

DAMPING SEISMIC VIBRATIONS IN HIGH-RISE BUILDINGS USING CONTROLLED REACTIVE DAMPERS

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Abstract

Introduction. The paper investigates the dependence of seismic displacements of high-rise buildings on the control parameters of a reactive damper (vibration absorber). A frequency-vector analysis of a building's finite element model is performed. The building's response to non-stationary seismic loads is analyzed with respect to changes in damper parameters: the specified control displacement, the ejection velocity of the reactive jet, and the duration of a single reactive impulse. An algorithm for optimizing the controlled damper parameters is presented. The effectiveness of using a reactive damper to reduce the amplitude of oscillations in a high-rise building is evaluated. Reactive vibration dampers are installed at either one or two levels along the building's height. **Methods.** A mathematical model of the "high-rise building – reactive damper" system under non-stationary (seismic) loading was studied using a software suite based on the finite element method (FEM). The dynamic response of the structure was determined by numerically solving the system of differential equations of motion using Newmark's step-by-step method, implemented by the authors in the Matrix Laboratory environment as a software package. **Results.** The effectiveness of the reactive damper in reducing the amplitude of oscillations in mechanical systems (high-rise buildings) under non-stationary loads is demonstrated. It is assumed that under seismic loading, the damper activates when the displacement of one of the structural nodes exceeds a predetermined value, and the velocity vector of that node determines the direction of the reactive force. Equations of motion for the finite element model of a plate-rod system with an active damper operating on the reactive jet principle are presented. In the Matrix Laboratory interactive numerical computing environment, a software package was developed to solve the system of differential equations describing the motion of the plate-rod FE model of a high-rise building with a damping system. Graphs are provided showing how the effectiveness of the damper varies depending on such parameters as the velocity and duration of the reactive jet ejection (V_{gas} and T_{gas}) as well as the allowable deviation (displacement threshold for damper activation, δ_{max}). The influence of these parameters on damper performance was studied. It was found that the use of a reactive damper with optimally selected parameters reduces the amplitude range of oscillations by 50–80 %, i.e., the reactive system effectively suppresses mechanical vibrations of buildings and structures. A software package was developed to select optimal reactive damper parameters for a given high-rise building.

Keywords: high-rise building, seismic loading, oscillatory motion, reactive damper, vibration level, displacements.

Introduction

Buildings and structures of high criticality, constructed in regions with high seismic activity, require special protection methods. The development of new and the improvement of existing methods for protecting these structures from collapsing is an important and relevant task in construction research. Damping of oscillations allows for effective control over the development of oscillation amplitudes in mechanical systems, and, due to its effectiveness, this method is starting to be widely used in modern construction. Reducing vibration levels in mechanical systems is achieved through various methods, including the use of roller mechanisms (Burtseva et al., 2015), composite polymers (Lasowicz and Jankowski, 2017), friction dampers (Seong and Min, 2011), as well as innovative technological developments (Abramyan et al., 2022).

Modern vibration damping systems encompass a wide range of dampers adapted and optimized for

various applications. In high-rise construction, the most widely used are dynamic vibration dampers such as tuned mass dampers (Etedali and Rakhshani, 2018; Marano et al., 2007; Owji et al., 2011) and tuned mass column dampers (Adam et al., 2017; Altay et al., 2017). Several studies (Tamrazyan and Chernik, 2021; Tamrazyan and Matseevich, 2024) provide assessments of the damageability and impact strength coefficients of high-rise building frames, affecting the oscillatory process under seismic disturbances. Other studies (Shein et al., 2022; Shein and Chumanov, 2021) proposed and analyzed innovative approaches to damping of oscillations in various structures. One such solution is a cable mechanism with a hydraulic cylinder operating in a single direction, for which a calculation algorithm was developed. A liquid damper was described in the work by Shein and Shmelev (2014), and the operating principle of a damper using the reactive impulse from burning fuel was presented in the study

of Shein and Zaytsev (2023). To improve the seismic resistance of buildings, foundation seismic isolation is sometimes used. In particular, Amanollah et al. (2023) examined the effectiveness of rubber-metal supports with a lead core under various earthquake scenarios. The effectiveness of the supports was analyzed using specialized software.

Due to the reactive nature of the force resisting motion, high damping efficiency in high-rise buildings can be achieved at minimal cost. For instance, to reduce the risk of Taipei 101 skyscraper collapsing during earthquakes, a massive 660-ton tuned mass damper is used, which, utilizing the inertia of its own movement, suppresses building's oscillations.

The aim of this study was to develop a mathematical model and calculation algorithm for a high-rise building equipped with reactive dampers for seismic protection and assess the effectiveness of this damping method.

This system generates alternating impulses at specified time intervals, which counteract bending deformations and oscillations of the structure arising from non-stationary seismic loads.

Subject, Objectives, and Methods

The effectiveness of using reactive dampers to reduce the vibration levels of the FE model of a high-rise building under seismic loading was investigated. The dampers were installed at either one or two levels along the building's height. The building is

square in plan (Fig. 1, a–b) with dimensions of 18×18 m and a height of 150 m (50 floors).

The load-bearing elements of the reinforced concrete frame of the building are columns, the core of rigidity, and cast-in-place slabs. The columns have square cross-sections measuring 50×50 and 70×70 cm in the lower and upper parts (halves) of the building, respectively, and are made of heavy concrete of grade M450. The main reinforcement of the columns consists of steel bars $\varnothing 32$ A400 with a spacing of 100 mm. The cross-section of the core of rigidity is box-shaped, measuring 6×6 m, with a wall thickness of $t = 250$ mm. The core material is heavy concrete of grade M450. The main reinforcement elements of the walls are steel bars $\varnothing 12$ A400 arranged in meshes with a cell size of 200×200 mm. The reinforcement of the slabs and roof, made of heavy concrete grade M400, consists of meshes of steel bars $\varnothing 10$ A400 with a spacing of 200 mm. The thickness of the elements is $t = 200$ mm. The reinforcement of the building's load-bearing elements is shown in Fig. 1c.

The seismic load was applied in accordance with the accelerogram of the earthquake that occurred in Loma Prieta, USA, on October 18, 1989, which is characterized by a pronounced peak in translational accelerations (Fig. 2).

The peak values of the seismic impact characteristics are presented in Table.

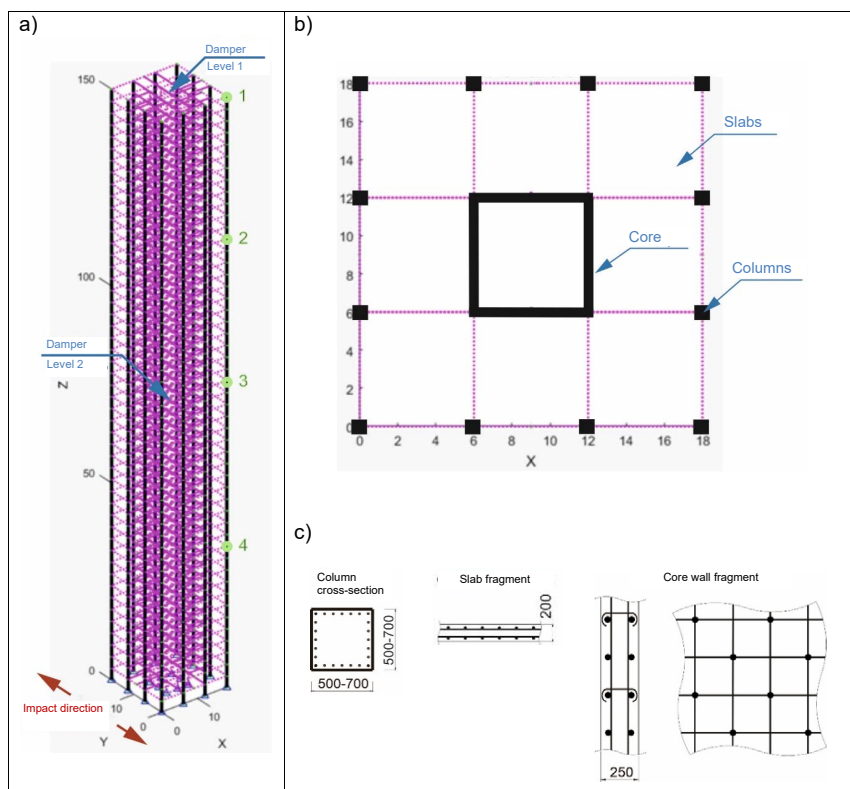


Fig. 1. Modeling of a high-rise building in the software package: (a) design mode; (b) layout of frame elements; (c) reinforcement of load-bearing elements

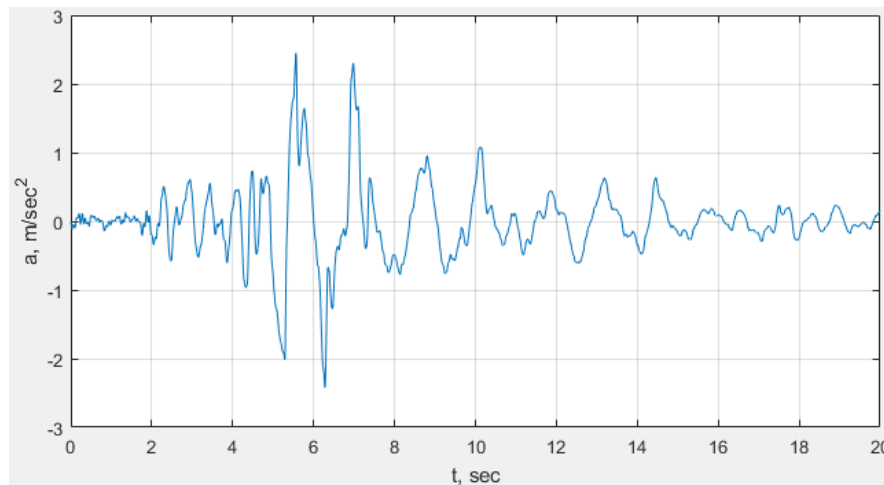


Fig. 2. Design accelerogram

Maximum values of the main seismic impact characteristics

Characteristic	Value (max)	Time t, s
Acceleration	2.451 m/s ²	5.56
Speed	0.427 m/s	5.35
Displacement	0.116 m	12.48

The studies were carried out using a software package developed by the authors in the Matrix Laboratory interactive numerical computing environment, which solves the system of differential equations describing the motion of the plate-rod FE model of the high-rise building with a damping system. The rectangular finite element of a thin plate used in the calculation of the plate-rod model is characterized by one linear (perpendicular to the FE

plane) and two rotational displacements (rotations around the local axes of the FE out of its plane) at the node. The rod finite element has six degrees of freedom at the node. In this study, the direction of the seismic load was chosen along one of the axes of the global coordinate system (OY axis). The disturbance was created by converting the kinematic effect into a force effect. Fig. 1a shows the FE model of the investigated high-rise building. The results of determining the displacements of the control nodes of the plate-rod model under the considered seismic impact are presented in Fig. 3.

Reducing the amplitude of oscillations at a certain moment will be achieved by alternating reactive impulses of the gas jet ejected at high velocity from the damper nozzles.

The damper represents a block consisting of two oppositely directed reactive units (Fig. 4).

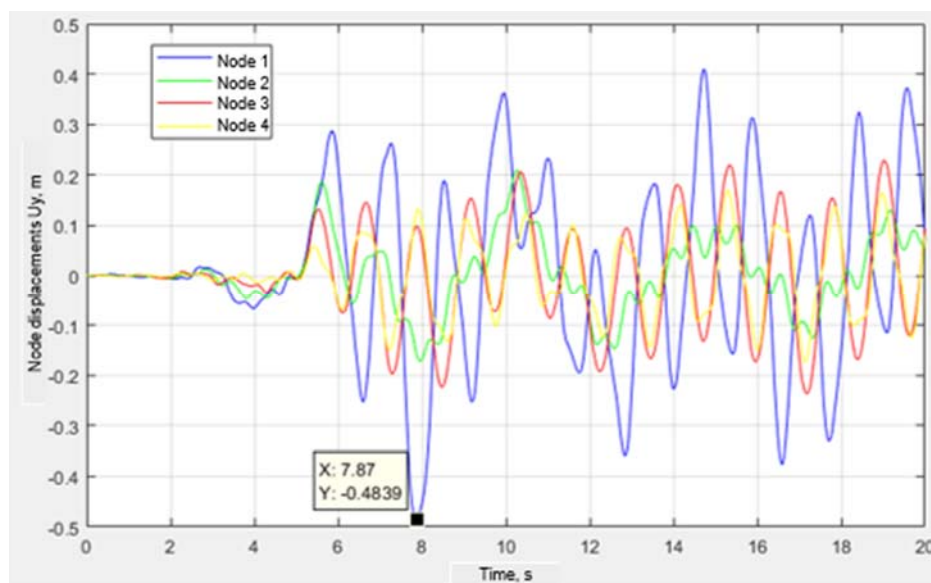


Fig. 3. Linear displacements along the Y-axis of nodes 1–4 of the design model of the building without damping

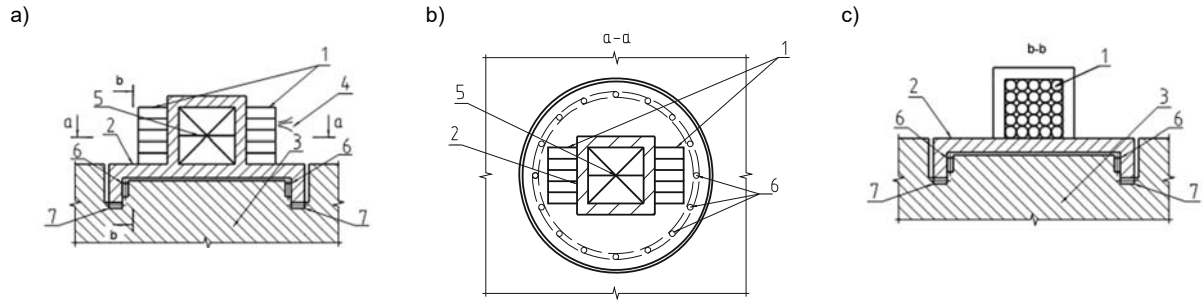


Fig. 4. Reactive vibration damper: (a) side view; (b) view a-a; (c) view b-b. 1 — sequentially operating reactive unit, 2 — support-rotating block, 3 — support surface, 4 — reactive impulses, 5 — stop to ensure the stiffness of the support block, 6 — vertical cylindrical rolling bearings, 7 — horizontal conical rolling bearings for horizontal orientation of the block

In the proposed studies, the dampers were installed at two levels along the height of the finite element model of the building (Fig. 1a). The reactive forces from the dampers were applied to the central node of the upper cross-section of the core of rigidity (level 1) and to the central node of the cross-section of the core of rigidity (level 2), the height position of which was determined based on the calculation of natural frequencies and mode shapes using the Frequencies module of the aforementioned software, which solves systems of equations of the following form:

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

where M is the mass matrix, K is the stiffness matrix, and ω is the natural frequency.

The effectiveness of both a single damper installed at level 1 and its operation in combination with a damper installed at level 2 was evaluated.

The dampers are activated when the displacement of one of the characteristic nodes 1 or 3, located at the damper installation level (Fig. 1a), exceeds the value δ_{max} . The vector of the damper reactive force is directed opposite to the velocity vector of the characteristic node.

The reactive force of the burning fuel is represented by the following relationship:

$$R = V_e \cdot \frac{dm}{dt}, \quad (2)$$

where V_e is the gas jet ejection velocity, and $\dot{m}$ is the fuel consumption rate.

The equation of motion for a node of the finite element model of the high-rise building with an operating damper is as follows:

$$(M_i + m_i)\ddot{u}_i + \sum_{j=1}^n k_{ij}u_j = P_i \mp V_e \cdot \dot{m}_i, \quad (3)$$

where m_i is the variable mass of the damper.

The mass matrix of the moving system and the external force vector can be represented as:

$$M = \text{diag}[M_1 \ M_2 \ \dots \ M_i + m_{i,t+\Delta t} \ \dots \ M_n], \quad (4)$$

$$P = [P_1 \ P_2 \ \dots \ P_i \mp V_e(m_{i,t+\Delta t} - m_{i,t}) / (\Delta t) \ \dots \ P_n]^T. \quad (5)$$

The main parameters of the damper affecting its performance are:

- gas jet velocity V_{gas} , m/s;
- operating time per activation T_{gas} , m/s;
- maximum displacement limit for the nodes of the damped structure δ_{max} , m.

The study analyzed the influence of these reactive damper characteristics on the effectiveness of reducing the vibration levels of the high-rise building.

Results and Discussion

Frequency-vector analysis

Fig. 5 shows the results of determining the first three frequencies and mode shapes of the investigated system using the developed software package.

The obtained results show that placing dampers at the roof level according to the first mode shape and at mid-height of the building according to the third mode shape will lead to more effective suppression of oscillations.

Suddenly applied load from the reactive damper (Fig. 6)

Let us assume that the velocity of the damper's reactive jet is constant:

$$V_e = \text{const}, \quad (6)$$

and the function of fuel mass loss is given as:

$$m = m_0(1 - \beta t), \quad (7)$$

where β is a constant factor, $[s^{(-1)}]$.

1.1. Damping of oscillations using a damper placed at one level

Fig. 7 presents the results of determining the displacements of characteristic nodes 1 and 3 of the high-rise building model upon the operation of a damper with specified parameters.

Graphs of the maximum displacements of nodes 1–4 of the design building model (Fig. 1a) as functions of the main damper characteristics are presented in Figs. 8–10.

1.2. Damping of oscillations using dampers placed at two levels

The results of the calculations over the time interval $5 \leq t \leq 10$ s, where a pronounced peak of translational accelerations is observed on the

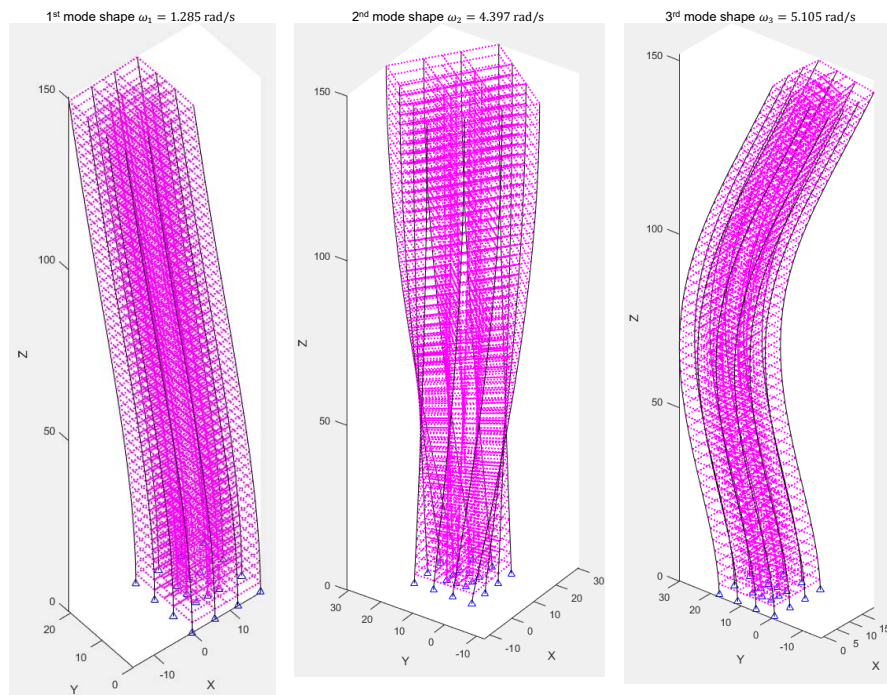


Fig. 5. Results of the frequency-vector analysis of the high-rise building model

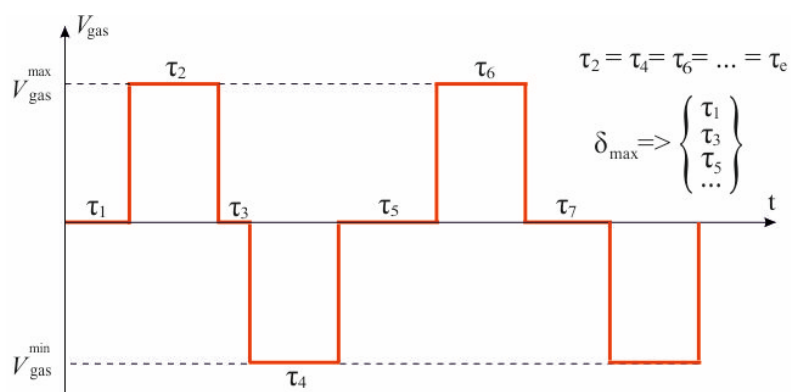


Fig. 6. Gas jet velocity under a suddenly applied load

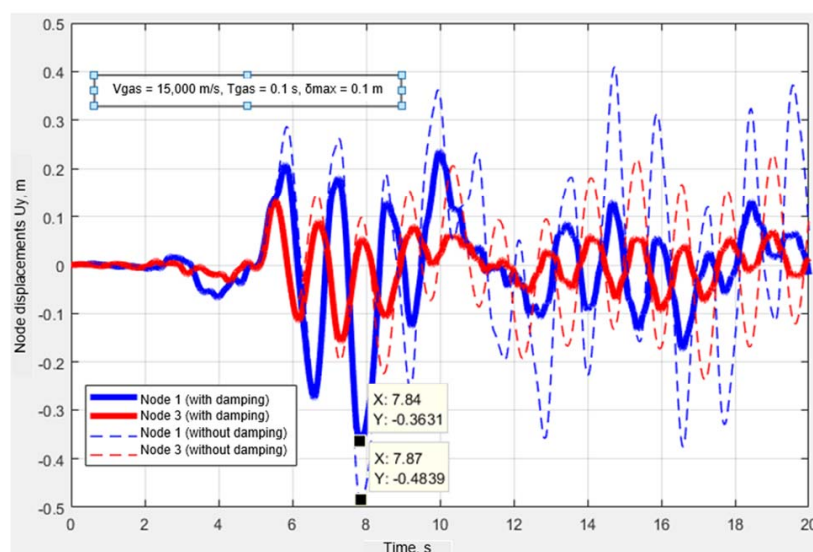


Fig. 7. Displacements of characteristic nodes 1 and 3 during oscillation damping

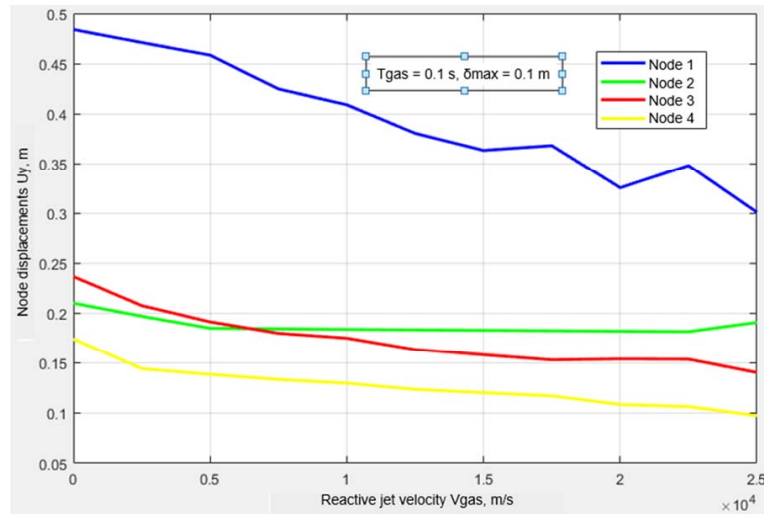


Fig. 8. Graph of the maximum displacements of nodes 1–4 of the building model depending on the damper parameter V_{gas}

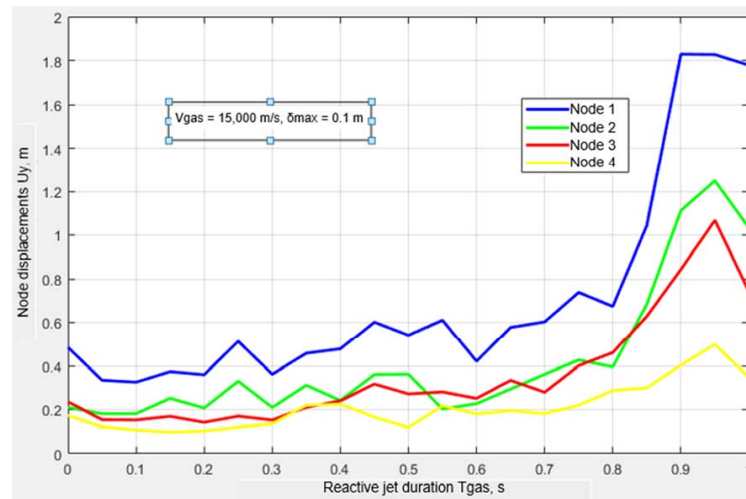


Fig. 9. Graph of the maximum displacements of nodes 1–4 of the building model depending on the damper parameter T_{gas}

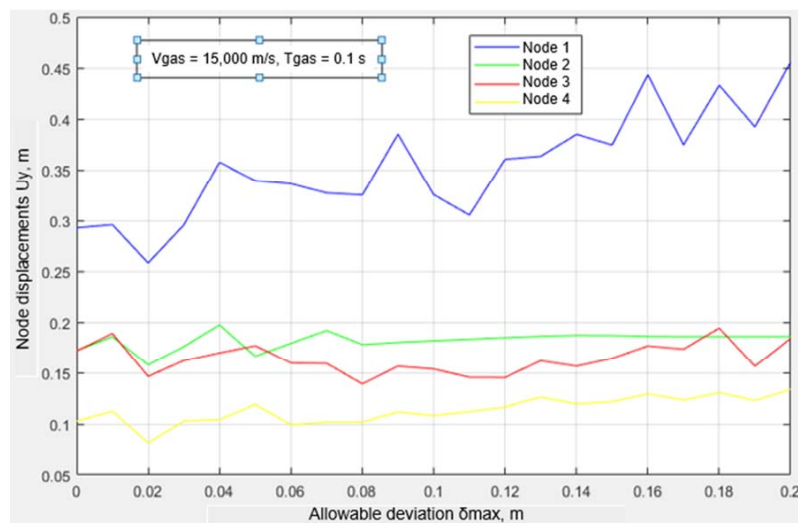


Fig. 10. Graph of the maximum displacements of nodes 1–4 of the building model depending on the damper parameter δ_{max}

accelerogram (Fig. 2), are presented in Fig. 11. In this case, the reactive force from the damper at level 2 was applied to the central node of the cross-section of the core of rigidity, located at mid-height of the building according to the results of the frequency-vector analysis. The direction of the force was taken opposite to the velocity vector of the node. The evaluation of damper efficiency was carried out based on the kinematic characteristics of nodes 1 and 3 of the building model, located in the planes of action of the corresponding reactive forces (Fig. 1a).

Optimization of Damper Parameters

Using the developed software package, a table was compiled showing the dependence of the maximum displacement of node 1 on the parameters V_{gas} and T_{gas} of the reactive damper located at level 1

(a function of two variables). By applying spline interpolation, the objective function was obtained in analytical form (Fig. 12):

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

The software package makes it possible to determine the minima of the objective function of the damper's variable parameters (Fig. 13).

Fig. 14 presents the results of the calculation with selected optimal damper characteristics, when four charges are activated simultaneously: $V_{gas} = 8,368$ m/s ($4 * 8268 = 33,472$ m/s), $T_{gas} = 0.051$ s.

Conclusions

The process of active damping of vibrations in high-rise buildings, caused by non-stationary natural impacts, has been studied. The practical

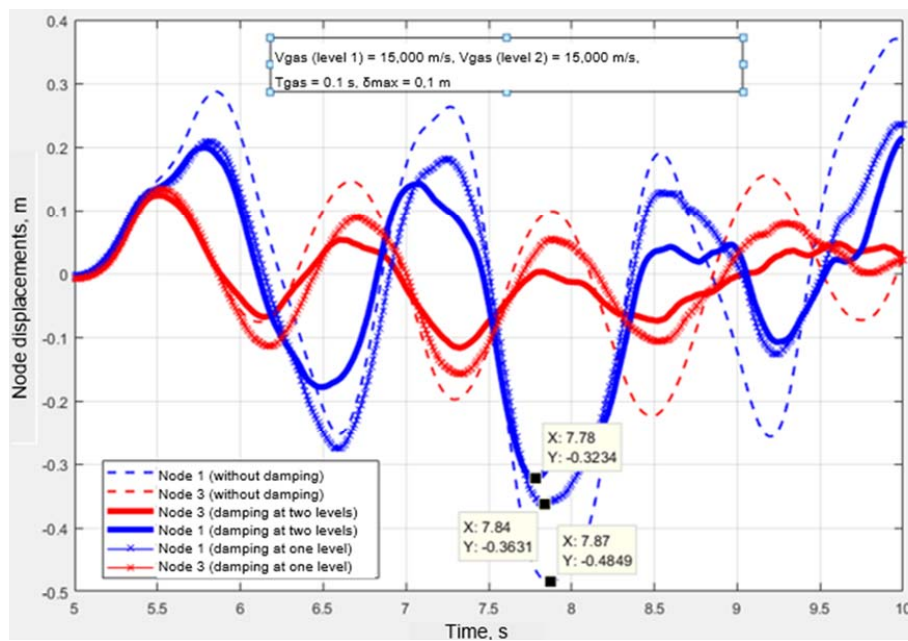


Fig. 11. Displacements of nodes 1 and 3 with dampers operating at two levels

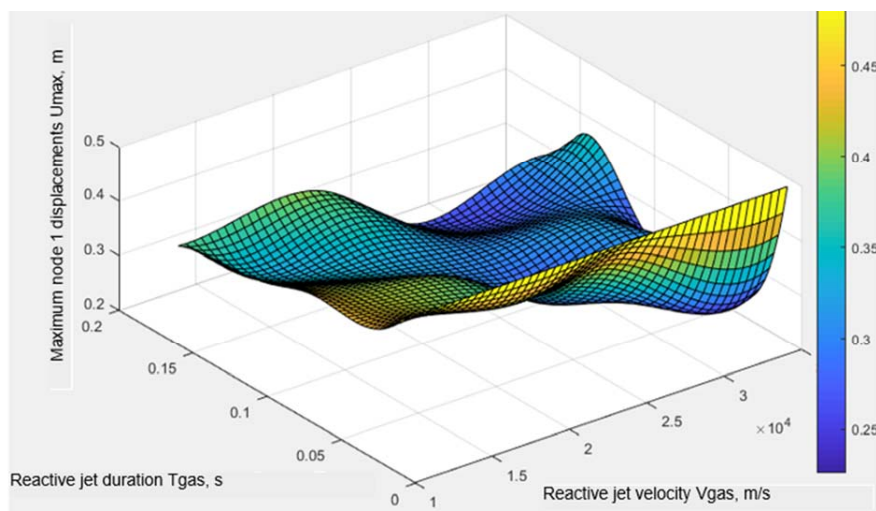


Fig. 12. Objective function of two variable parameters of the reactive damper

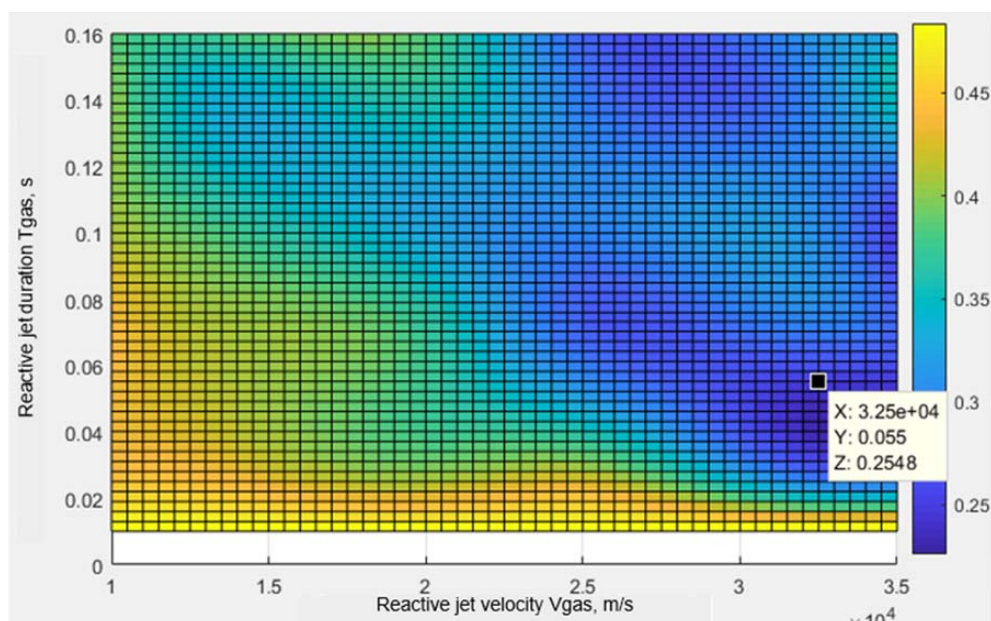


Fig. 13. Determination of local minima of the objective function of the maximum displacements of node 1

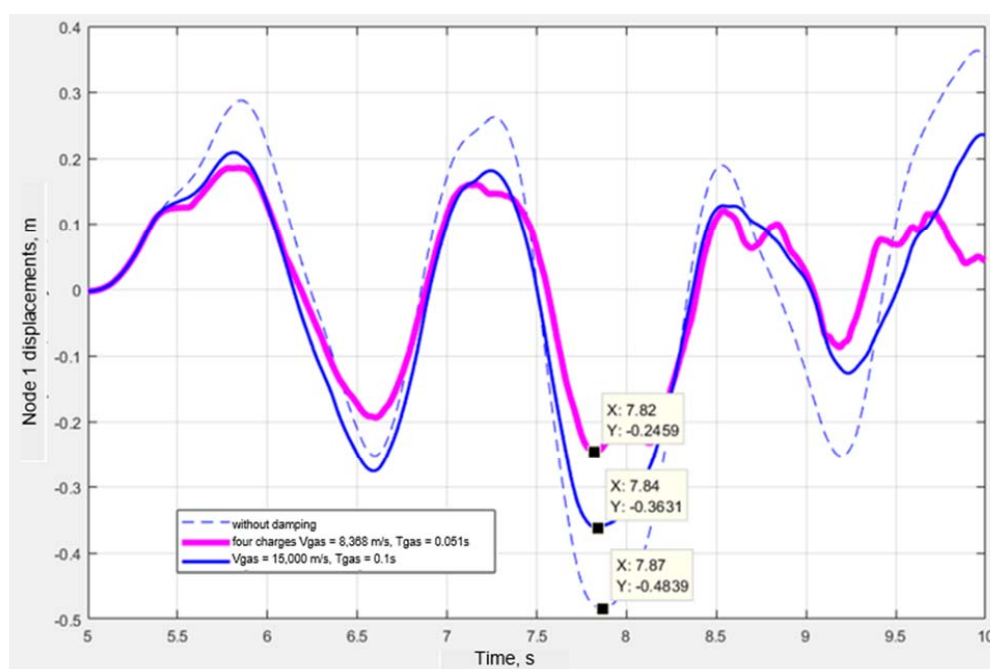


Fig. 14. Analysis of the displacements of node 1 with the obtained optimal characteristics of the reactive damper

suppression of vibrations in the mathematical model “building – damper” was carried out using controlled reactive impulses, which act as generators of resistance forces to motion. It has been shown that the proposed damping system makes it possible to reduce vibration amplitudes by more than half.

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ГАШЕНИЕ СЕЙСМИЧЕСКИХ КОЛЕБАНИЙ ВЫСОТНЫХ ЗДАНИЙ С ПОМОЩЬЮ УПРАВЛЯЕМЫХ РЕАКТИВНЫХ ДЕМПФЕРОВ

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Аннотация

Введение. Исследуется зависимость величины сейсмических перемещений высотных зданий от параметров управления реактивным демпфером (гасителем) колебаний. Выполнен частотно - векторный анализ конечно-элементной модели здания. Анализируется реакция здания, подверженного нестационарным сейсмическим воздействиям, на изменение параметров демпфера: заданной величины контрольного перемещения, скорости выбрасывания реактивной струи, времени однократного реактивного импульса. Представлен алгоритм оптимизации управляемых параметров демпфера. Оценивается эффективность применения реактивного демпфера для уменьшения размаха колебаний высотного здания. Реактивные демпферы колебаний устанавливаются как в одном, так и в двух уровнях по высоте здания. **Методы:** исследовалась математическая модель системы «высотное здание - реактивный демпфер» при нестационарном (сейсмическом) воздействии с использованием программного комплекса, основанного на методе конечных элементов (МКЭ). Динамический отклик конструкции определялся численным решением системы дифференциальных уравнений движения с помощью шагового метода Ньюмарка, реализованного авторами в среде «Matrix Laboratory» в виде программного комплекса. **Результаты:** Доказана эффективность применения реактивного демпфера для снижения размаха колебаний механических систем (высотных зданий) при нестационарных нагрузках. Принято, что при сейсмическом воздействии на сооружение демпфер активируется в случае, когда перемещение одного из узлов конструкции превышает наперед заданное значение, а вектор скорости этого узла определяет направление реактивной силы. Представлены уравнения движения конечно-элементной модели пластинчато-стержневой системы с активным демпфером, работающим на принципе реактивной струи. В интерактивной среде для численных вычислений «Matrix Laboratory» разработан программный комплекс для решения системы дифференциальных уравнений, описывающих движение пластинчато-стержневой КЭ модели высотного здания с системой демпфирования. Получены графики, показывающие, как изменяется эффективность работы демпфера в зависимости от таких параметров, как скорость и время выброса реактивной струи (V_{gas} и T_{gas}), а также от допустимого отклонения (ограничения по перемещениям для включения гасителя δ_{max}). Проведено исследование влияния указанных параметров на эффективность работы демпфера. Установлено, что применение реактивного демпфера с оптимально подобранными параметрами снижает размах амплитуд колебаний на 50–80 %, т.е. реактивная система эффективно гасит механические колебания зданий и сооружений. Разработан программный комплекс, позволяющий подобрать оптимальные, для данного высотного здания, параметры реактивного демпфера.

Ключевые слова: высотное здание, сейсмическое воздействие, колебательное движение, реактивный демпфер, уровень колебаний, перемещения.