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ANALYTICAL EVALUATION OF BASE CONTROL SYSTEM EFFECTIVENESS FOR REGULATION SEISMIC RESPONSE OF SUSPENDED EQUIPMENT BRACED WITH METAL FRAMES BY HYSTERESIS DAMPERS

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Abstract: Equipment suspended from metal frames, such as steam boilers, usually has a bracing system that reduces the oscillation amplitude of equipment during an earthquake to technologically acceptable values. Hysteresis dampers are often used as bracing elements, the installation of which affects frame dynamic response. If frame stress-strain state worsens when dampers are used, it is advisable to additionally use a Base Control System (BCS), the optimal parameters of which must be selected during the design process. This ensures both the strength and reliability of building structures in case of an earthquake, and the most financially economical technical solution. BCS includes elastic spring elements that carry the load from the frame and equipment, and viscous dampers that decrease vibrations and increase the overall damping of the structural system. Detailed finite element models are not applicable for optimization analysis purposes. It requires significant time and computing resources in conditions of the nonlinear nature of the constructive system. In this paper an analytical model of the "suspended equipment – frame" system with bracing hysteresis dampers and BCS is proposed. This model is easily implemented using MathCAD software programming tools. The paper also analyzes the possibility of implementing BCS for the purpose of seismic insulation of frames and boilers during seismic impacts of various frequency compositions. It is shown how different parameters of the seismic insulation elements can affect the efficiency of its installation. It is noted that it is necessary to determine the most optimal number of viscous dampers, at which the maximum decrease in the seismic response is observed.

Keywords: metal frame, suspended steam boiler, hysteresis damper, base control system, seismic response, earthquake, analytical model

АНАЛИТИЧЕСКАЯ ОЦЕНКА ЭФФЕКТИВНОСТИ ПРИМЕНЕНИЯ СИСТЕМЫ КОНТРОЛЯ ПЕРЕМЕЩЕНИЙ (BCS) ДЛЯ РЕГУЛИРОВАНИЯ СЕЙСМИЧЕСКОГО ОТКЛИКА ПОДВЕШЕННОГО ОБОРУДОВАНИЯ, РАСКРЕПЛЕННОГО УПРУГОПЛАСТИЧЕСКИМИ ДЕМПФЕРАМИ С МЕТАЛЛИЧЕСКИМИ КАРКАСАМИ

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Аннотация: Оборудование, подвешенное к опорным металлических каркасам, например, паровые котлоагрегаты, обычно имеет систему раскрепления, которая снижает амплитуду сейсмических колебаний до технологически приемлемых значений. В качестве элементов раскрепления используются упругопластические демпферы, установка которых влияет на динамические характеристики конструктивной системы. Если напряженно-деформированное состояние элементов металлического каркаса ухудшается при использовании демпферов, рекомендуется дополнительно использовать систему контроля перемещений (BCS), оптимальные параметры которой должны быть определены в процессе проектирования. При этом одновременно обеспечиваются требования к сейсмостойкости конструкций и экономичности принимаемых технических решений. BCS включает в себя блоки пружин – опоры, воспринимающие нагрузку от каркаса и оборудования, и вязкие демпферы, повышающие общее демпфирование системы. Подробные конечно-элементные модели не применимы для целей оптимизационного анализа эффективности BCS, поскольку в условиях нелинейного характера работы системы они требуют значительных временных и программно-вычислительных ресурсов. В данной статье предлагается аналитическая модель системы "подвесное оборудование – каркас" с упругопластическими демпферами и системой BCS, которая легко реализуется алгоритмами программы MathCAD. В статье также анализируется возможность применения BCS с целью сейсмоизоляции подвешенного оборудования (котлов) и каркасов при воздействиях различного частотного состава. Показано, как различные параметры элементов BCS могут влиять на эффективность. Отмечается, что необходимо определить наиболее оптимальное количество вязких демпферов, при котором наблюдается максимальное снижение сейсмического отклика.

Ключевые слова: металлический каркас, подвесной паровой котел, упругопластический демпфер, система контроля перемещений (BCS), сейсмическая реакция, землетрясение, аналитическая модель

INTRODUCTION

Large-sized suspended equipment can oscillate with considerable amplitude during an earthquake. As a rule, its displacements are limited to small values for technological reasons. First of all, it is possible to destroy pipelines and cables that ensure the normal operation of the equipment. In addition, significant displacements cause a high level of bending stresses in suspension system, which can lead to plastic deformations, suspension breakage and equipment collapse. Any of the above situations are considered emergencies. A minimal consequence of these is a temporary equipment failure. The most significant consequences are technogenic disasters, which can be accompanied by environmental damage, destruction of infrastructure, and loss of life. To ensure safe operation in case of earthquakes, various means of seismic isolation, energy dissipation and vibration damping are used [1-4].

Thermal power plants (TPP) are danger objects. Most of them are equipped with high-energy steam boilers suspended from freestanding metal frames inside TPP buildings (fig. 1). In this paper, boilers suspended from frames are considered as one of the most common types of sus-pended equipment.

Boilers and frames have weights up to several tens of thousands of tons, dimensions in plan and height up to 100 m [3-6]. The dynamic characteristics of the frames and boilers are well studied, and regardless of the standard sizes they have a number of similar characteristics [6]:

– the predominant oscillation frequencies of the frame in both horizontal directions are approximately the same and are in the range of 1 – 2 Hz;

– the predominant oscillation frequencies of suspended boilers are in the range of 0.1 – 0.5 Hz;

– the modal mass of the first oscillation frequency for the frame is 60 – 80%, the type of vibration is flexural, similar to a single-mass oscillator; the ratios between the frame mass (M_f) and boiler mass (M_b) as a rule, the ratio of M_f / M_b = 1/4 is observed.

– the torsional forms of natural oscillations are of little importance.

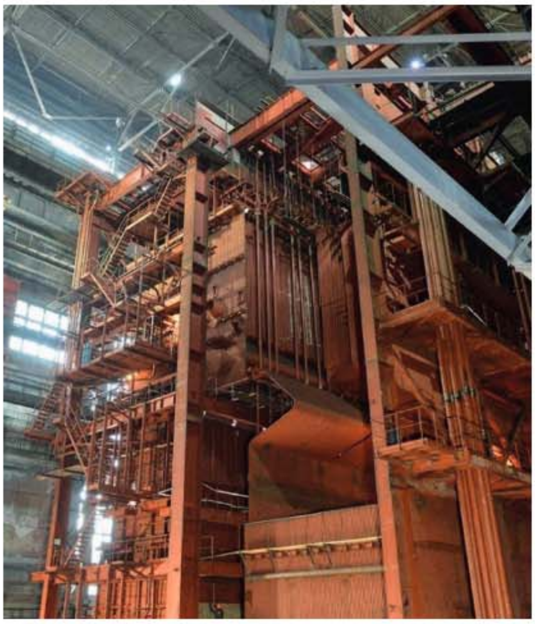
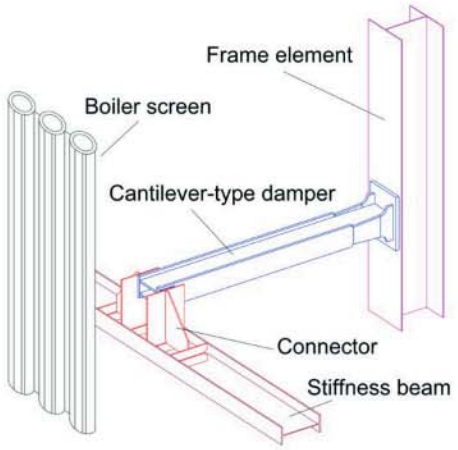
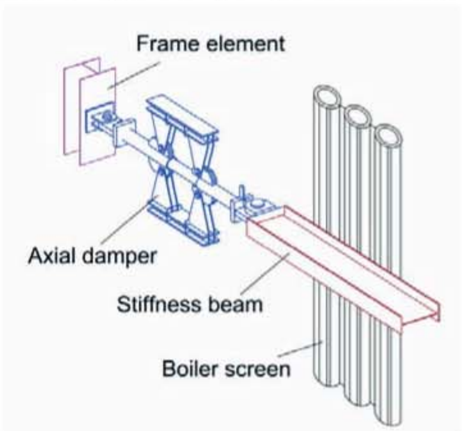


Figure 1. Metal frame with suspended equipment (steam boiler)

Studies [7-11] have shown that hysteresis dampers of various types, for example, cantilever type dampers and axial dampers (fig. 2) with a localized zone of plastic deformations, can be effective to reduce the amplitude of boiler vibrations and prevent emergencies. These structures have passed cyclic dynamic tests (fig. 3) showed stable hysteresis operation for a large number of loading cycles up to maximum operating amplitudes without failure. The hysteresis is reproduced qualitatively in numerical simulation programs (fig. 4). This allows you to carry out design work without additional expensive full-scale tests.



a) cantilever-type damper (installation scheme)



b) axial damper (installation scheme)

Figure 2. Hysteresis dampers for antiseismic bracing frame and boiler

Figure 3. Full-scale experiment for axial damper

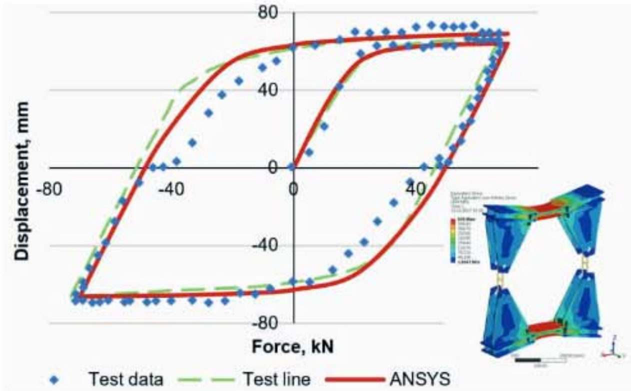


Figure 4. Comparison of test and numerical results for hysteresis damper

Hysteresis dampers reduces boiler displacements effectively during an earthquake. It is established that their introduction corrects the dynamic characteristics of the structural system "frame-boiler". Therefore, it is required to perform an optimization analysis of the effectiveness of the solution being developed. This makes it possible to reduce the movements of the frame elements and reduce the momentary load on the supporting zones of the frame columns, which ensures its earthquake resistance.

However, in some cases, the optimal parameters of hysteresis dampers cannot be selected. The introduction of these elements leads to a deterioration of the stress-strain state of the building structures of the frame. In this case, the design solutions of the frame are adjusted [12] (changes in the cross-sections of the elements; the device of additional connections and stiffness elements) or traditional seismic insulation systems are used [8,13,14].

Among all of the existing spatial passive 3D developments of isolation devices, the most effective and reliable system seems to be the Base Control System (BCS) [15-18]. The application of the base control system for various NPP equipment [17,18] and for massive turbine foundations [19,20] has been widely studied at the present time. However, possibilities of effective use BCS for the "frame-boiler" system have not been studied in detail before. This work is intended to fill this gap.

It is proposed to consider the possibility of using BCS that includes elastic elements – spring supports and viscous dampers (fig. 3 – a). Due to the application of spring elements the mode shape of the isolation structure is changed and fundamental period of vibration increases. The second measure is based on the increase of damping that may be combined with the reduction of the frequency. More other, BCS provides vibration damping in both the horizontal and vertical directions of seismic vibrations. It is known that most traditional means of seismic isolation increase the vertical response due to their significant rigidity. This is unacceptable for the frame-boiler system, since it is possible to significantly redistribute the forces in the suspensions and overload them, which requires compensatory measures. BCS has been experimentally tested and its effectiveness has been confirmed by CKTI-VIBROSEISM Co. Ltd. (fig. 3 – b) [13].

a) viscous damper and spring (BCS elements)

b) BCS full-scale test

Figure 5. Base Control System for regulating seismic response [13]

METHODS AND MATERIALS

It is impractical to perform full-scale tests or detailed finite element calculations for preliminary estimates of the effectiveness of BCS. Therefore, in this work, an analytical model of the structural system "suspended equipment (boiler) – hysteresis dampers – metal frame – BCS" is being developed.

The analytical model makes it possible to estimate the acceleration and displacement of its components, which are used as basic parameters for evaluating the effectiveness of the developed seismic insulation solutions. It is impossible to perform a direct assessment of the stress-strain state of building structures; however, an indirect qualitative assessment can be given.

The analytical model assumes the use of simplified models of dampers. One of the most widely accepted differential model Bouk-Wen [21-23] is used to describe the hysteresis nature of dampers. In this model, the restoring force and deformation are related by a nonlinear first-order differential equation containing a number of parameters that refine the shape of hysteresis loops in accordance with experimental data [24-26]. According to [21,24], a hysteresis damper can be represented as elastic post yielding spring (F^{el}) and hysteretic spring (Z), giving in total a full restoring force ($F_{u,Z}$):

$$F_{u,Z} = F^{el} + Z. \tag{1}$$

The hysteresis force Z is expressed as

$$\frac{dZ}{dt} = \left\{Ak_d - \left[\gamma + \beta sign\left(Z\frac{du}{dt}\right)\right]|Z|^n\right\}\frac{du}{dt}, \qquad (2)$$

there u – displacement;
t – time;
A, β, γ – parameters regulating the duration of plastic deformations and the shape of the hysteresis loop;
n – parameter regulating the sharpness of the transition from the elastic to the plastic stage;
k_d – a parameter equal to the difference between elastic k_i and plastic k_f stiffness according to a characteristic bilinear diagram:

$$k_d = k_i - k_f. \qquad (3)$$

Parameters A, β, γ, n are determined individually for each designed device with hysteresis according to experimental or calculated graphs of material deformation for one full cycle of operation.
Focusing on the researches of Aida, Nishida et al. [9,27] and decoupling criteria in regulatory documents (ASCE 4-16, ASN guide 2006, CEA 2008, ETC-C 2012) [28-30], it was previously proposed to idealize the "frame – N hysteresis dampers – boiler" system to 3DOF oscillator (fig. 5) [6,7], where:
– the subsystem approximating vertical load-bearing frame structures below the level of the mass center consists of mass m_1 and connection elastic bonds to the base with stiffness k_1 and damping c_1;
– the subsystem approximating the frame overlap with adjacent vertical structures consists of mass m_2 connected by elastic bonds (stiffness k_2 and damping c_2) with mass m_1;
– masses m_1 and m_2 with elastic bonds k_1, c_1 and k_2, c_2 provide the first modal response of the frame;
– the subsystem approximating a boiler consists of mass m_3, elastic bond with mass m_2 (a model of a boiler suspension system with stiffness k_3 and damping c_3) and hysteresis bond with mass m_1 (a model of dampers).

The features of k_1, k_2, c_1, c_2 parameter determination are presented in detail in the study [6].
The analytical model is determined by solving a system of 4 differential equations of motion, which is written as follows for 3DOF oscillator:

$$\begin{gathered}
m_1\frac{d^2x_1}{dt^2} + c_1\frac{dx_1}{dt} + k_1x_1 - c_2\frac{d(x_2 - x_1)}{dt} - \\
-k_2(x_2 - x_1) - Nk_f(x_3 - x_1) - NZ = -m_1y''(t), \\
m_2\frac{d^2x_2}{dt^2} + c_2\frac{d(x_2 - x_1)}{dt} + k_2(x_2 - x_1) - \\
-c_3\frac{d(x_3 - x_2)}{dt} - k_3(x_3 - x_2) = -m_2y''(t), \\
m_3\frac{d^2x_3}{dt^2} + c_3\frac{d(x_3 - x_2)}{dt} + k_3(x_3 - x_2) + \\
+Nk_f(x_3 - x_1) + NZ = -m_3y''(t), \\
\frac{dZ}{dt} = \left\{Ak_d - \left[\gamma + \beta sign\left(Z\frac{d(x_3 - x_1)}{dt}\right)\right]|Z|^n\right\}\frac{d(x_3 - x_1)}{dt},
\end{gathered} \qquad (4)$$

there $y''(t)$ – ground acceleration;
x_i – mass displacements (i = 1, 2, 3).

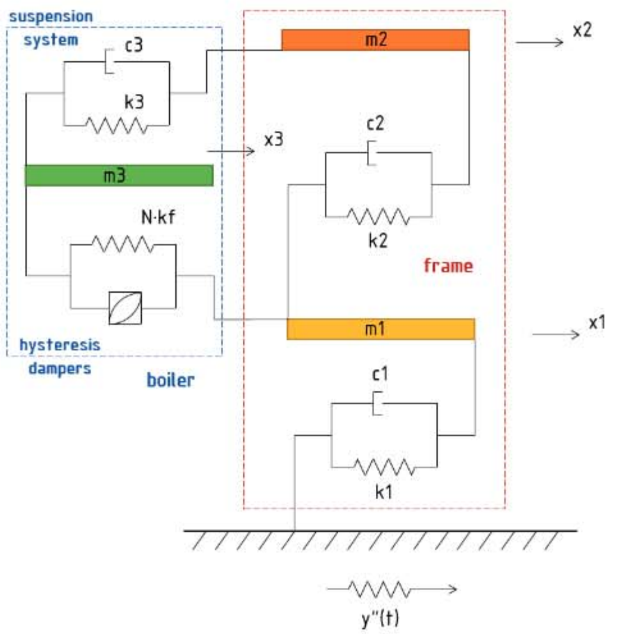


Figure 6. 3DOF oscillator – an analytical model of the "frame – N hysteresis dampers – boiler" system

3DOF model provides quantitative and qualitative matching of results with finite element calculations (the discrepancy between the results is up to 10%), which allows to use this model at the pre-initial design stages [6,7].

BCS is mounted to the foundation. To support the frame with a suspended boiler on it, it is necessary to arrange an intermediate plate (MS). Its load-bearing capacity should be sufficient to wear loads from higher structures.

According to experimental data [16], BCS spring elements (fig. 7) can be considered as elastic bonds (fig. 8) with a linear relationship between the applied force and the acquired displacement.

Figure 7. BCS spring block

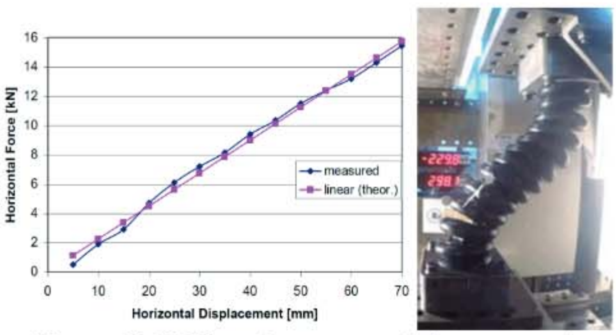


Figure 8. BCS spring test and theory results

Viscous dampers (fig. 9) are widely used for their essential advantages [31,32]:

– reducing vibration and dynamic response of systems in all degrees of freedom by tremendous increasing of system's damping with possibility to tune to optimal damping;

– developing high damping forces under any dynamic impact whereas slow motions are free; stability to high temperature, humid, toxic and radiation environment.

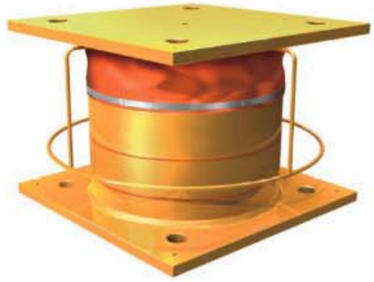


Figure 9. Viscous damper

Viscous liquid defines damper viscous-elastic behavior. The simplest mathematical model describing such behavior is a Maxwell Model consists of ideal viscous damper and spring element chain (2-parameters Maxwell Model). This model demonstrates the following typical features:

– reaction at the low frequency range is considered as viscous;

– reaction at the high frequency range is considered as essentially elastic.

Dynamic characteristics of viscous dampers derived from the experiments are more complex than 2-parameters Maxwell Model. It was recognized that a set of two parallel Maxwell chains, or 4-parameters Maxwell Model demonstrates quite appropriate results (fig. 10). This model is used in regulatory document [33] in the present time.

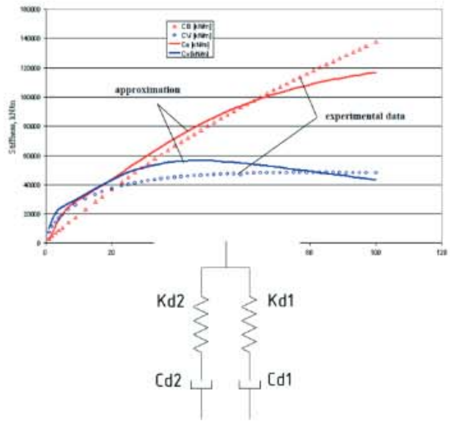


Figure 10. Approximation of test data with 4-parameters Maxwell Model for viscous damper

Considering BSC modeling features, 3DOF analytical model (fig. 6) can be supplemented and represented as in Figure 11.

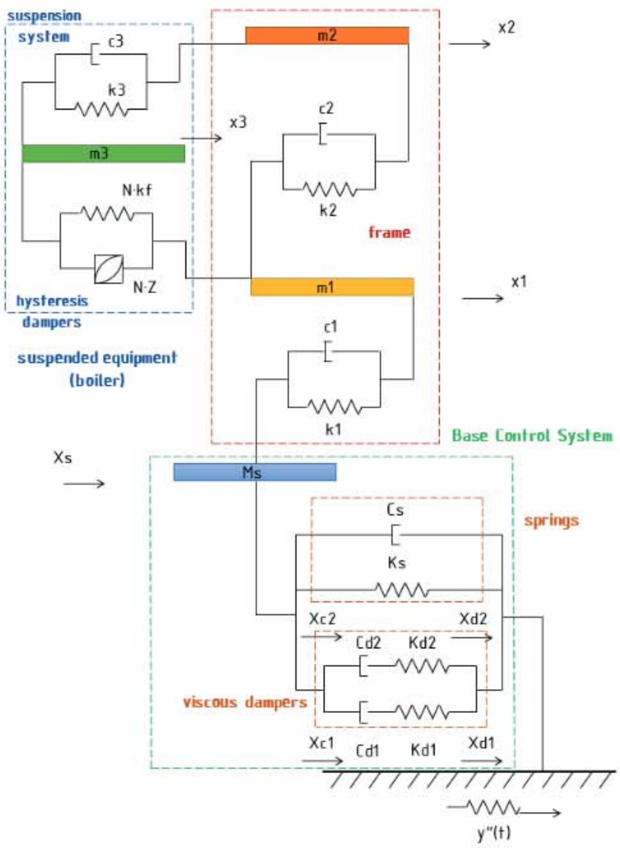


Figure 11. The "suspended equipment (boiler) – hysteresis dampers – metal frame – BCS" analytical model

The system of 7 differential equations of motion [34] for the "suspended equipment (boiler) – hysteresis dampers – metal frame – BCS" system is written as:

$$
\begin{gathered}
m_s\frac{d^2x_s}{dt^2}+c_s\frac{dx_s}{dt}+k_sx_s+k_{d1}(x_s-x_{d1})+ \\
+k_{d2}(x_s-x_{d2})-c_1\frac{d(x_1-x_s)}{dt}-k_1(x_1-x_s)= \\
=-m_sy^{"}(t), \\
k_{d1}x_{d1}=c_{d1}\frac{dx_{c1}}{dt}, \\
k_{d2}x_{d2}=c_{d2}\frac{dx_{c2}}{dt}, \\
m_1\frac{d^2x_1}{dt^2}+c_1\frac{d(x_1-x_s)}{dt}+k_1(x_1-x_s) \\
-c_2\frac{d(x_2-x_1)}{dt}- \\
-k_2(x_2-x_1)-Nk_f(x_3-x_1)-NZ=-m_1y^{"}(t), \\
m_2\frac{d^2x_2}{dt^2}+c_2\frac{d(x_2-x_1)}{dt}+k_2(x_2-x_1)- \\
-c_3\frac{d(x_3-x_2)}{dt}-k_3(x_3-x_2)=-m_2y^{"}(t), \\
m_3\frac{d^2x_3}{dt^2}+c_3\frac{d(x_3-x_2)}{dt}+k_3(x_3-x_2)+ \\
+Nk_f(x_3-x_1)+NZ=-m_3y^{"}(t), \\
\frac{dZ}{dt}=\left\{Ak_a-\left[\gamma+\beta sign\left(Z\frac{d(x_3-x_1)}{dt}\right)\right]|Z|^n\right\}\frac{d(x_3-x_1)}{dt},
\end{gathered}
\tag{5}
$$

there $k_{d1}, k_{d2}, c_{d1}, c_{d2}$ – stiffness and damping parameters of viscous dampers (4-parameters Maxwell Model);

$x_{d1}, x_{d2}, x_{c1}, x_{c2}$ – viscous damper model element displacements;

x_s – intermediate plate (Ms) displacements.

The solution of eq. (5) is performed automatically in the MathCAD program according to the algorithms described in [6].

RESULTS AND DISCUSSION

In this paper an analysis of the effect of adding BCS on boiler and frame response is performed (seismic displacements are compared as the main parameters regulated by the norms). The "frame - boiler" system without hysteresis dampers is considered as a basic situation. The first design situation considers the installation of hysteresis dampers only. These situations are analyzed using eq. (4). Next, the BCS parameters are varied (the number of dampers and the stiffness of spring supports). To analyze a system with an additional mounted BSC a model according to eq. (5) is used.

The "frame – N hysteresis dampers – boiler" system described in detail in the dissertation work was chosen as the research object [6]. The main parameters of the object for analytical models are:

– the first natural frequency – f_1 = 1.25 Hz;

– the total horizontal stiffness of the suspension system – 2202000 N/m;

– the frame mass – 1053138.1 N·s²/m; the overlap mass – 401355.7 N·s²/m; the frame mass below the level of the mass center of the boiler – 513720.2 N·s²/m; the boiler mass – 921238.4 N·s²/m;

– m_1 = 513720.2 N·s^2/m, k_1 = 95238095 N/m, c_1 = 699500 N·s/m;
– m_2 = 539417.9 N·s^2/m, k_2 = 81300812 N/m, c_2 = 662200 N·s/m;
– m_3 = 921238.4 N·s^2/m, k_3 = 2202000 N/m, c_3 = 142400 N·s/m;
– characteristics of hysteresis dampers: $k_i = 4.24 \cdot 10^6$ N/m, $k_f = 1.27 \cdot 10^5$ N/m, n = 2.0, A = 1.45, $\gamma = \beta = 0.00013$ N^{-1}/m;
– hysteresis damper number – 6 pcs (constant value).

3 variants of seismic impact spectrum (fig. 12) with different frequency compositions are considered:
– low-frequency spectrum (Bukharest, 1977) with maximum response below 1 Hz (the zone of the main oscillation frequencies for boilers);
– medium-frequency spectrum (synthesized [6]) with maximum response in the range of 1...2 Hz (characteristic range of the main oscillation frequencies for frames);
– high-frequency spectrum (Valparaiso, 1985) with maximum response in the range of 2...10 Hz (range of higher oscillation frequency forms for frames).

To perform calculations using eq. (4) and eq. (5), accelerograms of impacts were generated in the CVSpec program.

For the analysis, considering significant frame and boiler masses, viscous dampers of large standard size VD 630/325-15 were selected. Damper characteristics are shown in Table 1. In the work, the number of dampers is varied (the range from 2 to 42 pieces is considered).

The mass of the additional base plate is assumed to be no more than 5% of the total mass of the frame and boiler (M_s = 100000 N·s^2/m).

The total stiffness of spring supports varies 4 times (10000 kN/m, 20000 kN/m, 40000 kN/m, 60000 kN/m).

Further, all calculated results will be presented in figures, including cases when BCS seismic displacements exceed the acceptable parameter (Table 1). This makes it possible to analyze the effect of the introduction of additional damping on the seismic response of the system. In the tables such results are highlighted in red, and in figures they are indicated by unshaded markers.

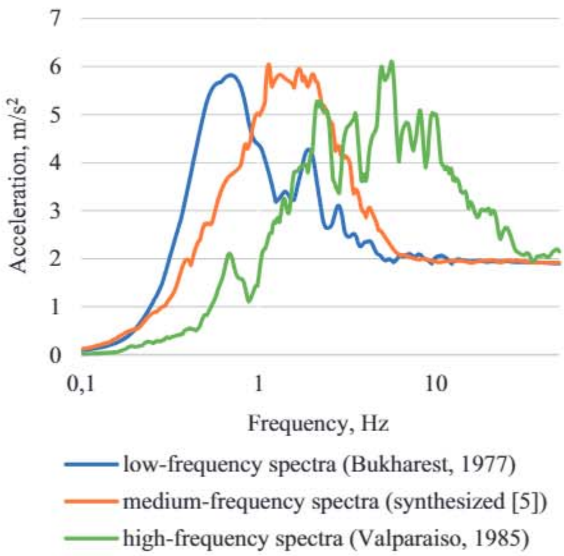


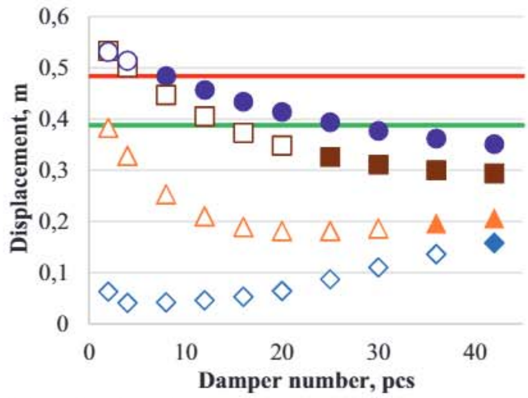
Figure 12. Seismic impact spectra

Table 1. VD 630/325-15 characteristics

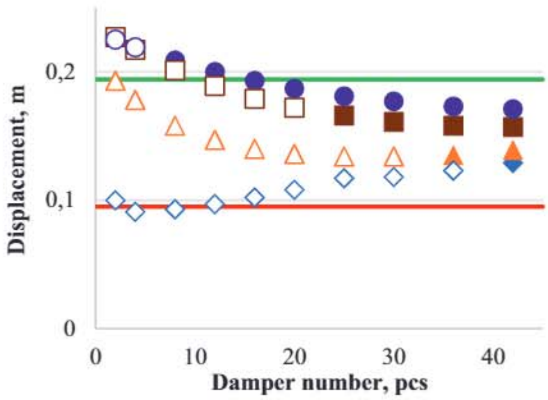
K_1, kN/m	K_2, kN/m	C_1, rad/sec	C_2, rad/sec	Acceptable displacement, mm
8479.9	14635.6	32.4	179.6	122

The first series of 42 calculations was performed for the low-frequency spectrum. Figure 13 shows the change nature in maximum seismic displacements for boiler (a) and frame overlap (b).

As we can see, the first design situation provides a relatively small (20%) decrease in boiler displacements and a sharp (up to 2 times) increase in frame overlap displacements, which significantly increases the loss probability of its overall stability and stresses in the frame columns. The addition of hysteresis dampers can increase the rigidity of the connections between the boiler and the frame. In the end, this requires consideration of a different system, when the frame and the boiler oscillate together. In this case, the oscillation frequency of the system will decrease significantly, which will lead to operation in the peak zone of the low-frequency spectrum.



a) boiler displacement



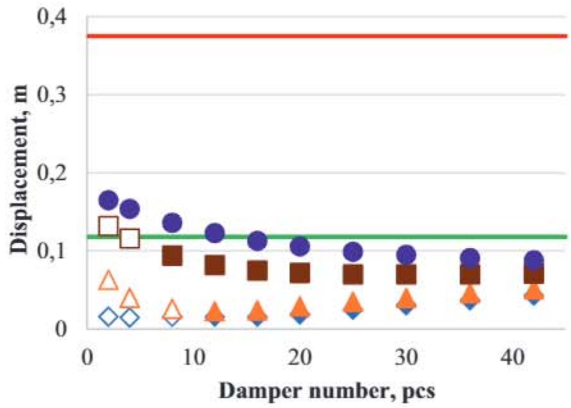
b) frame overlap displacement

Basic situation — First design situation
VD + 10000 kN/m — VD + 20000 kN/m
VD + 40000 kN/m — VD + 60000 kN/m

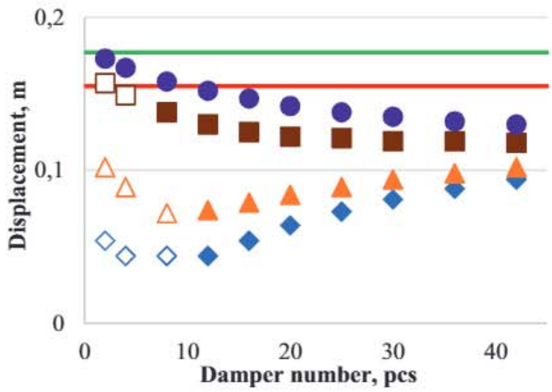
Figure 13. Results for the low-frequency spectrum (Bukharest, 1977)

With a low level of rigidity and additional damping of the seismic insulation, it becomes possible to significantly enhance the effect of the seismic insulation of the boiler. Its displacements are reduced many times, providing a technologically safe level. At the same time, the seismic response of the frame remains or slightly exceeds the basic situation level, and the dynamic factor is in the range of 1...1.4. However, this positive effect is achieved due to the possibility of significant movements of the seismic insulation, which in the case of BCS have limitations for both spring supports and viscous dampers. I.e. it is not feasible in practice and it is necessary to consider other means of seismic isolation. Increasing the rigidity of the seismic insulation significantly reduces the positive effects. It is known that BCS causes a decrease in the predominant oscillation frequency of the structure. For boiler frames with the first frequency at the level of 1...2 Hz, this leads to operation in the peak zone of low-frequency spectrum. Accordingly, in almost all cases, there is an increase in the response of the system in comparison with the basic situation.

The second series of 42 calculations was performed for the medium-frequency spectrum. Figure 14 shows the change nature in maximum seismic displacements for boiler (a) and frame overlap (b).



a) boiler displacement



b) frame overlap displacement

Basic situation — First design situation
VD + 10000 kN/m — VD + 20000 kN/m
VD + 40000 kN/m — VD + 60000 kN/m

Figure 14. Results for the medium-frequency spectrum (synthesized [5])

In almost all cases, BCS shows effectiveness. Reduction in the frame seismic response can reach 70% in comparison with the basic situation. BSC spring elements with low rigidity (up to 20% of rigidity for vertical frame structures below the level of the mass center) ensures maximum effect. For more rigid BSC spring elements, there is a significant decrease in efficiency (with a low level of damping, the dynamic factor is in the range of 1...1.2). This positive effect is logical, since a decrease in the frame predominant oscillation frequency ensures operation in the zone to the left of the peak acceleration values of the spectrum. In addition, BSC spring elements with low rigidity provides an additional reduction in the seismic response of the boiler compared to the first design situation by an amount from 40 to 90%.

With low stiffness of the BCS spring elements, the zone of the optimum number of viscous dampers (additional damping) is clearly visible, after which an increase in their number leads to a tightening of the BCS and a decrease in the positive effect. For cases of high rigidity of BCS spring elements, the optimum is determined by the asymptote. The required optimal number of viscous dampers increases, making this solution both technically and economically impractical.

The third series of 42 calculations was performed for the high-frequency spectrum. Figure 15 shows the change nature in maximum seismic displacements for boiler (a) and frame overlap (b).

For seismic impacts with predominant high frequencies (compared to the system frequency), the seismic isolation effect is maximal in the absence of additional damping or at a relatively low level (combined with low BCS rigidity). As damping and stiffness of BCS increase, seismic insulating effect decreases. With very high damping or significant rigidity, the system acquires signs of a rigid connection between the object and the base, as a result of which a negative effect of amplifying the seismic response of structures is possible. The dynamic factor can reach 1.2...1.8 relative to the basic situation. Adjusting the BCS stiffness has the least effect on the seismic response of the boiler. Basically, the introduction of BSC provides an additional reduction in the seismic response of the boiler.

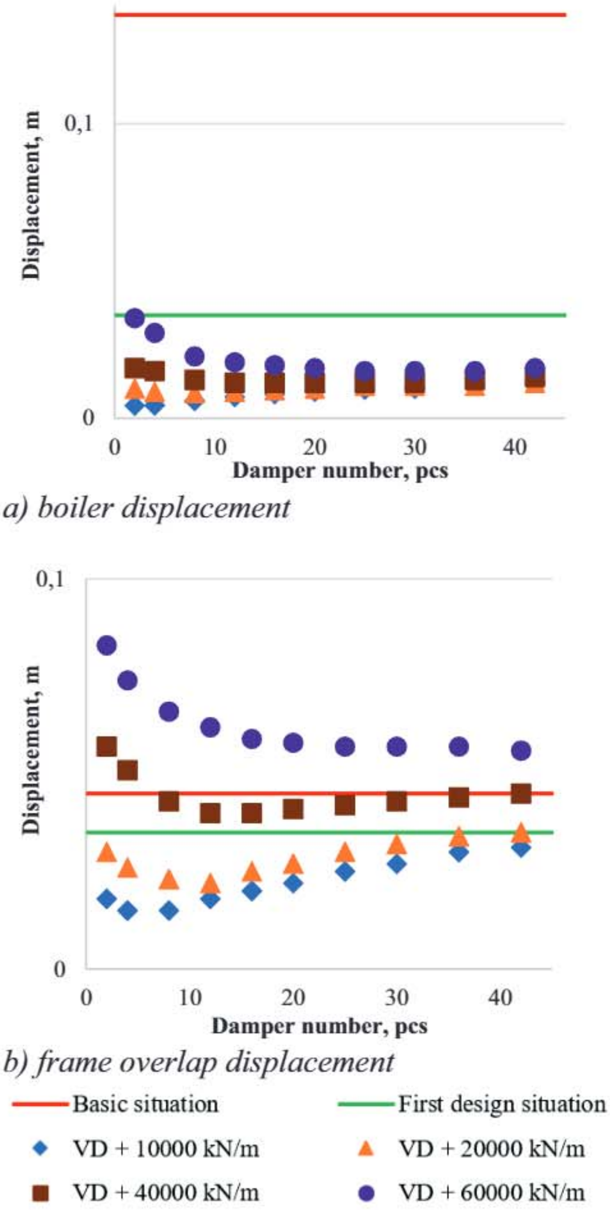


Figure 15. Results for the high-frequency spectrum (Valparaiso, 1985)

CONCLUSION

In this article, a nonlinear analytical model of the "suspended equipment (boiler) – hysteresis dampers – frame – BCS" system is developed. It allows you to make a preliminary assessment of the effectiveness for developed seismic insulation system to ensure the required level of earthquake resistance of metal frames and boilers suspended from them. This model is implemented by the algorithms of the MathCAD program. It allows optimization analysis by varying parameters (characteristics of hysteresis dampers, types and number of viscous dampers, stiffness of spring supports) to select the most technically and economically reasonable seismic insulation system.

Using BSC for seismic insulation of frames and boilers braced by hysteresis dampers is possible and can have significant positive effects on the seismic response both frame and boiler.

Significant limitations are observed only for low-frequency seismic impacts with peak accelerations up to 1 Hz, which is due to the design features of the “frame-boiler” systems. For such impacts, an additional tightening of the frame can be proposed as a recommendation, which can increase the predominant oscillation frequency.

BSC is most effective for seismic impacts with peak accelerations above 1 Hz. At the same time, there may be both a significant decrease in the frame response and an additional decrease in the boiler response (relative to a system with hysteresis dampers only). This is important because there may be restrictions on the number of hysteresis dampers or their standard sizes, when using only hysteresis dampers does not provide the required response of either the boiler or the frame.

There are optimal combinations of BCS stiffness and damping to maximize seismic response reduction.

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