

DAMPING OF TORSIONAL VIBRATIONS OF HIGH-RISE BUILDINGS UNDER SEISMIC EFFECTS USING DAMPERS GENERATING REACTIVE FORCE COUPLES

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Abstract

Introduction. To ensure the safety of buildings and structures in seismically active regions, special protection measures against destruction are applied. One of the most universal, effective, and economical methods of active vibration suppression is the method of reactive damping. An important form of natural vibrations of buildings is torsional motion. Certain segments of seismic accelerograms can provoke the development of such vibrations. There is a relationship between torsional and bending modes of vibration: bending vibrations can cause torsional deformations, and vice versa. This occurs because the centres of mass and the centres of stiffness of structural sections do not generally coincide, which leads to the occurrence of coupled bending-torsional vibrations. The aim of this work is to investigate the response of finite element (FE) models of high-rise buildings to seismic effects represented as harmonic functions with variable frequencies, varying the direction of the effect and the position of the centre of mass, as well as a comprehensive study of the results of experiments on damping torsional vibrations of high-rise buildings using a pair of reactive dampers capable of generating variable moments counteracting torsional vibrations. **Methods.** To evaluate the behaviour of high-rise buildings with reactive dampers under harmonic loads, an appropriate mathematical model was investigated. The calculations were performed using a software package based on the finite element method (FEM), and the dynamic response of the structure was determined numerically using the Newmark method. **Results.** The developed software tool allowed for frequency-vector analysis considering the displacement of the centre of mass from the centre of stiffness, and provided data on the torsional angles of the building at various positions of its centre of mass and variations in the parameters of the harmonic effect (frequency and direction) considering internal friction. A comprehensive study of the results of experiments on damping torsional vibrations of high-rise buildings using a pair of reactive dampers capable of generating variable moments counteracting torsional vibrations was conducted. It is shown that the use of reactive dampers with optimally selected parameters reduces the amplitude range of torsional vibrations by 50–80 %.

Keywords: high-rise buildings, seismic effect, oscillatory motion, centre of mass, torsional vibrations, reactive damper, vibration level.

Introduction

The issue of wind and seismic protection of high-rise buildings against destruction is extremely relevant. Within the framework of scientific research, an active search is underway for innovative, economically feasible, and relatively easy-to-implement solutions aimed at effective vibration damping and counteraction to dynamic loads.

Thus, Jung et al. (2024) analyse the seismic resistance of multi-storey reinforced concrete frames infilled with precast modular blocks. As a solution to the identified problems of traditional seismic strengthening methods (for frames with transverse, stone walls and precast panels), a new concept is proposed — the use of precast modular block walls. The study by Tan et al. (2023) is devoted to assessing the effect of wind loads on seismically isolated high-rise structures developed using an integrated seismic protection design approach.

This method is based on the theory of complex response spectrum and complex complete quadratic combination. The study by Wang et al. (2024) examines how various types of dampers (inerters and negative stiffness) installed on outriggers of high-rise buildings affect vibration damping. Special attention is paid to considering soil-structure interaction. The development and verification of an innovative hybrid damper designed to combat vibrations of high-rise buildings is presented in research by Lai et al. (2024). This damper utilises velocity-squared damping. It was successfully modelled numerically and confirmed by experiments. The works (Shein et al., 2023; Shein et al., 2025) contain numerical confirmation of the effectiveness of a reactive damper for reducing rectilinear seismic vibrations of tower structures and high-rise buildings. The results demonstrate a high level of damping, which allows, when using a damping device with carefully

calculated characteristics, to ensure a reduction in the amplitude range of rectilinear mechanical vibrations of structures by 50–80 %, thereby confirming its practical value.

Regulatory documents require that in areas of increased seismic activity, symmetrical in plan (geometric and stiffness) structural solutions for buildings and structures should be adopted.

However, even in buildings with an ideal architectural and planning solution, the torsion effect is observed, because the random eccentricity between the centres of mass and stiffness causes rotation of the floors, even with rectilinear motion of the base (Botis and Cerbu, 2020; Hussein, 2019). This rotation overloads the perimeter columns and external walls. Analysis of the consequences of earthquakes has revealed frequent destruction of the end parts of buildings (Bondarev, 2017). The unevenness of torsion increases the risk of building destruction under strong dynamic effects, therefore, there is a need to apply special protection measures (Zhang et al., 2025; Calvi et al., 2026). The aim of this work is to develop and evaluate an innovative approach to damping torsional vibrations of high-rise buildings during seismic activity using reactive systems that generate pairs of gas jets with a high ejection velocity. These systems create alternating force couples at specified time intervals, which counteract torsional deformations and torsional vibrations of the high-rise building that occur under non-stationary seismic loads.

Subject, Tasks and Methods

Within the framework of this study, the functioning of reactive damper systems designed to damp vibrations of a high-rise building under seismic loads was investigated. The building, having a rectangular base with dimensions of 42×18 m and a height of 150 m (corresponding to 50 storeys), has a frame-core structural scheme with a central rigid core. Detailed stiffness and geometric parameters of the reinforced concrete frame elements are given in Table 1.

The detailing of the reinforcement of the structural elements of the building is shown in Fig. 1c.

The displacements of the centre of mass (CM) of the high-rise building along the coordinate axes OX and OY were modelled by changing the specific weight of the finite elements of the model located at the perimeter.

The seismic effect was modelled by an accelerogram in the form of a harmonic function:

$$f = A \sin(pt), \quad (1)$$

where $A = 5 \text{ m/s}^2$ is the amplitude of the translational acceleration (const), p is variable frequency of the disturbing effects.

The research work is based on the software package “Fluctuations”, developed in the MatLab environment. The main equation adopted in the software package and describing the dynamics of plate-rod systems using the finite element method (FEM) has the form:

$$M\ddot{U} + C\dot{U} + KU = P, \quad (2)$$

where M , C and K are the matrices of masses, internal friction (damping) and stiffness corresponding to the finite element discretisation of the system, P is the column vector of external forces (seismic load).

This package provides a numerical solution to the system of differential equations (2).

For modelling the columns of the high-rise building, bar finite elements with 6 degrees of freedom in each node are used (three linear displacements along the coordinate axes of the global coordinate system and three angles of rotation around these axes). For modelling floor and roof slabs, rectangular thin plate finite elements are used, possessing 3 degrees of freedom in the node: one linear displacement along the normal to the element plane and two angles of rotation around its local coordinate axes.

The calculation of the internal friction matrix C is carried out according to the following relationship:

$$C = \alpha \cdot M + \beta \cdot K, \quad (3)$$

To calculate the constants α and β of Equation (3), it is necessary to determine the two lowest frequencies of the natural vibration frequency spectrum of the building under consideration. These values were determined using a separate block of the “Fluctuations” software, which solves the system of equations describing the free vibrations of the finite element model of the building under study:

$$\left| M^{-1}K - \omega^2 E \right| = 0, \quad (4)$$

where ω is an element of the natural vibration frequency spectrum.

The seismic load was specified based on the modification of the linear translational movements of the base of the building under consideration into the force effect on it. The direction of the seismic load in

Table 1. Stiffness and geometric parameters of the reinforced concrete frame elements

Element	Dimensions	Concrete Class	Reinforcement
1. Rigid core	6000 x 6000 mm, wall thickness $t_{\text{wall}} = 250 \text{ mm}$	Heavy, B35	Steel mesh Ø12 A400, spacing – 200 mm
2. Columns	700 x 700 mm – lower part of the building (1/2 of height), 500 x 500 mm – upper part	Heavy, B35	Ø32 A400, spacing – 100 mm (working)
3. Slabs	$t = 200 \text{ mm}$	Heavy, B35	Steel mesh Ø10 A400, spacing – 200 mm

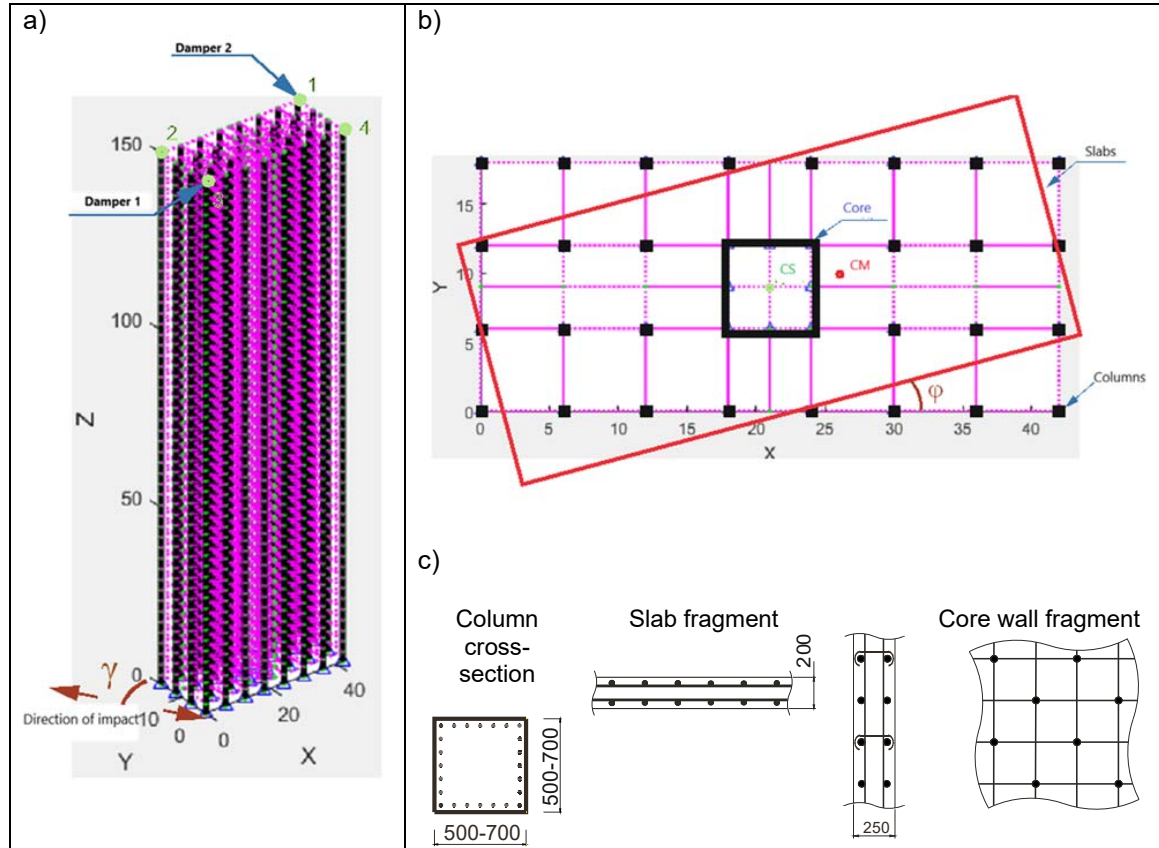


Fig. 1. Design scheme of the building: (a) modelling of the design scheme in the software package; (b) location of structural elements; (c) schemes detailing the reinforcement of various building structures

the horizontal plane OXY depended on the value of the angle θ with the OY axis of the general reference system (Fig. 1a).

To reduce the amplitude of torsional vibrations, the principle of operation of vibration dampers was used (Shein et al., 2025): alternating-sign reactive forces creating a reactive couple are generated by gas jets escaping from nozzle openings under high pressure.

In the proposed studies, the dampers were located in two nodes of the finite element model of the building (Fig. 1a), located at opposite ends of the diagonal. The mutually opposite reactive forces from the dampers, creating a reactive couple, were directed orthogonally to this diagonal.

The dampers were activated when the controlled angle of rotation of the roof around the vertical axis of symmetry passing through the centre of stiffness (CS) (Fig. 1b) reached a specified value $\varphi_{\max}$. The direction of the reactive forces of the dampers was determined by the direction of the velocity vectors of the nodes in which they were located, i.e., opposite to them.

The reactive force arising from the combustion of the fuel mixture is represented by a known function of the form:

$$R = V_e \cdot \frac{dm}{dt}. \quad (5)$$

where V_e is the exhaust velocity of the combustion products, $\dot{m}$ is the rate of change of its mass.

The equation of motion of a finite element node of the design model of the building under study, considering the effects of the reactive force of the damper on it, takes the form:

$$(M_i + m_i)\ddot{u}_i + \sum_{j=1}^n c_{ij}\dot{u}_j + \sum_{j=1}^n k_{ij}u_j = P_i \mp v_e \cdot \dot{m}_i, \quad (6)$$

where m_i is the variable mass of the damper, the diagonal mass matrix:

$$M = \text{diag}[M_1 \ M_2 \ \dots \ M_i + m_{i,t+\Delta t} \ \dots \ M_n], \quad (7)$$

and the column vector of external forces:

$$P = [P_1 \ P_2 \ \dots \ P_i \mp V_e(m_{i,t+\Delta t} - m_{i,t}) / (\Delta t) \ \dots \ P_n]^T. \quad (8)$$

The optimal result of vibration damping is determined by the following key damper parameters:

- exhaust velocity of fuel combustion products (reactive jet) — V_{gas} , m/s,
- time of one cycle of its exhaust — T_{gas} , s,
- maximum permissible value of the angle of rotation of the roof around the vertical axis of symmetry of the protected mechanical system — $\varphi_{\max}$, rad.

The study investigated how the change in the position of the centre of mass affects the torsional

angle of the high-rise building at various directions of seismic effect and various natural vibration frequencies, as well as how the main damper parameters affect the effectiveness of damping torsional vibrations of the building under study.

Results and Discussion

1. Analysis of frequencies and modes of vibration of the high-rise building at various positions of its centre of mass

Using the software package, a frequency analysis of the building was performed depending on the displacement of the centre of mass from the centre of stiffness. The mosaics of the first three natural frequencies, depending on the CM displacement, are shown in Fig. 2.

The characteristic first three natural vibration modes are shown in Fig. 3.

The results obtained show that when the CM is displaced, no significant changes in the values of natural vibration frequencies occur; however, the fundamental mode shapes become bending-torsional.

2. Analysis of torsional angles of the high-rise building at various positions of its centre of mass and changes in the parameters (frequency and direction) of the harmonic effect

Figs. 4–6 show graphs of the torsional angles of the roof slab depending on the displacement of the centre of mass from the centre of stiffness along the coordinate axes OX (X_{cw}) and OY (Y_{cw}).

3. Damping of torsional vibrations using dampers generating reactive couples

Within the framework of this analysis, we proceed from the assumption of the constancy of the gas exhaust velocity from the damper nozzle:

$$V_e = \text{const}, \quad (9)$$

The change in the mass of the fuel fluid is modelled by a decreasing function:

$$m = m_0(1 - \beta t), \quad (10)$$

where β — const [c^{-1}].

The shape of the pulses from the reactive dampers is assumed to be rectangular (sudden application) (Fig. 7).

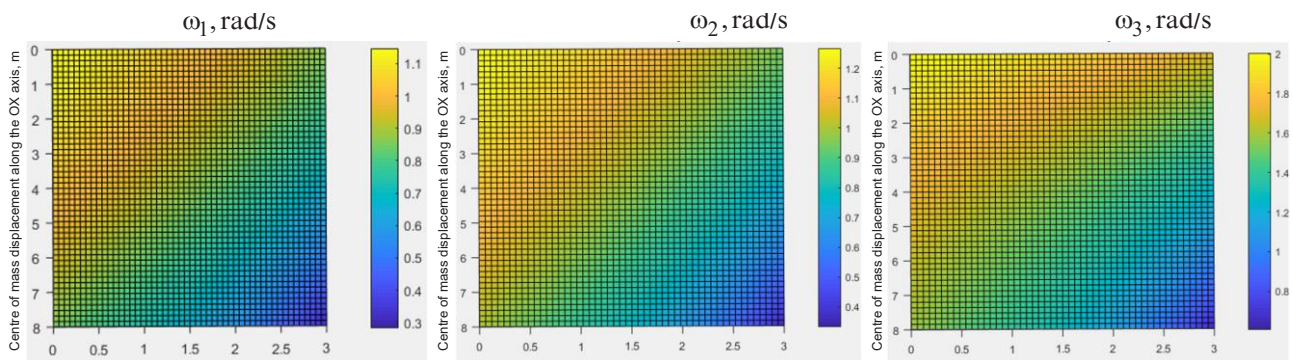


Fig. 2. Frequency mosaics

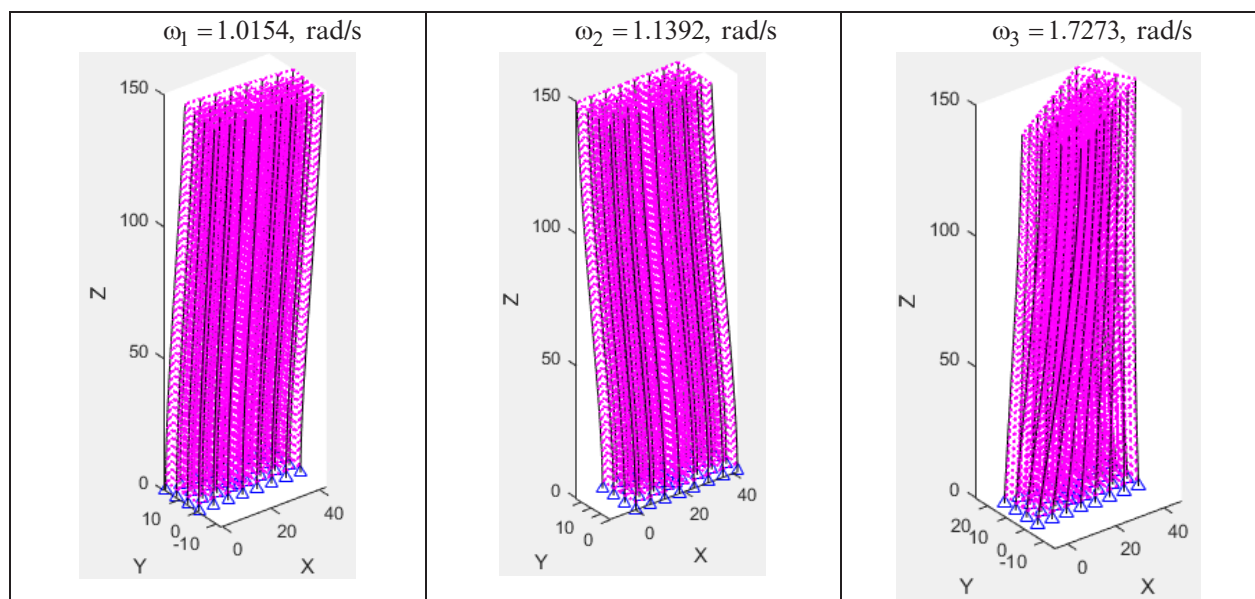


Fig. 3. Vibration modes

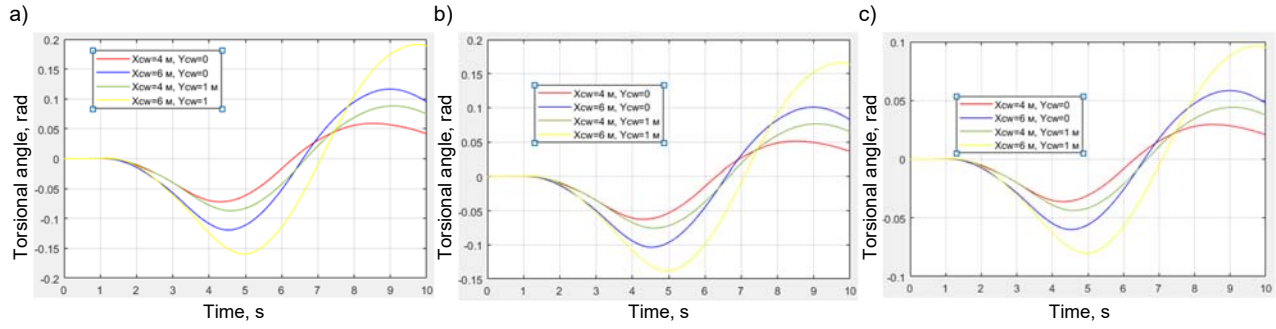


Fig. 4. Torsional angles of the building φ at the disturbing effect frequency $p = 0.5$ rad/s: a) $\gamma = 0^\circ$, b) $\gamma = 30^\circ$, c) $\gamma = 60^\circ$

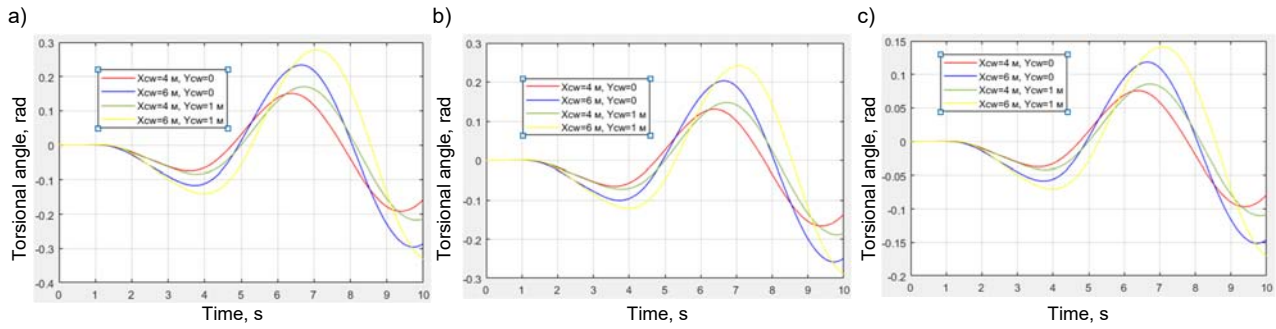


Fig. 5. Torsional angles of the building φ at the disturbing effect frequency $p = 1$ rad/s: a) $\gamma = 0^\circ$, b) $\gamma = 30^\circ$, c) $\gamma = 60^\circ$

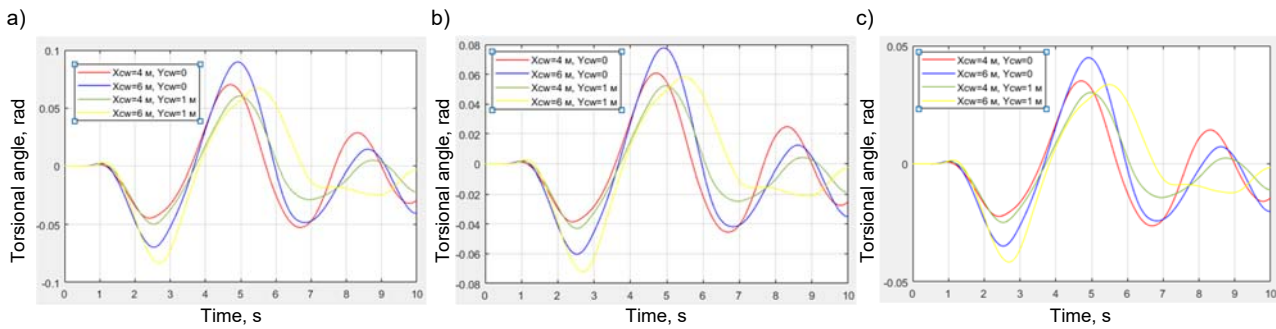


Fig. 6. Torsional angles of the building φ at the disturbing effect frequency $p = 2$ rad/s: a) $\gamma = 0^\circ$, b) $\gamma = 30^\circ$, c) $\gamma = 60^\circ$

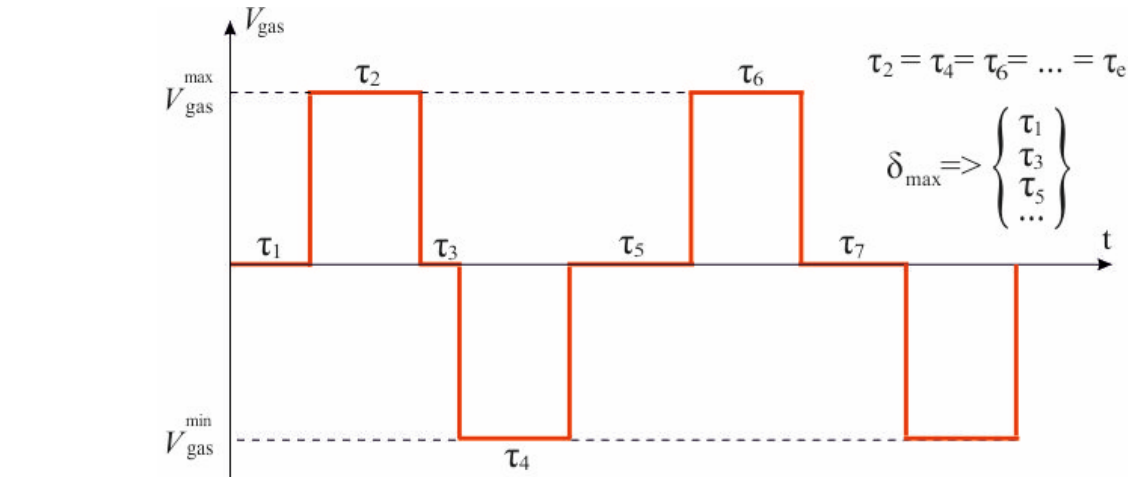


Fig. 7. Dependence of the jet velocity V_{gas} on time

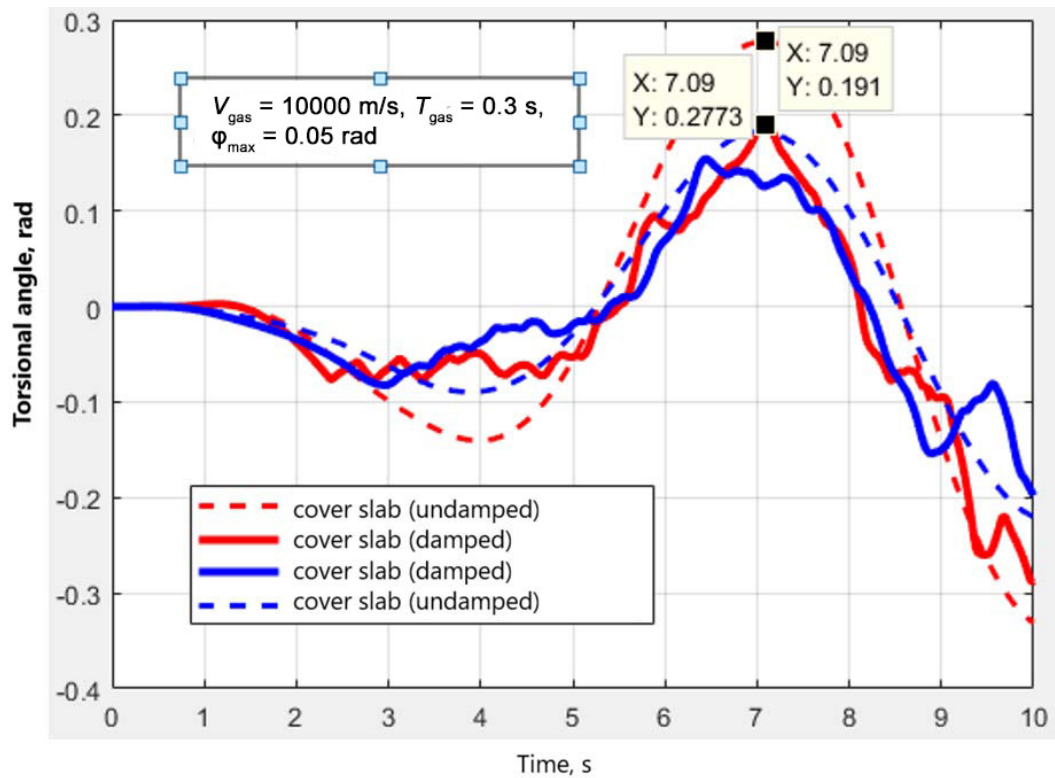


Fig. 8. Torsional angles of slabs

The efficiency of the damper system was assessed based on the analysis of the torsional angles of the roof slab and the floor slab located in the middle of the building height.

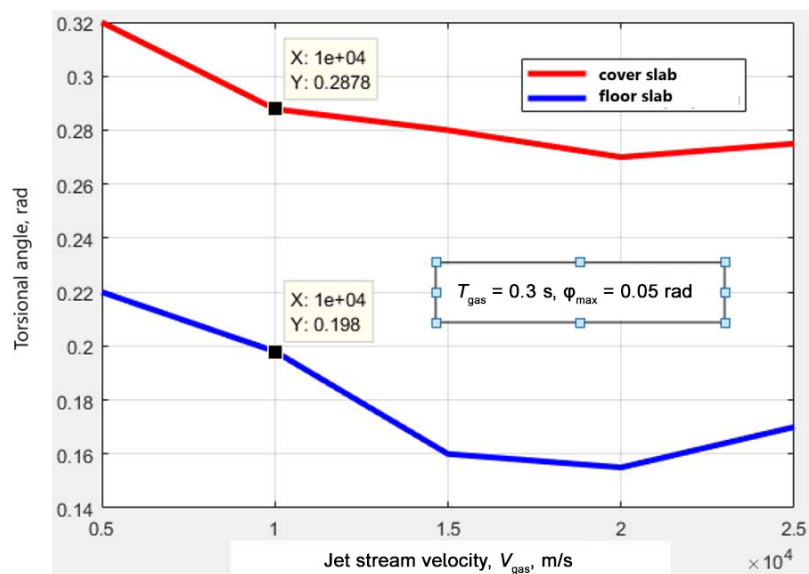
The results obtained at the selected values in the first approximation: $V_{\text{gas}} = 10000 \text{ m/s}$, $T_{\text{gas}} = 0.3 \text{ s}$, $\phi_{\text{max}} = 0.05 \text{ rad}$, are shown in Fig. 8.

The maximum torsional angles of slabs in the form of functional dependences on the main damper

characteristics V_{gas} , T_{gas} , ϕ_{max} are shown in the following graphs (Figs. 9–11).

4. Optimisation of the main characteristics of reactive dampers

Using the developed software package, a tabular dependence of the maximum torsional angle of the floor slab on the velocity V_{gas} and time T_{gas} of the reactive jet exhaust of the dampers was constructed. Using the module of the developed software package

Fig. 9. Maximum torsional angles of slabs as functions of V_{gas} functions of angle ϕ_{max}

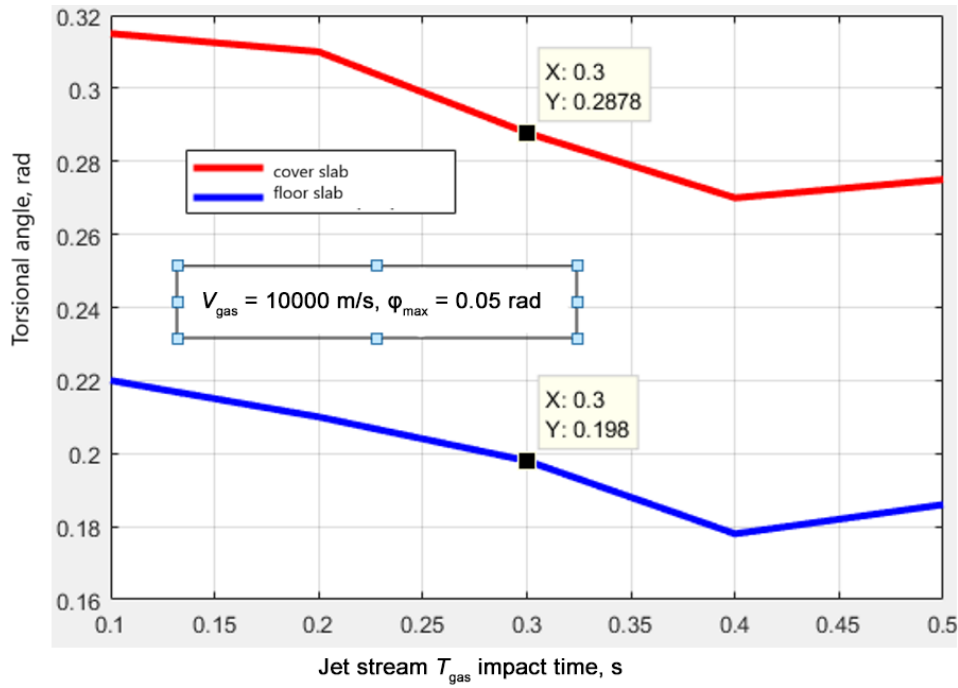


Fig. 10. Maximum torsional angles of slabs as functions of T_{gas}

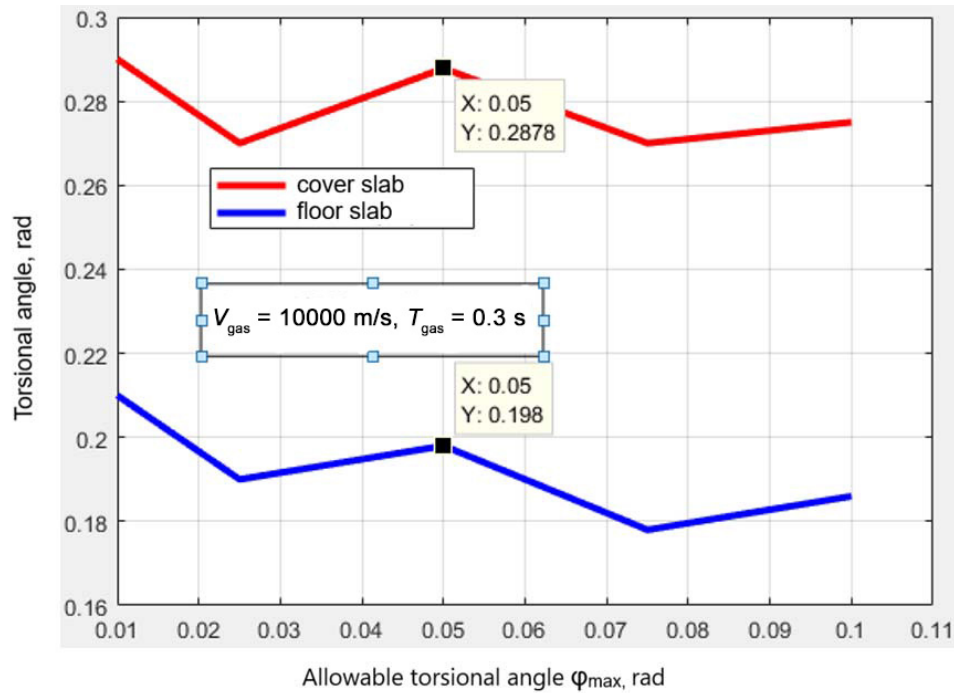


Fig. 11. Maximum torsional angles of slabs as functions of angle ϕ_{max}

for solving optimisation problems, the objective function of the form was minimised (Fig. 12):

$$U_{max}(V_{gas}, T_{gas}) \rightarrow \min.$$

Fig. 13 shows the local minimum of the function of two variables found using the software tool.

The optimal damper characteristics for this task, obtained by calculation: $V_{gas} = 17000$ m/s, $T_{gas} = 0.08$ s (Fig. 14).

Conclusions

The influence of the eccentricity between the CM and the CS on the torsional vibrations of the floors of high-rise buildings around the centre of mass has been investigated. A mathematical model of a high-rise building equipped with dampers generating reactive force couples counteracting torsion has been developed. Numerical testing

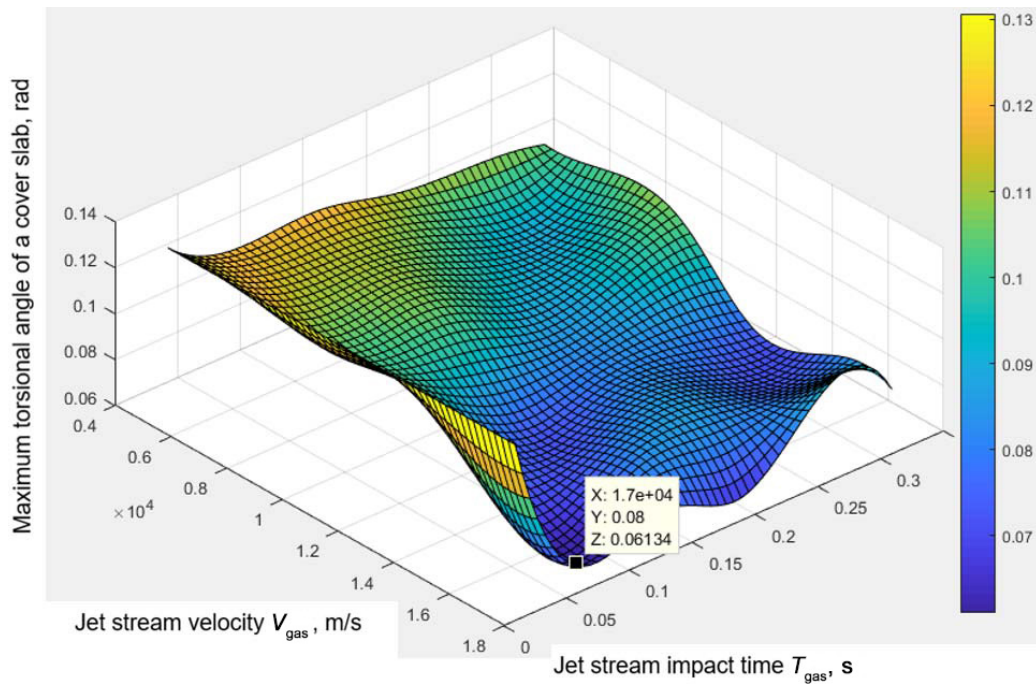


Fig. 12. Analytical function of the torsional angle of the floor slab

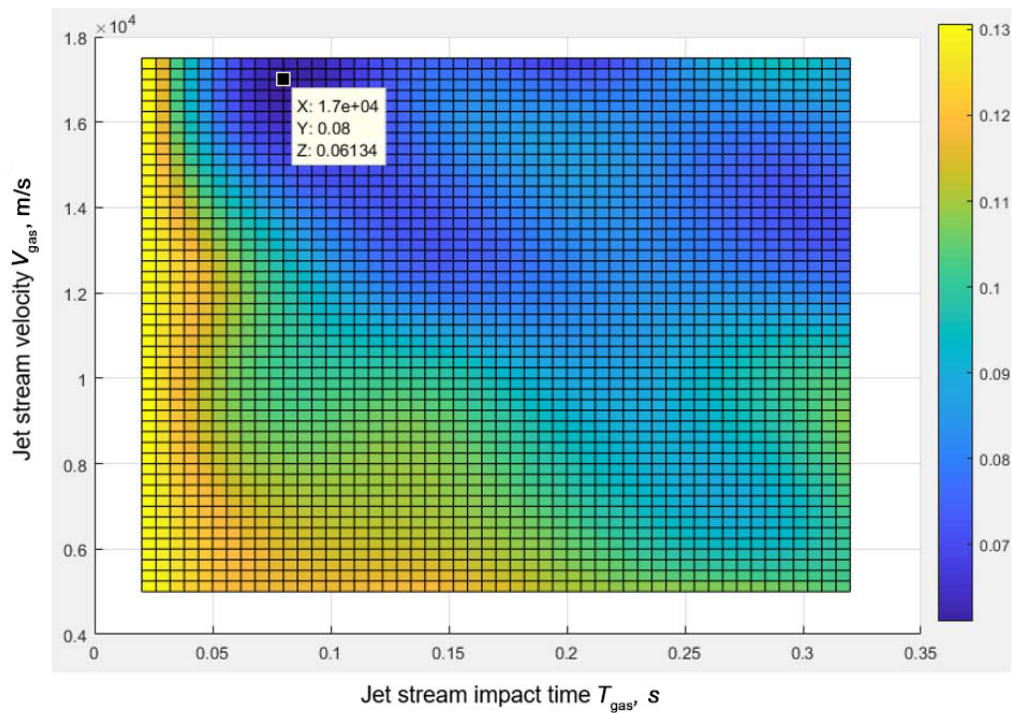


Fig. 13. Maximum torsional angles of the floor slab with local minimum

of the technical means, mathematical model and programme in the MATLAB environment for damping torsional vibrations has been carried out. The evaluation of the performance of the dampers, as well as the selection, tuning and optimisation of their parameters, was carried out based on the results of the analysis of numerical experiments. It is shown that reactive damping of torsional

vibrations can provide increased survivability of high-rise buildings, reducing the level of torsional vibrations by 50–80 %.

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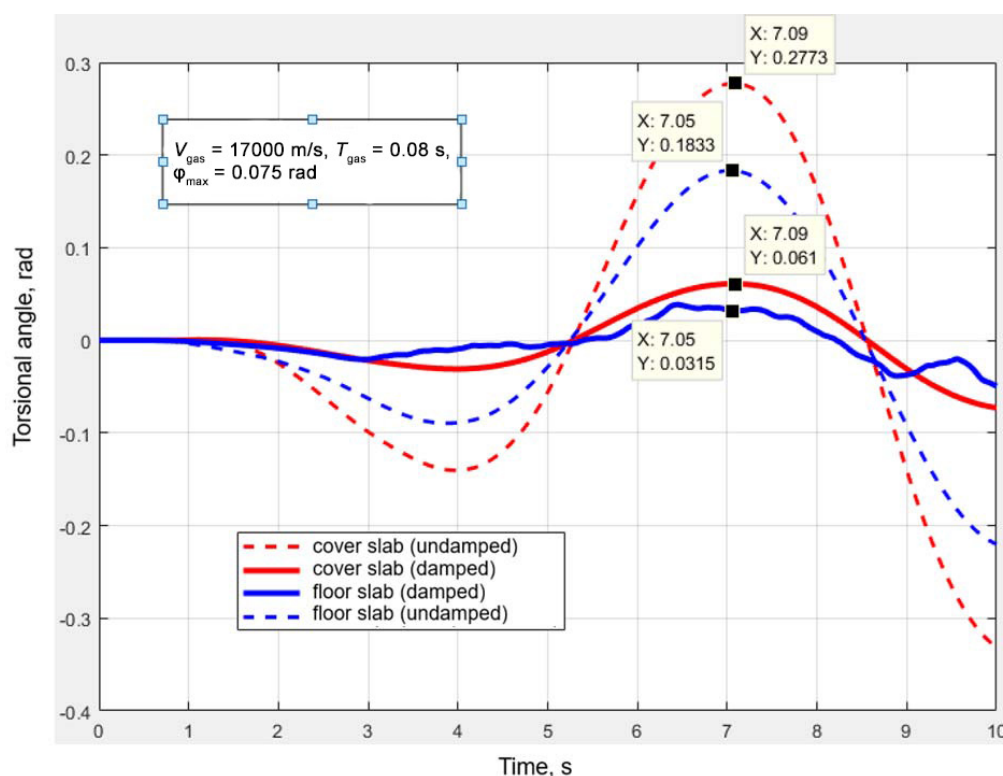


Fig. 14. Torsional angles of slabs at the found optimal damper characteristics

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ГАШЕНИЕ КРУТИЛЬНЫХ КОЛЕБАНИЙ ВЫСОТНЫХ ЗДАНИЙ ПРИ СЕЙСМИЧЕСКИХ ВОЗДЕЙСТВИЯХ С ИСПОЛЬЗОВАНИЕМ ДЕМПФЕРОВ, СОЗДАЮЩИХ РЕАКТИВНЫЕ ПАРЫ СИЛ

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Аннотация

Введение. Для обеспечения безопасности зданий и сооружений в сейсмически активных районах применяются специальные меры защиты от разрушений. Одним из наиболее универсальных, действенных и экономичных методов активного подавления колебаний является способ реактивного демпфирования. Важной формой собственных колебаний зданий являются крутильные движения. Определенные участки сейсмических акселерограмм могут провоцировать развитие таких колебаний. Между крутильными и изгибными формами колебаний существует взаимосвязь: изгибные колебания могут вызывать крутильные деформации, и наоборот. Это происходит из-за того, что центры масс и центры жесткости сечений сооружений в общем случае не совпадают, что приводит к возникновению комбинированных изгибно-крутильных колебаний. Целью данной работы является исследование реакции конечно-элементных (КЭ) моделей высотных зданий на сейсмические воздействия, представленные в виде гармонических функций с переменными частотами при варьировании направления воздействия и положения центра масс, а также всестороннее изучение результатов экспериментов по гашению крутильных колебаний высотных зданий с использованием пары реактивных демпферов, способных генерировать переменные моменты, противодействующие торсионным колебаниям. **Методы.** Для оценки поведения высотных зданий с реактивными демпферами при гармонических нагрузках была исследована соответствующая математическая модель. Расчеты проводились с использованием программного комплекса на основе метода конечных элементов (МКЭ), а динамический отклик конструкции определялся численно методом Ньюмарка. **Результаты.** Разработанное программное средство позволило провести частотно-векторный анализ, учитывающий смещение центра масс от центра жесткости, и получить данные об углах закручивания здания при различных положениях его центра масс и вариациях параметров гармонического воздействия (частоты и направления) с учетом внутреннего трения. Проведено всестороннее изучение результатов экспериментов по гашению крутильных колебаний высотных зданий с использованием пары реактивных демпферов, способных генерировать переменные моменты, противодействующие торсионным колебаниям. Показано, что применение реактивных демпферов с оптимально подобранными параметрами снижает размах амплитуд крутильных колебаний на 50–80 %.

Ключевые слова: высотное здание, сейсмическое воздействие, колебательное движение, центр масс, крутильные колебания, реактивный демпфер, уровень колебаний.