(t)\Phi \quad (6)$$

where:

$y(t)$ – vector of the concentrated mass movement;

$x(t)$ – response of the system;

Φ – vector of modal displacement at the tip of the cantilever.

Then the human comfort criteria – acceleration at the tip of tower for the first translational mode shape - can be found from the equation (7):

$$y''(t) = -\frac{F_0}{2M\xi} \sin(2\pi ft - \frac{\pi}{2}) \quad (7)$$

where F_0 – amplitude of the lateral load, N;

M – system's mass, kg;

f – system's natural frequency, Hz;

ξ – structural damping ratio.

III. RESULTS AND DISCUSSION

The determined natural frequencies of the sightseeing tower for the first two mode shapes are beyond the critical frequency range of $0.5\text{Hz} \leq f_i \leq 1.2\text{Hz}$ and equal to 1.26Hz and 1.3Hz for the translational mode shapes. For the torsional

mode shape, the tower is already within the critical range of $1.25\text{Hz} \leq f_i \leq 2.3\text{Hz}$. This means that the live load of sightseers should be taken into account for determining the tower's natural frequency. Figure 5 presents the natural frequency dependence on the additional live load of sightseers.

The chart shows that the movement of visitors up and down the tower may induce the vibration combined in torsional and translational directions. When the live load increases, the torsional vibration gets less frequent and leaves the critical range when the live load is around 1.7 Hz, which is a significant number of people on the tower.

In this paper it is assumed that sightseers' stream is up and down the same and therefore longitudinal sightseers' force component compensate each other and looked only at lateral force component influence on the tower's vibration. To mention that the accidental situation - intentional tower swaying was not analysed.

Fujino [3] has estimated from the video recording of a moving crowd that minimum 20% of the pedestrians were walking on the bridge synchronously with the bridge's lateral vibration, which had the frequency of about 0.9 Hz and the amplitude of 10 mm [6]. Similar process of the tower sightseers' synchronization is assumed to happen, because it is natural for a man to compensate an additional lateral movement of his centre of gravity by swaying with the structure's displacement. The initial amplitude of 10 mm is 1/3350 of the sightseeing tower's deflection and it can be easily initiated by wind forces.

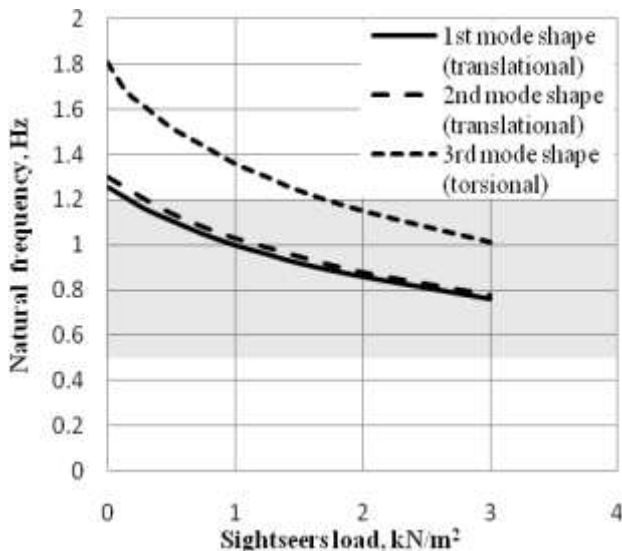


Fig.5. Calculated natural frequencies of the tower as a function of the applied live load

In this study the range of sightseers' synchronisation has been taken from 15% to 30%, looked at the initiated acceleration from this phenomenon and presented in Figure 6.

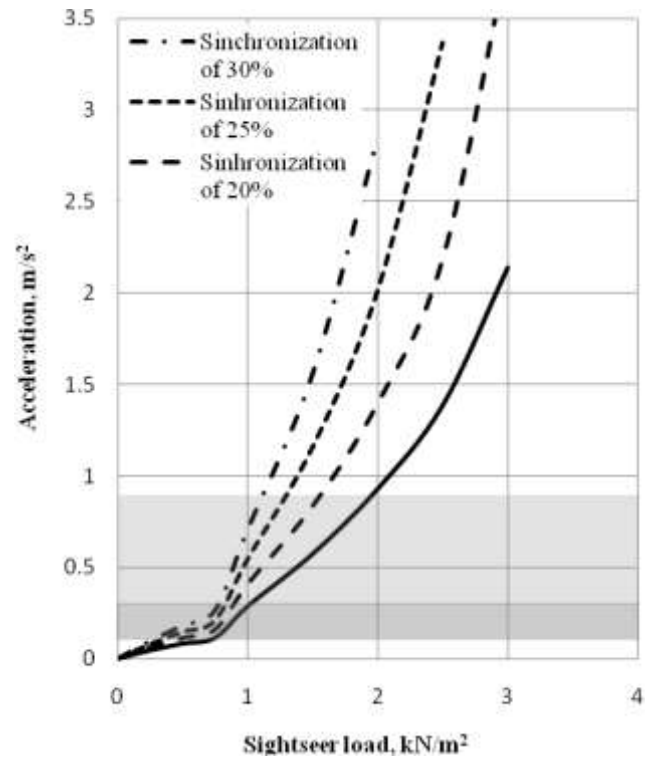


Fig.6. Maximum resonance acceleration

During the sightseers' synchronization with the structure, their step frequency matches with the tower's natural frequency. The calculated resonance maximum acceleration is presented in Figure 6 and shows that the average comfort level for the tower visitors is when the sightseers' stream does not exceed 0.75 kN/m^2 . It corresponds to 180 sightseers with the average weight of 75kg.

When a higher live load and degree of synchronization is present, the acceleration increases to the unacceptable level. If 15% of synchronization occurs, the allowable live load will be almost 2 kN/m^2 until the unacceptable level is reached, in comparison with the synchronization level of 30%, when the unacceptable level will be reached with the 1.2 kN/m^2 live load.

IV. CONCLUSIONS

According to the analytical calculations of the existing 34 m high steel lattice sightseeing tower, the dynamic performance is susceptible to the human induced vibrations. It has been concluded that, for the steel lattice tower type structures with natural frequencies close to the lateral pacing frequency, it is important to take into account the potential live load for the tower's modal mass calculations.

The existing sightseeing tower in Dzintari has the critical natural frequency for the torsional mode shape. Therefore, even the relatively light live load induces tower vibrations created by the sightseers' pacing force longitudinal component. The additional increase of a live load adds transversional vibrations created by the sightseers' pacing

force horizontal component and depends on the degree of the sightseers' synchronization. There is a necessity of further research to evaluate the degree of the human synchronization effect during operation of the tower type structure. The recommended maximum allowable live load to meet the average degree of comfort level for the tower visitors is 135 kN in respect to the tower transversional vibrations. No resonance accelerations for the torsional vibration mode, which could further limit the maximum live load, have been calculated in this study.

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Līga Gaile, Ivars Rādiņš. Cilvēku izraisīto svārstību ietekme uz konsoles veida konstrukcijām

Tērauda torņi galvenokārt tiek aprēķināti uz vēja slodžu iedarbi, neņemot vērā cilvēku slodzi. Tērauda skatu torņiem, kas ir samērā vieglas konstrukcijas, cilvēku masas un pārvietošanās izraisītās slodzes var būtiski iespaidot gan pašsvārstību frekvences, gan svārstību amplitūdas un paātrinājumus. Tāpēc, projektējot tērauda skatu torņus ar režģotu karkasu un zemu pašsvārstību frekvenci, nepieciešams izvērtēt mijiedarbību starp cilvēkiem un konstrukciju. Drošas ekspluatācijas un pieļaujama cilvēku komforta nodrošināšanai rakstā tiek analizēta torņa konstrukcijas darbība cilvēku kustību izraisīto slodžu ietekmē. Cilvēki pārvietojoties rada dinamiskas, laikā mainīgas slodzes vertikālā, garenvirzienā un šķērsvirzienā, kuru frekvences ir tuvas konstrukcijas pašsvārstību frekvencēm. Uz torņu konstrukcijām būtiskāko iespaidu atstāj garenvirziena un šķērsvirziena slodzes, pie kam pirmās izraisa torņa vērpes, bet otrās - šķērssvārstības. Gājēju izraisītajām slodzēm raksturīgs sinhronizācijas efekts - cilvēki instinktīvi reaģē uz konstrukcijas kustībām gadījumā, kad konstrukcijas pašsvārstību frekvence ir tuva cilvēku dabisko kustību frekvencei. Apskatīti dažādi cilvēku uzvedības un konstrukcijas darbības sinhronizācijas līmeņi, kā arī to iedarbība uz konstrukciju kopumā. Darbā analizētas iespējamās svārstību formas esošam 34 metru augstam skatu torņim ar režģotu tērauda karkasu. Konstatēts, ka skatu torņa pašsvārstību frekvences ir būtiski atkarīgas no apmeklētāju skaita. Aprēķinu rezultāti rāda, ka pie mazas slodzes (maza cilvēku skaits) diskomfortu var izsaukt vērpes svārstības. Palielinoties slodzei, vērpes svārstību pašsvārstību frekvence iziet no cilvēku kustībai raksturīgā frekvenču diapazona un aktuālas kļūst svārstības šķērsvirzienā, kuru pašsvārstību frekvences mazas slodzes gadījumā ir ārpus bīstamo frekvenču diapazona. Analīzes rezultātā iegūtas rekomendācijas maksimāli pieļaujamam cilvēku skaitam, kurš var vienlaicīgi atrasties uz torņa, ar mērķi garantēt konstrukcijas ekspluatācijas drošību un komfortu. Analizējamās būves dinamiskās īpašības noteiktas, izmantojot galīgo elementu modelēšanas paņēmieni.

Лига Гайле, Иварс Радиньш. Влияние колебаний, вызванных людьми, на сооружения консольного типа

Стальные вышки, в основном, рассчитаны на воздействие ветровой нагрузки, без учета нагрузки, вызванной людьми. Для стальных смотровых вышек, которые являются сравнительно легкими конструкциями, масса людей и нагрузки, вызванные их перемещением, могут существенно повлиять как на частоты собственных колебаний, так и на амплитуды колебаний и ускорения. Поэтому при проектировании стальных смотровых вышек с решетчатым каркасом и низкой частотой собственных колебаний необходимо учитывать взаимодействие собственных колебаний конструкции и колебаний, вызванных движением людей. Целью данного исследования является обеспечение приемлемого уровня комфорта людей и безопасной эксплуатации. Люди при перемещении создают динамические, изменяющиеся во времени нагрузки в вертикальном, продольном и поперечном направлениях, частоты которых близки к частотам собственных колебаний конструкций. Для вышек наиболее значимы нагрузки в продольном и поперечном направлениях, причем первые создают колебания кручения, а вторые - поперечные колебания. Для нагрузок, созданных пешеходами, характерен эффект синхронизации - люди инстинктивно реагируют в ответ на колебания конструкции, когда частота собственных колебаний конструкции близка к частоте естественных перемещений людей. Рассмотрены отдельные уровни синхронизации поведения конструкции и людей, а также их воздействие на конструкцию в целом. В работе проанализированы динамические характеристики возможных форм колебаний существующей смотровой вышки высотой 34 метра со стальным решетчатым каркасом. Результаты расчета показывают, что собственные колебания смотровой вышки существенно зависят от количества посетителей. При небольшой нагрузке (мало посетителей) причиной дискомфорта могут стать колебания кручения. При увеличении нагрузки частота собственных колебаний кручения выходит из диапазона частот характерного для нагрузок вызванных перемещением людей и актуальными становятся поперечные колебания, собственные колебания которых при малых нагрузках находятся за пределами критического диапазона частот. Результатом анализа являются рекомендации по максимально допустимому количеству человек, одновременно находящихся на вышке, для обеспечения безопасной эксплуатации. Исследование динамического поведения анализируемого сооружения выполнялось на основе метода конечных элементов.