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K. K. Walsh

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Resettable stiffness dampers have been shown to be effective for seismic protection of buildings and bridges subject to near-field ground motions. However, the effectiveness of the damper is compromised by the stiffness it adds to the structure in which it is installed. In the present study, the displacement-based adjustable stiffness energy dissipation (D-BASED) system is presented that combines passive resettable stiffness with passive negative stiffness to achieve different levels of damping for a desired damper stiffness. It is shown that increasing the negative stiffness relative to the resettable stiffness in the D-BASED system increases the equivalent damping ratio, resulting in a more efficient damper than the resettable stiffness damper alone. Numerical simulations of a seismically-excited five-story base-isolated building with the D-BASED system installed at the isolation level are performed, and the results show that the D-BASED system with overall negative stiffness generally outperforms a passive resettable stiffness damper and the D-BASED system with positive and zero stiffness.

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Introduction

Resettable stiffness dampers, with their ability to produce large rate-independent forces while simultaneously dissipating energy from vibrating structures, represent an effective seismic protection strategy, particularly in the presence of near-field ground motions. Past research has shown these dampers to be effective in a variety of applications, including supplemental damping [1]-[3], seismic isolation [4], [5], and tuned mass damping [6]-[8]. Moreover, recent advances in the development of a mechanical resetting mechanism means that these dampers may be operated passively [9], resulting in a more robust and reliable control system that will be more attractive to structure owners. However, resettable stiffness dampers suffer from the drawback that they add stiffness to the structure in which they are installed. This has the dual effect of compromising their damping potential while increasing the forces at the damper connections and structure base. Past research has shown that using negative stiffness damping can increase the effective damping ratio while also limiting the transmission of excessive forces to the structure in which the dampers are installed [10]-[13]. Therefore, an improvement in resettable stiffness dampers may be realized through negative stiffness. The objective of the research presented herein is to investigate a new resettable stiffness damper, the displacement-based adjustable stiffness energy dissipation (D-BASED) system, that combines the resettable passive stiffness damper (RPSD) with a passive negative stiffness device (PNSD) to achieve positive, zero, or negative stiffness damping. It will be shown that through different combinations of resettable and negative stiffness, the D-BASED system can be designed to provide different damping to a structure for a given damper stiffness.

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Reseting Passive Stiffness Damper (RPSD)

Description

A schematic of the RPSD is shown in Fig. 1 [9]. It consists of a piston, pneumatic cylinder, external loop connecting the two sides of the cylinder, rack-lever mechanism, and a mechanically operated bypass valve. The rack-lever system consists of a grooved rack connected to the damper piston. Mounted above the rack is a vertical channel containing a spring-loaded lever (spring not shown). The lever is free to translate in the vertical direction and rotate about the end in the channel. The starting position of the lever is one where the lever is oriented at some angle with respect to the rack, and with its free end resting in the grooves of the rack. Mounted above the lever in the channel is a mechanically operated, normally-closed valve with spring return. For each change in direction of the damper piston, the rack forces the lever to move up the vertical channel and engage the valve piston, thereby opening the valve. The valve remains open until the lever moves back down the channel and disengages the valve piston, at which time the valve closes. During the time that the valve is closed, motion of the piston compresses the gas in the cylinder and energy is stored in the damper. When the valve is opened, the stored energy is dissipated as heat. Through the process of opening and closing the valve each time the damper piston changes direction, the RPSD is capable of extracting energy from the structure in which it is installed. For the RPSD used in the D-BASED system described herein, the attachment point for the passive negative stiffness device (PNSD) will be at the end of the damper piston (for single acting cylinder), or both ends (for double acting cylinder) as shown in Fig. 1.

![Figure 1. Schematic of the RPSD.](image)

Force Resetting

Resetting of the RPSD force is based on the relationship between the rack and lever displacement each time there is a change in direction of the damper piston. Past research has shown that the following conditions can be used to account for resetting of the RPSD force [9]:

\[ F_{rs} = -k_{rs} \cdot x_r(t), \]  

(1)

where

\[ x_r(t) = x_e(t) - x_p(t), \]  

(2)
and

\[ x_e(t) = x_p(t) \quad \text{if} \quad x_1 \leq |x_L(t)| \leq x_2 \quad \text{and} \quad \dot{x}_p(t_0 - \Delta t) \cdot y^*(t) > 0. \]  

(3)

In Equations (1)-(3), \( k_r \) is the effective stiffness of the resettable damper, \( x_r(t) \) is the resetting displacement, \( x_e(t) \) is the engaging displacement, \( x_p(t) \) is the piston displacement, \( \dot{x}_p(t) \) is the piston velocity, \( t_0 \) is the time at the instant there is a change in piston direction, \( \Delta t \) is the time increment, and the term \( y^*(t) \) is defined as:

\[ y^*(t) = -\left[ \frac{\dot{x}_p(t_0 - \Delta t)}{|\dot{x}_p(t_0 - \Delta t)|} \right] \frac{dx}{dx^2} x_L(t)^2 + \frac{2d}{x_0} x_L(t), \]  

(4)

where

\[ x_L(t) = x_l - x_p(t), \]  

(5)

and

\[ x_l = x_p(t) \quad \text{if} \quad \dot{x}_p(t) = 0 \quad \text{and} \quad \dot{x}_p(t_0 - \Delta t) \cdot y^*(t) < 0. \]  

(6)

A hysteresis plot for the RPSD obtained from small-scale laboratory experiments is shown in Fig. 2, along with a theoretical hysteresis plot calculated using Eqs. (1)-(6). In region 1 in Fig. 2, a change in piston direction has occurred, the lever is moving up the channel toward the on-off valve, but has not triggered the valve. As a result, there is a decrease in the RPSD force, and energy that was stored in the damper is released back into the structure. In region 2, the lever has engaged the valve, the valve has opened, and the damper force is zero. During this time, no new energy is being stored in the damper. In region 3, the lever has disengaged the valve, the valve has closed, the damper force increases again, and energy is once again stored in the damper. Figure 2 reveals that maximum energy dissipation occurs when regions 1 and 2 are minimized, that is, when the distance the piston has to travel for resetting to occur, or the resetting distance (0 to 2\( \cdot x_0 \)), is small relative to the total piston travel (i.e. peak-to-peak piston displacement) after resetting.

Figure 2. Plot of (a) vertical versus horizontal lever displacement and (b) RPSD hysteresis.
Passive Negative Stiffness Device (PNSD)

Description

For the passive negative stiffness device (PNSD), a simple 2-link mechanism is adopted as shown in Fig. 3(a). It consists of two links with length \( l \) pinned together at B. The other ends of the links are pinned to roller guides at A and C. The roller guides are constrained to translate in the \( y \)-direction by the channel, while the links are free to rotate about their connection points. Pre-compressed springs are located between each roller guide and support. In the equilibrium position shown in Fig. 3(a), the forces from the pre-compressed springs \( F_s(t) \) act through the longitudinal axis of the links (\( y \)-direction), and no horizontal force is exerted on point B. However, displacement \( x(t) \) of point B as shown in Fig. 3(b) causes corresponding displacement \( y(t) \) of points A and C, resulting in a horizontal force \( F_{ns}(t) \) that acts in the direction of displacement \( x(t) \). It will be shown that \( F_{ns}(t) \) is increases with increasing \( x(t) \), thereby resulting in negative stiffness. For the PNSD used in the D-BASED system proposed herein, the attachment point for the RPSD is at B’ as shown in Fig. 3(b). The D-BASED system with RPSD attached at B’ could be installed such that the PNSD was horizontal or vertical using a chevron bracing configuration.

![Fig. 3](image)

Figure 3. 2-link passive negative stiffness device (PNSD) in the (a) undeformed and (b) deformed position with (c) corresponding force-displacement plot.

Negative Stiffness Force

Neglecting inertia, and friction in the pin connections, the PNSD force can be determined as that required to keep the system in equilibrium at a given deformation \( \theta(t) \). Force equilibrium at point A in Fig. 3(b) gives the force in the link \( F_l(t) \) as:

\[
F_l(t) = \frac{F_s(t) - F_f(t)}{\sin \theta(t)},
\]  

(7)
where the rolling friction force \( F_f(t) \) between the roller guide and the channel is taken to be the product of the normal force on the channel wall \( F_n(t) \) and the rolling friction coefficient \( \mu_r \), or:

\[
F_f(t) = \mu_r \cdot F_n(t),
\]

and the normal force on the channel wall is:

\[
F_n(t) = \frac{F_s(t) - F_f(t)}{\tan(\theta(t))} = \frac{F_s(t)}{\left(\mu_r + \tan(\theta(t))\right)}.
\]

Then, equilibrium of forces at point B’ in Fig. 3(b) gives the PNSD force \( F_{ns}(t) \) as:

\[
F_{ns}(t) = 2F_f(t) \cdot \cos(\theta(t)) = \frac{2(F_s(t) - F_f(t))}{\tan(\theta(t))}.
\]

Combining Eqs. 8-10 then gives:

\[
F_{ns}(t) = 2 \cdot \frac{F_s(t)}{\tan(\theta(t))} \left(1 - \frac{\mu_r}{\left(\mu_r + \tan(\theta(t))\right)}\right).
\]

In Eq. 11, the spring force \( F_s(t) \) is taken as the product of the spring constant \( k_s \) and spring deformation, or:

\[
F_s(t) = k_s \cdot (u_c - y(t)),
\]

where \( u_c \) is the amount the spring is pre-compressed, and \( y(t) \) is given by:

\[
y(t) = l \left\{1 - \sin \left[\cos^{-1} \left(\frac{x(t)}{l}\right)\right]\right\} \text{ where } -l \leq x(t) \leq l \text{ and } 0 \leq y(t) \leq l.
\]

Combining Eqs. 11-13 gives the final PNSD force as:

\[
F_{ns}(t) = -f(t) \cdot \left[k_s^* \cdot \left(\frac{x(t)}{l}\right) \left(1 - \sin \left[\cos^{-1} \left(\frac{x(t)}{l}\right)\right]\right]\right] \left(1 - \frac{\mu_r}{\left(\mu_r + \tan(\theta(t))\right)}\right),
\]

where \( f(t) = 1/\tan(\theta(t)) \) is an amplification factor that changes nonlinearly with the deformation of the mechanism, \( k_s^* = 2k_s \) is the effective stiffness, and the (-) sign in front of Eq. 14 indicates that the force is in the direction of the displacement rather than opposing it (i.e. negative stiffness). A plot of the PNSD force \( F_{ns}(t) \) versus displacement \( x(t) \) is shown in Fig. 3(c) for rolling friction values \( \mu_r \) ranging in order of magnitude from \( 10^{-1} \) to \( 10^{-4} \). Figure 3(c) shows that for \( \mu_r = 10^{-1} \), the friction reduces the negative stiffness as the mechanism moves away from the equilibrium position and adds to the negative stiffness when the mechanism is moving toward equilibrium. The figure also shows that the effect of rolling friction on the negative stiffness is negligible for values of \( \mu_r \leq 10^{-2} \).
Displacement-Based Adjustable Stiffness Energy Dissipation (D-BASED) System

The displacement-based adjustable stiffness energy dissipation (D-BASED) system combines the RPSD in parallel with the PNSD to produce a passive resettable stiffness damper with adjustable stiffness. The system can be designed to have any stiffness within practical limits, and with different damping, through the proper selection of the positive and negative stiffness of the RPSD and PNSD, respectively. From the plot of the typical RPSD hysteresis shown in Fig. 2, it can be shown that the energy dissipated by the damper per cycle of harmonic motion is given by:

\[ E_{rs} = 4 \cdot k_{rs} (X - x_0)^2 = 4 \cdot k_{rs} \cdot X^2 \cdot (1 - R)^2, \]  

where \( X \) is the amplitude of the harmonic motion, \( x_0 \) is related to the resetting distance (0 to 2\( x_0 \)), and the ratio \( R = x_0/X \) should be minimized to maximize energy dissipation in the damper. From Eq. 15, it can be seen that the energy dissipated per cycle of motion is directly related to the effective stiffness \( k_{rs} \) of the RPSD. Assuming that the energy dissipated due to friction between components in the PNSD is small relative to the energy dissipated by the RPSD, then the energy dissipated by the D-BASED system would be equal to the energy dissipated by the RPSD, or \( E_{DB} = E_{rs} \). For an ideal D-BASED system with \( R=0 \), and overall stiffness \( k_{DB} = k_{rs} - k_{s}^* \), installed in an undamped single-degree-of-freedom (SDOF) structure with mass \( m \) and stiffness \( k \) as shown in Fig. 4(a), it can be shown that the corresponding equivalent damping ratio is:

\[ \zeta_{DB} = \frac{1}{4\pi} \cdot \frac{E_{DB}}{E_{el}} = \frac{2k_{rs}}{\pi(k + k_{DB})} = \frac{2k_{rs}}{\pi(k + (k_{rs} - k_{s}^*))} = \frac{2k_{rs}}{\pi(k + (k_{rs} - \beta k_{rs}))} \]  

(16)

where \( \beta = k_{s}^*/k_{rs} \) is defined as the ratio of the PNSD to RPSD stiffness for convenience. Equation 16 shows that in the absence of the PNSD (\( \beta=0 \)), the increase in the damping ratio with increasing RPSD stiffness \( k_{rs} \) is diminished due to the contribution of \( k_{rs} \) increasing the elastic strain energy of the RPSD-structure. However, Eq. 16 shows that the addition of the PNSD to the system results in an increase in the damping ratio with increasing \( \beta \), that is, with increasing negative stiffness \( k_{s}^* \). It should be noted that in order to maintain stability of the structure, the negative stiffness of the PNSD should be less than the structure stiffness \( k_{s}^* < k \), leading to \( \beta < k/k_{rs} \) and \( \zeta_{DB} < 2/\pi \).
Figure 4. (a) SDOF Building model with D-BASED system and (b) equivalent damping ratio of D-BASED system versus RPSD stiffness.

In order to demonstrate the effect of adding negative stiffness on the damping ratio of the D-BASED system, the equivalent damping ratio $\zeta_{DB}$ was calculated for increasing RPSD stiffness $k_{rs}$ and different values of $\beta$, and the results are plotted in Fig. 4(b). Figure 4(b) shows that for the D-BASED system without negative stiffness ($\beta=0$), or the RPSD, the effectiveness of the damper is diminished for increasing $k_{rs}$ as the elastic strain energy becomes large relative to the dissipated energy. A similar effect is observed for $\beta=0.5$. When the negative stiffness of the PNSD is equal to the RPSD stiffness ($\beta=1$), no stiffness is added to the structure and $\zeta_{DB}$ increases in proportion to the RPSD stiffness $k_{rs}$. When the negative stiffness of the PNSD is greater than the RPSD stiffness ($\beta>1$), the overall stiffness of the D-BASED-structure is reduced, and the rate of increase in $\zeta_{DB}$ is higher with increasing RPSD stiffness $k_{rs}$.

**Seismically-Excited Base-Isolated Building**

To evaluate the proposed D-BASED system for seismic protection, numerical simulations were carried out for a seismically-excited five-story base-isolated building adopted from the literature [14], and the properties are shown in Table 1. The base-isolated building was modelled as a linear system and subjected to the Northridge earthquake with a PGA of 0.84g. The D-BASED system with positive, zero, and negative stiffness was considered at the isolation level, along with the RPSD for comparison. The RPSD used in the analysis (RPSD and D-BASED system) was modelled with a lever length of $L=12.7$ mm, initial horizontal position of $x_o=11$ mm, and engaging distance $d_e=2$ mm. For the PNSD used in the D-BASED system, the 2-link mechanism with link lengths of $l=1.6$ m was used. The stiffness for the RPSD and the D-BASED system are presented in Table 2 in terms of the isolator stiffness $k_i$, along with the resulting isolation period for each case.
Table 1. Properties of five-story base-isolated building.

<table>
<thead>
<tr>
<th>Level</th>
<th>Mass (kg)</th>
<th>Stiffness (kN/m)</th>
<th>Damping (kN·s/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>6800</td>
<td>231.5</td>
<td>7.45</td>
</tr>
<tr>
<td>1st</td>
<td>5897</td>
<td>33732</td>
<td>67</td>
</tr>
<tr>
<td>2nd</td>
<td>5897</td>
<td>29093</td>
<td>58</td>
</tr>
<tr>
<td>3rd</td>
<td>5897</td>
<td>28621</td>
<td>57</td>
</tr>
<tr>
<td>4th</td>
<td>5897</td>
<td>24954</td>
<td>50</td>
</tr>
<tr>
<td>5th</td>
<td>5897</td>
<td>19059</td>
<td>38</td>
</tr>
</tbody>
</table>

Table 2. Parameters for RPSD and D-BASED system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No Control</th>
<th>RPSD</th>
<th>D-BASED</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{rs}$</td>
<td>-</td>
<td>0.5·$k_i$</td>
<td>0.75·$k_i$</td>
</tr>
<tr>
<td>$k^*_s$</td>
<td>-</td>
<td>-</td>
<td>0.25·$k_i$</td>
</tr>
<tr>
<td>$k_{DB}$</td>
<td>-</td>
<td>-</td>
<td>0.5·$k_i$</td>
</tr>
<tr>
<td>$(k_{rs}$ or $k_{DB}) + k_i$</td>
<td>$k_i$</td>
<td>1.5·$k_i$</td>
<td>1.5·$k_i$</td>
</tr>
<tr>
<td>$T$ (s)</td>
<td>2.5</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

The results for each case are presented in Table 3 in terms of percent reductions in the peak drift and absolute acceleration responses with respect to the base-isolated building with no damper. The best overall control performance was observed for the D-BASED system with negative stiffness, which yielded a comparable response to the other cases in terms of peak base drifts, but outperformed the RPSD and other D-BASED systems in terms of the peak base acceleration and superstructure response. Another important response quantity for the seismic design of structures is the total peak force transmitted to the foundation during an earthquake, or peak base shear. Percent reductions in peak base shear with respect to the base-isolated building with no damper were found to be 7 %, 15 %, 37 % and 68 % for the RPSD and D-BASED systems with positive, zero, and negative stiffness, respectively. Once again, the D-BASED system with negative overall stiffness outperformed the other systems. It should be noted that the superior performance of the D-BASED system with negative stiffness may be attributed in part to a reduction in the overall isolation stiffness, thereby shifting the isolation period further from the dominant period(s) of the earthquake. Furthermore, the performance of the RPSD and D-BASED system with positive stiffness may be compromised by the increase in isolation stiffness, thereby shifting the isolation period toward the dominant period(s) of the earthquake. For both of these cases, addition of the D-BASED system changes the isolator dynamics, making it difficult to isolate its effect on the building response. On the other hand, the D-BASED system with zero overall stiffness does not affect the isolator dynamics, allowing for a more direct evaluation of its performance. The results for the D-BASED system with zero stiffness show significant reductions in the peak base and superstructure drift responses at all but the top level, and the peak acceleration responses at all but the base and top level. It should be noted that the large negative percent reduction (or percent increase) in the peak base acceleration is due to spikes in the acceleration response resulting from a discontinuity in the D-BASED force at the instant of RPSD resetting, and is not representative of an overall increase in the acceleration response. The force-displacement plots for the D-BASED system with zero and negative stiffness are shown in Fig. 9, along with those for the isolator and total base force.
Table 3. Percent reductions in peak responses.

<table>
<thead>
<tr>
<th>Level</th>
<th>Base</th>
<th>RPSD</th>
<th>D-BASED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x_{peak} (mm)</td>
<td>a_{peak} (g)</td>
<td>x_{peak}</td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
</tr>
<tr>
<td>Base</td>
<td>822.12</td>
<td>0.53</td>
<td>51%</td>
</tr>
<tr>
<td>1</td>
<td>4.62</td>
<td>0.53</td>
<td>6%</td>
</tr>
<tr>
<td>2</td>
<td>4.30</td>
<td>0.54</td>
<td>4%</td>
</tr>
<tr>
<td>3</td>
<td>3.29</td>
<td>0.54</td>
<td>1%</td>
</tr>
<tr>
<td>4</td>
<td>2.52</td>
<td>0.54</td>
<td>-1%</td>
</tr>
<tr>
<td>5</td>
<td>1.65</td>
<td>0.54</td>
<td>-2%</td>
</tr>
</tbody>
</table>

Figure 5. Force-displacement plots for D-BASED system with (a) zero and (b) negative stiffness subject to the Northridge earthquake.

Conclusions

The displacement-based adjustable stiffness energy dissipation (D-BASED) system was presented for seismic protection of buildings and bridges. It combines passive resettable stiffness with passive negative stiffness to achieve different levels of damping for a desired damper stiffness. It was shown that increasing the negative stiffness in the damper relative to the resettable stiffness resulted in a higher equivalent damping ratio. Numerical simulations of a seismically-excited five-story linear base-isolated building with the D-BASED system installed at the isolation level were performed. The results showed that the D-BASED system with negative overall stiffness outperformed a passive resettable stiffness damper and the D-BASED system with zero and positive stiffness in terms of peak base acceleration, superstructure peak drift and acceleration, and the peak base shear, while still performing comparably in terms of peak base drift. The results indicate that the combination of negative stiffness with resettable stiffness in the D-BASED system yields a more effective damper than the resettable stiffness damper alone. However, additional research is needed to investigate the D-BASED system for other types of structures and ground motions.
References


