Seismic and shock effects reduction by vibration protection systems equipped with amplifiers of inertial characteristics

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Abstract. The article considers the issue of reducing the impact pulse on an object by creating an energy absorber on the pulse distribution path, using the increasing additional inertia principle in relative motion.

Introduction
Depending on the seismological conditions’ complexity, such special seismic protective measures as seismic isolation and seismic suppression are applied. The main construction task in earthquake-prone areas is to ensure the normal operation of facilities for relatively frequent earthquakes (with a frequency of 1 every 50 years, that is, the possibility of effectively performing restoration work after rare strong earthquakes (with a frequency - 1 per 500 years).

The structures strengthening in accordance with the SNIP requirements should ensure the damage absence during frequent weak effects, the limited damage caused by medium-strength earthquakes and a quick recovery possibility after devastating earthquakes. Average seismological conditions suggest situational seismicity of 7, 8 points. In this case, the calculated effect acceleration is 4 times less than the maximum. In many cases, this condition is not satisfied, i.e. the weak effects repeatability in relation to strong is significantly higher.

The likelihood of rapid recovery under severe seismic load requires the creation of an entire infrastructure with high seismic protection requirements. This is a complex task; this work does not claim to be solved. However, the simpler task of reducing the weak repetitive transmission effects can be solved using the special vibration and seismic protection systems [1-5].

Math modeling
The use of dynamic dampeners located on buildings and structures is widely known. Dampeners can be placed either on horizontal or on vertical guides. The lack of absorbers should be attributed to their high mass. However, they are simple and reliable. The second way is the use of shock-absorbing structures on the vibrations’ distribution. Seismic protection schemes using anti-phase oscillations by fixing the rod-type shock absorbers supports, which play the role of fixed support parts, beams are fixed to the same support with spring-type shock absorbers used less widely because they require more complex technical solutions. All these decisions are based on vibro-protective elements working as elastic elements with a known stiffness. For the special systems the systems containing both elastic...
and elastically dissipative elements [6] have been proposed since the mid-50s, and since the mid-1980s they have become elastic-inertial. These elements use essence lies in the creation both the elastic-dissipative forces and the additional inertial forces, which, when creating antiphase oscillations, significantly improve the vibration-protective properties.

Let us consider the physical principles underlying the operation of the devices described in [1-5]. Let there be a mass \( m_1 \) which, when set on an elastic element with rigidity \( C \), will provide oscillations with the required frequency.

\[
\omega = \sqrt{\frac{m_1}{C}}
\]  

(1)

However, this mass is 10% of the weight of the structure’s springless part. It is obvious that this mass is necessary to be reduced. To replace mass 1, we need to create its equivalent with similar inertia.

![Figure 1](image)

Figure 1.

We use the locking handle in Figure 1 [7] then the mass \( m_1 \) equivalent to mass \( m_2 \) should balance the mass \( m_1 \) and this will depend on the locking handle’s geometry. Let the mass \( m_2 \) become less than the mass \( m_1 \) by 100 times without losing the inertial properties then the ratio of the locking handle \( b / a = 100 \)

\[
m_1 = \frac{b}{a} \cdot m_2
\]

That is, \( b \) is greater than 100 times. Here the problem arises as the implementation of this locking handle will depend on the possibility of creating the minimum technologically distance \( a \) and ensuring the dynamic course of the locking handle \( b \). The solution to this problem is the use of a hydraulic system with an inertial converter for which the following dependence is valid.

\[
m_1 = \frac{D^4}{d^2} \cdot m_2
\]

Where mass is 2 mass of fluid in the hydraulic converter channel.

Thus, the use of a system with an inertial converter will reduce the structure size without its inertial properties loss. Comparative characteristics are presented in Table 1.
We believe that, in addition to the liquid mass \( m_2 \), the hydraulic converter operation takes the liquid mass contained in the hydraulic converter chambers, taking into account the liquid compressibility due to the empirical coefficient and denote the reduced mass as the mass \( m_{\text{it}} \).

| Table 1. The mechanical locking handle and the hydro-inert converter comparison |
|-------------------|----------------|----------------|----------------|----------------|
| Mass ratio \( [m_1/m_2] \) | \( a, [\text{mm}] \) | \( b, [\text{mm}] \) | \( d_{1r}, [\text{mm}] \) | \( D_{1r}, [\text{mm}] \) |
| 625 | 100 | 62500 | 4 | 20 |
| 10000 | 100 | 10 [m] | 4 | 40 |
| 100000000 | 100 | more than 40 m | 4 | 80 |

The motion equation for a system with an inertial converter will be:

\[
\begin{align*}
\ddot{m}_1 x &= F_0 - c_1 x - b_1 \dot{x} - p_1 A \\
p_1 &= p_2 \\
m_{\text{it}} x &= p_2 A - c_{\text{it}} x - b_{\text{it}} \dot{x} \\
F_0 &= (m_1 + m_{\text{it}}) x + (b_1 + b_{\text{it}}) \dot{x} + (c_1 + c_{\text{it}}) x \\
m_{\text{it}} x &= -N - c_1 x - b_1 \dot{x} - c_{\text{it}} x - b_{\text{it}} \dot{x} \\
R(x) &= -N(x) \\
R &= (m_{\text{it}}) x + (b_1 + b_{\text{it}}) \dot{x} + (c_1 + c_{\text{it}})
\end{align*}
\]

In this case, the transfer function will appear as:

\[
T_1(p) = \left. \frac{m_{\text{it}} \cdot p^2 + (b_1 + b_{\text{it}}) \cdot p + c_1 + c_{\text{it}}}{(m_1 + m_{\text{it}}) \cdot p^2 + (b_1 + b_{\text{it}}) \cdot p + c_1 + c_{\text{it}}} \right|
\]

\( m_{\text{it}} \) - inertia created in the hydraulic converter channel
\( m_1 \) is the object part mass attributable to the vibration protection element
\( b_1 \) - spring damping
\( b_{\text{it}} \) - damping in the hydraulic converter channel
\( c_1 \) - stiffness of the springs providing static stiffness
\( c_{\text{it}} \) - stiffness of the springs providing fluid oscillation in the channel

With the system specific parameters, which form the solution to be searched for, the expression under the root sign is determined as:

\[
(b_1 + b_{\text{it}})^2 - 4(c_1 + c_{\text{it}})(m_{\text{it}} + m_1)
\]

In case \( (b_1 + b_{\text{it}}) > \sqrt{4(c_1 + c_{\text{it}})(m_{\text{it}} + m_1)} \), then the solution is obtained by hyperbolic functions, if vice versa, then by trigonometric functions.

To solve the problem, we use the Delta function (Dirac function) [8] for one real variable which can be defined as function (2), satisfying the following conditions:
\[ \delta(t) = \begin{cases} +\infty, & t = 0 \\ 0, & t \neq 0 \end{cases} \tag{2} \]

That is, this function is non-zero only at the point \( t = 0 \), where it goes to infinity so that its integral over any neighborhood of \( t = 0 \) is 1. In this sense, the delta function concept is similar to the point mass physical concepts. \[ \text{[2]} \]

\[ T(p) = \frac{m_{\mu}}{m_{\mu} + m_t} \cdot \frac{p^2 + b_1 + b_2 \cdot p + c_1 + c_{\mu}}{p^2 + b_1 + b_2 \cdot p + c_1 + c_{\mu}} \] \tag{3} \]

Let us show the expression (4) in the hyperbolic function form (5) and implement the Laplace transformation:

\[ F1(p) = \frac{p + \frac{1}{2} \cdot \frac{b_1 + b_2}{m_{\mu} + m_t}}{\left( p + \frac{1}{2} \cdot \frac{b_1 + b_2}{m_{\mu} + m_t} \right)^2 - \left[ \frac{\sqrt{(b_1 + b_2)^2 - 4 \cdot (c_1 + c_{\mu}) \cdot (m_{\mu} + m_t)}}{2 \cdot (m_{\mu} + m_t)} \right]^2} \] \tag{4} \]

\[ F1(t) = e^{-\frac{1}{2} \cdot \frac{b_1 + b_2}{m_{\mu} + m_t}} \cdot \text{ch} \left[ \frac{\sqrt{b_1^2 - 4 \cdot (c_1 + c_{\mu}) \cdot (m_{\mu} + m_t)}}{2 \cdot (m_{\mu} + m_t)} \right] \cdot \text{sh} \left[ \frac{\sqrt{(b_1 + b_2)^2 - 4 \cdot (c_1 + c_{\mu}) \cdot (m_{\mu} + m_t)}}{2 \cdot (m_{\mu} + m_t)} \right] \] \tag{5} \]

Let it be:

\[ k3 = \text{ch} \left[ \frac{\sqrt{b_1^2 - 4 \cdot (c_1 + c_{\mu}) \cdot (m_{\mu} + m_t)}}{2 \cdot (m_{\mu} + m_t)} \right] \]
\[ k4 = \cdot \text{sh} \left[ \frac{\sqrt{(b_1 + b_2)^2 - 4 \cdot (c_1 + c_{\mu}) \cdot (m_{\mu} + m_t)}}{2 \cdot (m_{\mu} + m_t)} \right] \]

\[ k5(t) = e^{-\frac{1}{2} \cdot \frac{b_1 + b_2}{m_{\mu} + m_t}} \cdot \theta(t) \]
\[ d = c_1 + c_{\mu} \]

\[ T(t) = \frac{m_{\mu}}{m_{\mu} + m_t} \cdot \delta(t) + \frac{m_{\mu}}{m_{\mu} + m_t} \cdot k5(t) \cdot [b_1 + b_2 \cdot k3] + [k6 \cdot k5(t) \cdot k4] \] \tag{6} \]
Let us consider the presented function assuming that the initial part \( t_1 = 0 \) is not considered.

If the inverse Laplace transform function is represented (discarding the delta function in section 0), the transfer function form will be (7):

\[
T(t) = \frac{m_u}{(m_u + m_i)^2} \cdot e^{-\frac{1}{2} \frac{b_1}{m_u + m_i}} \cdot \left[ b_1 \cdot \cosh(K7) + \frac{2 \cdot c_1 \cdot (m_i + m_u) - b_1^2}{\sqrt{b_1^2 - 4 \cdot 2 \cdot c_1 \cdot (m_i + m_u)}} \right] + \sinh(K7)
\]

\[
K7 = \frac{\sqrt{b_1^2 - 4 \cdot c_1 \cdot m_i}}{2 \cdot (m_i + m_u)}
\]

Summary

Figure 2. Transient damping of oscillations in a system with an inertial converter.

Figure 2 shows that in spite of the system high inertia with a hydraulic converter, a more efficient energy absorption takes place by the inertial channel, and increased damping leads to the oscillations rapid damping. We believe that the introduction of systems with inertial converters will significantly increase the seismic protection systems effectiveness.

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