Way of Simulating of Seismic Impacts on Building and Structures

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Abstract. The article includes the method of simulating of seismic impact to structures by system of vibration directional machines. Essence of the method concludes in reproducing of powerful vibrating machines in the different stores of the structure where oscillation characteristics are selected based on the spectrum of acceleration of the earthquake and so that the values of the inertial forces arising in the structure during their operation are equal to the true values of seismic forces which arise during the same earthquake. The offered method gives an opportunity for modeling of the stress-strain stain of the structure is taking place during the earthquakes without moving its foundation.

1. Introduction
The complexity of the problem of seismic impact on buildings and structures makes it necessary to use different approaches to its solution. Works as [1,2,3,4,5,6,7,8,9], held to investigated questions, have a theoretical nature. The most adequate reflection of the actual picture of seismic impact can be reached through experimental studies. Of course, the most reliable way of experience of seismic effects can be instrumental observation of the behaviour of a full-scale building or structure during strong earthquakes. A network of engineering seismometric stations (ESS) has been established in our country to achieve this purpose.

However, the problem of seismic effects using the ESS has its drawbacks, because it gives the opportunity of experimental earthquake effects only on buildings of those design solutions, on which they are aimed. In addition, with the help of ESS, it is possible to investigate the behaviour of buildings and structures only during earthquakes, an imposing volume of information collected regarding the earthquakes accumulated in various countries remains unused.

In this paper, an attempt has been made to find a way to reproduce the seismic effect on the buildings and structures by system of the vibration machines system. Particularly, the reliability of the research results depends on largely on the method of modelling seismic loads. In accurate modelling, the foundation of the investigated structure must be involved in such a complex oscillatory motion, which takes place during real earthquakes. The methods currently used for such excitation with the help of a specially installed on the ground vibrator, a directional underground explosion or seismic platform software control are associated with serious, sometimes insuperable technical and organizational difficulties. In addition, with such excitations, the dynamic behaviour of the structure is estimated by modelling the movement of its foundation. Ensuring the strength and reliability of the structure during earthquakes is due to the stress-strain state arising in it: its movement as a solid body, as is partially the case with seismic effects (through the base), does not affect the stress-strain state.

Therefore, it is practically expedient to simulate directly the stress-strain state of the structure itself, which occurs during earthquakes, without modelling the movement of its base (ground). This will not only significantly increase the degree of accuracy in modelling the effects of an earthquake (for the construction), but also greatly facilitate its practical implementation.
2. Methods

In order to identify the essence of the proposed method, consider the following task. Suppose that the base of a building or structure is subject to kinematic perturbation in the accelerogram of an earthquake (Figure 1).

The design scheme of the building, as is customary in the theory of seismic resistance, has taken in the form of a weightless bar with concentrated masses. For now, we have limited by elastic work of the structure and assume that the vibrations of the base occur only in the direction of one of the main axes of symmetry of the building.

Herewith values of seismic (inertial) forces $S_i(t)$ will be:

$$S_i(t) = m_i(y_i'' + y_0'') = m_i \sum_{k=1}^{n} \eta_{ik} \tau(T_k, \delta_k, t),$$

where

- $m_k$ is the mass of the concentrated load;
- $T_k$ - period of the $k$-th form of free vibrations;
- $y_0''$ is the acceleration of the oscillation of the base;
- $\delta_k$ - attenuation coefficient $k$ - form of free oscillations;
- $\eta_{ik}$ - coefficient of oscillation shapes.

$$\tau(T_k, \delta_k, t) = \frac{2\pi}{T_k} \int_0^t y_0''(\xi) e^{-\delta_k(t-\xi)} \sin \frac{2\pi}{T_k}(t - \xi) d\xi$$

(1)

Herewith values of seismic (inertial) forces $S_i(t)$ will be:

$$\eta_{ik} = C_{ik} \frac{\sum_{i=1}^{n} m_i C_{ij}}{\sum_{i=1}^{n} m_i C_{ij}^2}$$

where

- $C_{ik}$ - amplitude of free oscillations.
Now consider the following auxiliary task. Suppose that at the level of some \( \nu \)-th floor of the same building, a powerful inertial action vibrator is installed (Fig. 1b), when turned on, the building makes forced oscillations with amplitude \( A \) and frequency \( \theta \).

**Figure 2. Console**

3. Results

Vibration directional machines are used in testing high-rise buildings increasingly and their models in order to determine the dynamic characteristics. In [10, 11, 12, 13, 14, 15, 16] it is experimentally shown that with the simultaneous action of several vibrating machines it is possible to obtain a programmable complex dynamic load, applicable in order to simulate seismic loads.

Here is given an analysis of the oscillations of the building with the simultaneous action of a system of vibrating machines located on all floors.

The console bearing the “\( n \)” concentrated masses was adopted as the design scheme of the building (Figure 2).

Denoting the masses by \( m_i \) and the corresponding horizontal deflections through \( y_i \), the inertial forces developed by the masses will be equal to \( m_i y_i'' \).

The oscillations of the system are expressed taking into account the attenuation according to [17] by the equation:

\[
\sum_{n=1}^{N} \left( m_n y_n'' + F_n(t) + a_n (y_n - y_{n-1}) + \mu_n a_n (y_n' - y_{n-1}') \right) = 0
\]

where

- \( a_n \) is the stiffness of the corresponding bar;
- \( \mu_n \) - coefficient of viscous resistance of each bar;
- \( F_n(t) \) - external force.

For sections between the masses “\( n-1 \)” and “\( n-2 \)” we get:

\[
\sum_{n-1}^{N} \left( m_{n-1} y_{n-1}'' + F_{n-1}(t) + a_{n-1} (y_{n-1} - y_{n-2}) + \mu_{n-1} a_{n-1} (y_{n-1}' - y_{n-2}') \right) = 0
\]
Considering (3), equation (4) takes the form:

\[ m_{n-1}y_{n-1}'' + F_{n-1}(t) + a_{n-1}(y_{n-1}' - y_{n-2}') - a_n(y_n - y_{n-1}) + \]

\[ + \mu_{n-1}a_{n-1}(y_{n-1}' - y_{n-2}') - \mu_na_n(y_n - y_{n-1}) = 0 \]  

(5)

An equation of type (5) can be obtained for all masses, taking \( n = 1,2, \ldots \).

In order to find a solution to system (5), we replace the unknown values \( y_i \) of \( y \) through the generalized coordinates \( g_k(t) \):

\[ y_i = \sum_{k=1}^{n} C_{ik} g_k(t) \]  

(6)

The values of \( C_{ik} \) are determined from the equation of free oscillations of the system (without attenuation):

\[ -m_iC_i\omega_i^2 + a_i(C_{ik} - C_{i-1k}) - a_{i+1}(C_{i+1k} - C_{ik}) = 0 \]  

(7)

where \( \omega_i \) is the circular frequency in the “K” form of the system's own oscillation.

Substituting (6) into (7) we obtain the system of equations concerning the new coordinates \( g_k(t) \):

\[ m_{n-1}\sum_{k=1}^{n} C_{n-1k}g_k''(t) + F_{n-1}(t) + a_{n-1}\left[\sum_{k=1}^{n} C_{n-1k}g_k(t) - \sum_{k=1}^{n} C_{n-2k}g_k(t)\right] - \]

\[ -a_n\left[\sum_{k=1}^{n} C_{ik}g_k(t) - \sum_{k=1}^{n} C_{n-ik}g_k(t)\right] + \mu_{n-1}a_{n-1}\left[\sum_{k=1}^{n} C_{n-1k}g_k'(t) - \sum_{k=1}^{n} C_{n-2k}g_k'(t)\right] - \]

\[ -\mu_na_n\left[\sum_{k=1}^{n} C_{ik}g_k'(t) - C_{n-1k}g_k'(t)\right] = 0 \]  

(8)

Multiplying (8) by \( C_{ik} \) and summing all the equations, first accepting \( n-1=i, n=i+1 \), after some transformations, we get:

\[ \sum_{i=1}^{n} \sum_{k=1}^{n} C_{y_i}m_iC_{ik}g_k''(t) + \sum_{i=1}^{n} C_{y_i}F_i(t) + \sum_{i=1}^{n} \sum_{k=1}^{n} \left[ C_{y_i}a_iC_{ik}g_k(t) - C_{y_i}a_{i+1}C_{i+1k}g_k(t)\right] - \]

\[ -\sum_{i=1}^{n} \sum_{k=1}^{n} \left[ C_{y_i}a_{i+1}C_{i+1k}g_k(t) - C_{y_i}a_iC_{ik}g_k(t)\right] + \sum_{i=1}^{n} \sum_{k=1}^{n} C_{y_i}\mu_iC_{ik}g_k'(t)a_i(C_{ik} - C_{i-1k}) - \]

\[ -\sum_{i=1}^{n} \sum_{k=1}^{n} C_{y_i}\mu_{i+1}C_{i+1k}g_k'(t)(C_{i+1k} - C_{ik})a_{i+1} = 0 \]  

(9)

As can be seen from (9), the separation of oscillations according to the main forms \( g_k(t) \) is possible only when \( \mu=\text{const} \). In this case, using expression (7) and the condition of the possibility of virtual work from (9), we obtain:

\[ \sum_{i=1}^{n} g_i(t)C_{y_i}^2m_i\omega_i^2 + \sum_{i=1}^{n} C_{y_i}^2m_i\omega_i^2(t) + \sum_{i=1}^{n} C_{y_i}m_iC_{y_i}(t)\mu\omega_i^2 = -\sum_{i=1}^{n} C_{y_i}F_i(t) \]  

(10)
From its substituting instead \( \mu, \mu = \frac{\alpha_j}{\omega_j} \), we get:

\[
g_j'(t_i + g_j'(t) \alpha_j \omega_j + \omega_j^2 g_j(t)) = \sum_{i=1}^{n} \frac{C_j F(t)}{\sum_{i=2}^{n} C_j m_i}
\]

(11)

where

\( \alpha_j = \frac{\xi}{\pi} \) - the attenuation coefficient.

The general solution of equation (11) will be:

\[
g_j(t) = e^{-\frac{\alpha_j \omega_j}{2}} \left( A_j \sin \omega_j t + B_j \cos \omega_j t \right) - \frac{1}{\omega_j} \sum_{k=1}^{n} C_j \int_{0}^{t} e^{-\frac{\alpha_j \omega_j (t - \xi)}{2}} F_k(\xi) \sin \omega_j (t - \xi) d\xi
\]

(12)

Considering the rapid attenuation of free oscillations in time, their effect on forced oscillations of the system can be neglected. Then

\[
g_j(t) = -\frac{1}{\omega_j} \sum_{i=1}^{n} C_j \int_{0}^{t} e^{-\frac{\alpha_j \omega_j (t - \xi)}{2}} F_k(\xi) \sin \omega_j (t - \xi) d\xi
\]

(13)

Substituting the value of \( g_j(t) \) from (13) into (6), we get:

\[
y_j = \sum_{k=1}^{n} C_{ik} g_k(t) = \sum_{j=1}^{n} C_j g_j(t) = \sum_{j=1}^{n} C_j \left[ -\frac{1}{\omega_j} \sum_{k=1}^{n} C_{kj} \int_{0}^{t} e^{-\frac{\alpha_j \omega_j (t - \xi)}{2}} F_k(\xi) \sin \omega_j (t - \xi) d\xi \right]
\]

(14)

Further, assuming that the external influence is the sum of the “N” effects changing according to an arbitrary law \( f_u(t) \), i.e.

\[
F_k = \sum_{i=1}^{n} A_{ku} f_u(t)
\]

(15)

Where \( A_{ku} \) is the amplitude of the force \( F_k \), from expression (14) we get:
\[ y_i = \sum_{j=1}^{n} C_{ij} \left[ \frac{1}{\omega_j^2} \sum_{k=1}^{n} C_{jk}^2 m_k \left\{ e^{-\frac{\alpha t}{2}} \sum_{u=1}^{N} A_{ju} f_u (\xi) \sin \omega_j (t - \xi) \right\} \right] = \]

\[ = -\sum_{j=1}^{n} C_{ij} \left[ \frac{1}{\omega_j^2} \sum_{k=1}^{n} C_{jk}^2 m_k \sum_{v=1}^{n} \beta_{vj} (t) \right] \]

where

\[ \beta_{ij} (t) = \omega_j t e^{-\frac{\alpha t}{2}} \sum_{u=1}^{N} A_{ju} f_u (\xi) \sin \omega_j (t - \xi) d\xi \]

Since in this case external influences (stimulated by mechanical vibrators) change according to the sine law, then

\[ f_u (t) = \sin \theta u \xi \]

Taking into account (18), integrating expression (17) by time, we get:

\[ \beta_{ij} (t) = \sum_{u=1}^{N} A_{ju} \frac{\sin (\omega_j (t + \varphi_u))}{\sqrt{1 - \left(\frac{\theta u}{\omega_j}\right)^2 + \alpha_j^2}} \]

where

\[ \tan \varphi_u = -\alpha_j \frac{1}{1 - \left(\frac{\theta u}{\omega_j}\right)^2} \]

Substituting expression (19) into (6), we obtain the formula for determining the magnitudes of the displacements of the points of the structure with "n" concentrated masses under the influence of the "N" vibratory machines:

\[ y_i = \sum_{j=1}^{n} C_{ij} \left[ \frac{1}{\omega_j^2} \sum_{k=1}^{n} C_{jk}^2 m_k \sum_{u=1}^{N} A_{ju} \sin (\theta_j (t + \varphi_u) \right] \frac{1}{\sqrt{1 - \left(\frac{\theta_j}{\omega_j}\right)^2 + \alpha_j^2}} \]

From the expression (21) it follows that each vibrator operating in a specific resonant mode, except for resonant ones, excites all possible “n” modes of oscillations in the system. As a result, there is an overlap of “n” various forms of vibrations. However, due to the fact that in the resonant mode the term corresponding to expression (21) increases dramatically (at least 30 times at \( \delta = 0.1 \)) in comparison with the other components of the overlay, the resulting superposition can be neglected and the resonant oscillations can be considered proper.
Therefore, exciting resonant oscillations of the appropriate form by means of each machine, it is possible to obtain a superposition of these vibration modes. The magnitude of the displacements in each form can be adjusted by the mass of the eccentric of the machine. This makes possibility to program complex dynamic loads and, particularly seismic loads.

4. Discussions
Investigation of seismic resistance of buildings and structures on the proposed method of simulating seismic effects should be carried out as follows:

- Conduct a calculation-theoretical analysis of the reaction (stress-strain state) of the test structure;
- Based on the analysis of the reaction of the test structure, determine the number of oscillation modes that need to be taken into account and accordingly, the number of vibrating machines to be taken into account and the corresponding locations for their installation;
- Select the parameters of vibrating machines making different forms of oscillations, i.e. conforming for preventing possible interaction of vibration machines to each other and in order to its stability of functioning in resonance mode and in order to its power select in 1.5 – 2 times more intensive than it requires;
- In the modelling of two-component (space) seismic impacts vibrating machines should be state on perpendicular directions of main axises in experimental structures [18];
- In case of researching aspects of seismic-state models of buildings and structures, it is realized by the way of common nature structure and model expediently.

5. Conclusions
Thus, a method has been developed for reproducing seismic impacts on buildings and structures by simulating their stress-strain state, which occurs during earthquakes, using several simultaneously operating vibrating machines installed on the building and excite resonant vibrations on individual forms of free oscillations.

It has been solved the problem of determining the eccentric masses of vibrating machines by known dynamic characteristics of the building (Tk, δk) and the accelerogram of the reproduced earthquake under the condition that the maximum values of seismic forces in this form of oscillation according to the accelerogram of the earthquake and vibration excitation coincide. The developed method of experimental reproduction of seismic impacts allows investigating the behaviour of buildings and structures in various earthquakes for a relatively small material and labour cost with sufficient accuracy for practical purposes. The offered method as well applied in experiences with nature building and structures as its model.

The analysis of building vibrations during one-time impacts of vibrating machines installed at another stores of building had been realized in this article.

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