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Effect of Impact Damper on SDOF System Vibrations under Harmonic and Impulsive Excitations

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Abstract. Impact damper is a highly sensitive instrument, which belongs to the category of passive vibration devices used to attenuate the vibration of discrete and continuous systems.
In this paper, the effect of single unit impact damper on the single degree of freedom system under two different excitations is investigated. A study is made of the general behavior of a single particle impact damper; with the main emphasis on sinusoidal and impulse excitations. The effects of mass ratio, coefficient of restitution, and gap size are determined by using a MATLAB program.
It is found that the impact damper is an efficient device for reducing the vibration of structures subjected to impulsive and harmonic excitations. Numerical investigations are compared with each other. Effect of this damper shows that the system under consideration can serve as an efficient damper.
It is observed that the response of the system varies with small changes in the particle's mass, the coefficient of restitution and particle's clearance. There are critical values of the particle's parameters which an increase or a decrease does not contribute significantly toward amplitude reduction of the system.

1. Introduction

Structural control technology offers many new ways to protect structures from natural and other types of hazards. Semiactive structural control technology, appears to combine the best features of both passive and active control systems and to offer a viable means of protecting civil engineering structural systems against earthquake and wind load.[1]

An impact damper generally consists of a mass which is allowed to travel freely between two defined stops. Under the right conditions, the vibration of the system to which the impact damper is attached will cause the mass of the impact damper to strike the structure. Therefore, there is a need to understand the particle's motion, at varying parameters, as it travels between the container's boundaries to explore the potential of the impact damper.[2] The mass of the damper, the distance of travel, the excitation frequency, the peak values of modal amplitude at the location of the impact damper should be further investigated.

For more than three decades, researchers have studied the possibility of using impact damper to improve approaches to reduce structural responses (In 1973 S. F. Masri studied that chain-type impact dampers offer a simple and reliable method for attenuating wind-induced vibrations of tall flexible structures and also he performed experiments on a class of nonlinear dissipative cantilever and simply supported beams subjected to external sinusoidal excitation. In addition the damper was more effective when located away from the node of the mode shape[3]; Ranjit K. Roy and Richard D. Rocke and J. Eari Foster referred when the impact damper attached to a vibrating mechanical system the collision of the particle with the container boundaries results in a reduction of the vibration amplitude of the primary system through momentum transfer in 1975[4]; Akl and Butt (1994) performed effect of impact damper in vibration control of flexible structures; [5]; R. Chalmers and S. E. Semercigl were mentioned that a properly designed impact damper, is more effective and less sensitive to the changes in the external load and the system's parameters in 1990[6]; Aamir S. Butt and Fred A. Akl studied that impact damper can reduce the response of a vibrating continuous system if used effectively, and that its effectiveness depends on the behavior of the particle in 1997[7]; R.D. Nayeri and S.F. Masri and J.P. Caffrey investigated a comprehensive study concerning the development and evaluation of practical design strategies for maximizing the damping efficiency of multiple-unit particle dampers under random excitation in 2007[8];). It is found that the impact damper is an efficient device for reducing the vibrations of multidegree-of-freedom systems, particularly in structures such as tall buildings.[9]

While numerous analytical and experimental studies have been conducted over many years to develop strategies for modeling and controlling the behavior of impact dampers, no guidelines currently exist for determining optimum strategies for maximizing the performance of particle dampers, whether in a single unit or in arrays of dampers, under different excitation.[10] Numerical simulation studies for SDOF demonstrate the feasibility, reliability, and robustness of the control method. We studied an extensive set of numerical simulation on SDOF under harmonic and impulsive excitations. The mass of damper, the distance of travel, and the coefficient of restitution were monitored by different values. The Figures Indicate that SDOF system is sensitive for a range of gaps, masses, and coefficients of restitution.

2. Triangular Impulsive Load

For the first study, the SDOF system is affected by triangular impulsive load, with the initial force F0, which after td it will be changed to zero in a linear situation.
Mass of the oscillator is m and the impulsive force is:

$$P(t) = F_0\left(1 - t/t_d\right) \tag{1}$$

Initial position of free mass is in the middle of container which is better than resting to one of its two walls. Because when the force is applied to the same direction of mass damper, it will stick for a while to the wall and when force is changed, it starts moving; by passing d the first impact will be occurred; so the initial position of freemass is located in the middle of container.

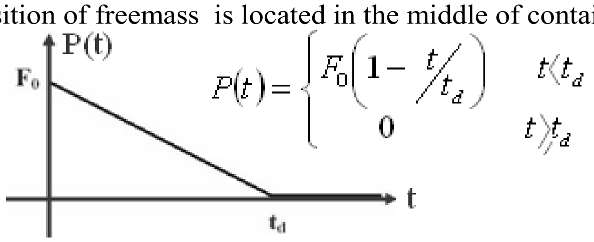

Fig. 1 Variation of impulsive load

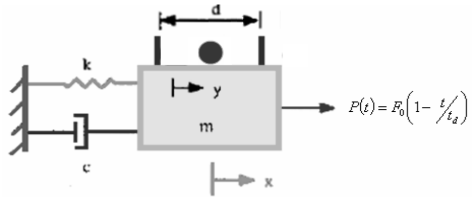

Fig. 2 Initial position of free mass is in the middle of container subjected to impulsive excitation

In numerical simulation the effect of mass damper was seen just at impacts, so during the moving of mass damper its velocity is constant and does not have any changes, thus it is assumed that oscillator's surface is frictionless; but in experimental model it is impossible to omit the friction, so there should be some differences between mechanical model and numerical simulation results. In this study, the momentum which causes at impacts is considered by:

$$\dot{y}^{+} = -e\dot{y}^{-} \qquad 0\langle e\langle 1 \tag{2}$$

The value of *e* is between zero and one, when it is closer to zero, the amplitude of system will be damped sooner. By following the equation:

$$(m+M)\dot{x}^{-} + m(1+e)\dot{y}^{-} = (M+m)\dot{x}^{+} \tag{3}$$

Which M is mass damper and an impact helps to reduce of excitation when at the time of impact $\dot{y}^{-}$ and $\dot{x}^{-}$ become the opposite of each other, so for this purpose if *d* is chosen too small, the undesired impacts will be increased. In this situation total number of impacts will be decreased and desired impacts would be increased, so that by decreasing *e*, damping of the system will be increased for two reasons, first if the value of *e* is closer to zero and the direction of impact is undesired (it means $\dot{y}^{-}$ and $\dot{x}^{-}$ are not opposite of each other), the raising of momentum will be decreased (term of $m(1+e)\dot{y}^{-}$ will be smaller) and second, if the direction of impact is desired for the system, the decreasing velocity of mass damper with the change of direction will cause the next desired impact, so in this condition the best value for e with considering the results will be 0.5.

3. Harmonic Excitation

The SDOF system is utilized by mass damper $M = \mu m$ which is a coefficient of oscillator mass m, so μ is mass ratio and system is excited by sinusoidal load.

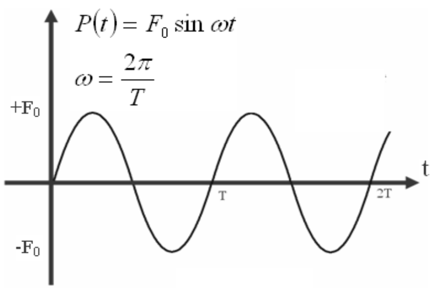

Fig. 3 Harmonic excitation applied to SDOF

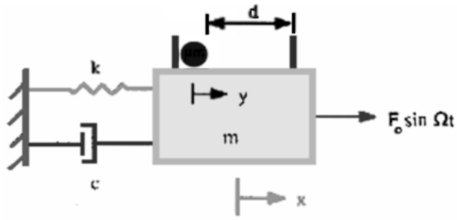

Fig. 4 Model of single unit impact damper Subjected to harmonic excitation

The initial displacement and velocity values for the primary and secondary masses are considered to be zero. The free mass particle is considered to be resting at the left wall of the container. When excitation is applied to the oscillator, the free particle starts moving relative to the primary mass. It is assumed that the oscillator's surface which comes in contact with the particle is frictionless. Therefore, the velocity of the particle stays constant between impacts. The motion of an oscillator to a sinusoidal excitation, between impacts, is given by the differential equation:

$$\ddot{X} + 2\xi\omega_n \dot{X} + \omega_n^2 X = \frac{F_0}{m}\sin\Omega t \qquad \textbf{(4)}$$

Which $\dot{X}$ is oscillator velocity and ω_n is natural frequency and Ω is frequency of the forced harmonic excitation. If $\dot{Y}$ is the absolute velocity of the particle just after the previous impact and $\dot{X}(t)$ is the velocity of the oscillator at time *t*, then the relative velocity of the particle is:

$$\dot{y}(t) = \dot{Y} - \dot{X}(t) \qquad \textbf{(5)}$$

The acceleration of the particle during the time interval Δt is calculated from:

$$\ddot{y}(t) = \frac{\dot{y}(t) - \dot{y}(t-\Delta t)}{\Delta t} \qquad \textbf{(6)}$$

The total displacement *s(t)* traveled by the particle since the previous impact is calculated:

$$s(t) = \sum \underbrace{s(t-\Delta t)} + \underbrace{s(\Delta t)} \qquad \textbf{(7)}$$

Which $s(t)$ is total displacement and $s(t-\Delta t)$ is summation of displacement by the particle during each time interval except the last and $s(\Delta t)$ is displacement by the particle during the last time interval Δt.

From the restitution model the relationship between the particle's relative velocity before and after an impact was mentioned in equation (2), and from the conservation of momentum:

$$\dot{X}_+ + \mu(\dot{X}_+ + \dot{y}_+) = \dot{X}_- + \mu(\dot{X}_- + \dot{y}_-) \qquad \textbf{(8)}$$

By substituting the two above equations, the velocity of the oscillator just after the impact is obtained as:

$$\dot{X}_+ = \dot{X}_- + \frac{\mu(1+e)\dot{y}}{(1+\mu)} \qquad \textbf{(9)}$$

And the absolute velocity of the particle is stored as:

$$\dot{Y} = \dot{X}_+ + \dot{y}_+ \qquad \textbf{(10)}$$

The positions of the two masses do not change at impact because it is assumed to occur during an infinitesimal increment of time. The velocity and displacement of the oscillator just after the previous impact are used as initial conditions to obtain its time history solution until the next impact.[11]

4. Analytical Procedures

The efficiency of impact damper has led to a number of investigations to study its behavior. Theoretical analyses in this paper have been confined to the case of an impact damper attached to a single degree of freedom main system.

It should be again noted that the absolute velocity of the particle is constant between impacts since the container's surface which comes in contact with the particle is assumed to be frictionless. The position of mass does not change at impact because it is assumed to occur during an infinitesimal increment of time. It had been stated that an impact damper effectively reduces the amplitude of the system only during impacts when the direction of the particle is against of the system. The momentum transfer between the particle and the system becomes maximum at a specific gap. That value produces the maximum reduction in the system's velocity at each impact, thus lowering its overall amplitude. It must be noted that the system exhibits a different value of the optimum gap at each mode of vibration. That value of the gap is smaller for modes occurring at higher frequencies. It is observed that the tendency of the particle to be suspended between the container boundaries in a larger gap. This is due to the particle having to travel further to reach the other wall, which allows the system to go through several cycles of motion before contact.

5. Numerical Observations

If the gap between the auxiliary mass and the end stops is properly adjusted, the mass collides with the stops causing the attenuation of the vibration amplitude of the main system. It is also observed that, too small or too large gap does not cause a reduction in the magnitude of the system's velocity; while a specific value produces maximum damping in the structure. If the gap is too small, it does not allow the system to reverse direction after a previous impact. On the other hand if it is too large, the system reverses its direction twice before coming in contact with the particle, as shown in Figs. 5 to 9 respectively for harmonic and impulsive excitations.

Note: The solid blue line (x) is oscillator displacement without impact damper, the dash green line (X) shows oscillator displacement which utilizes by impact damper, the red solid line (y) indicates relative particle displacement and the dash red line (Y) is absolute particle displacement. μ is mass ratio (particle's mass divided by the oscillator's mass, d is allowable particle travel and e is coefficient of restitution which exists between particle and container walls.

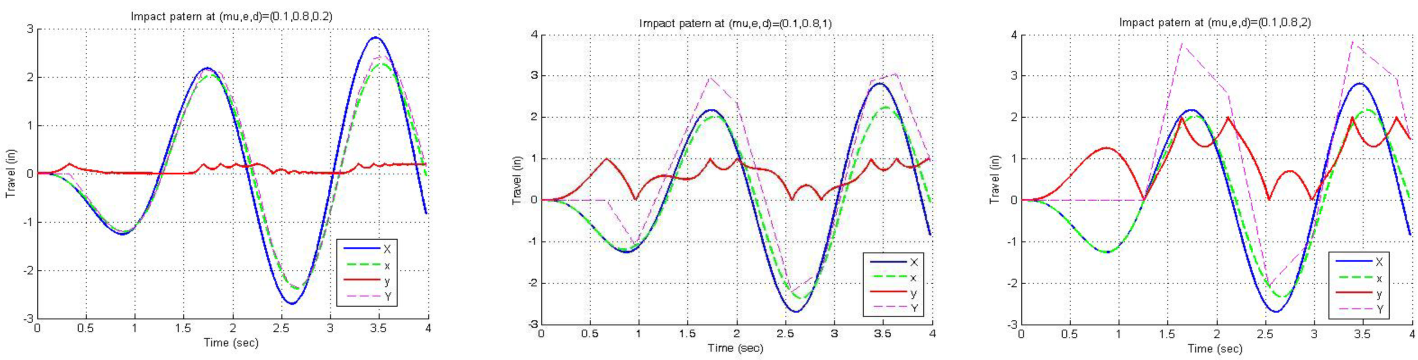

Fig. 5 Displacement response function
with $\mu = 0.1$ $e = 0.8$, $d = 0.2$ 1.0 2.0
for harmonic excitation

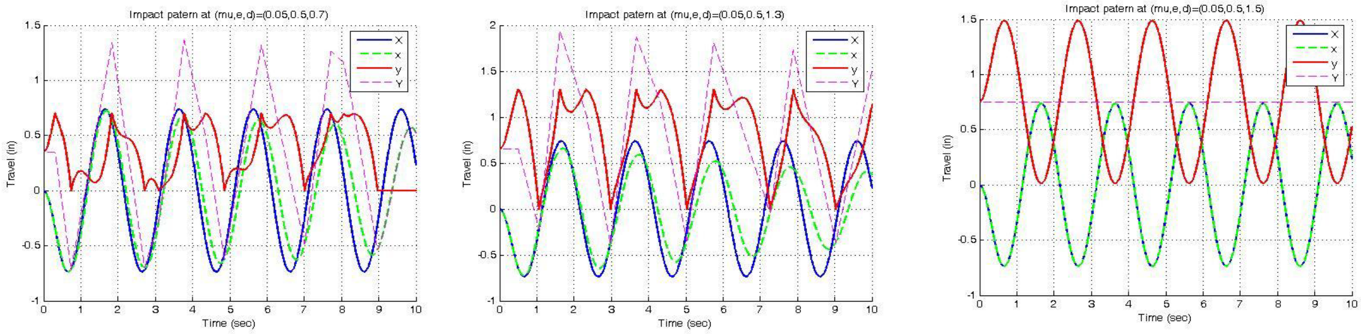

Fig. 6 Displacement response function

with $\mu = 0.05$ $e = 0.5,$ $d = 0.7$ 1.3 1,5

for impulsive excitation

This is achieved through energy dissipation in impacts and through the counteraction of the external excitation by the result of returning forces.

Figures 7 and 8 show that there is a critical value of the particle's mass beyond which an increase in the mass does not improve damping. This phenomenon can be explained by considering the conservation of momentum between the particle and the system. As the particles mass is increased, its absolute velocity immediately after the impact decreases, which in turn reduces its relative velocity and it takes longer to travel toward the other wall of the container.

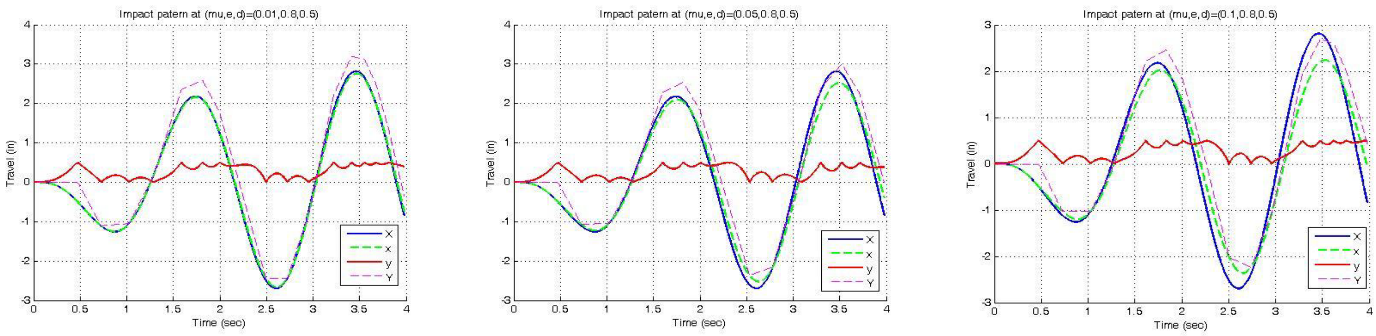

Fig. 7 Displacement response function

with $\mu = 0.01$ 0.05 0.1 $e = 0.8,$ $d = 0.5$

for harmonic excitation

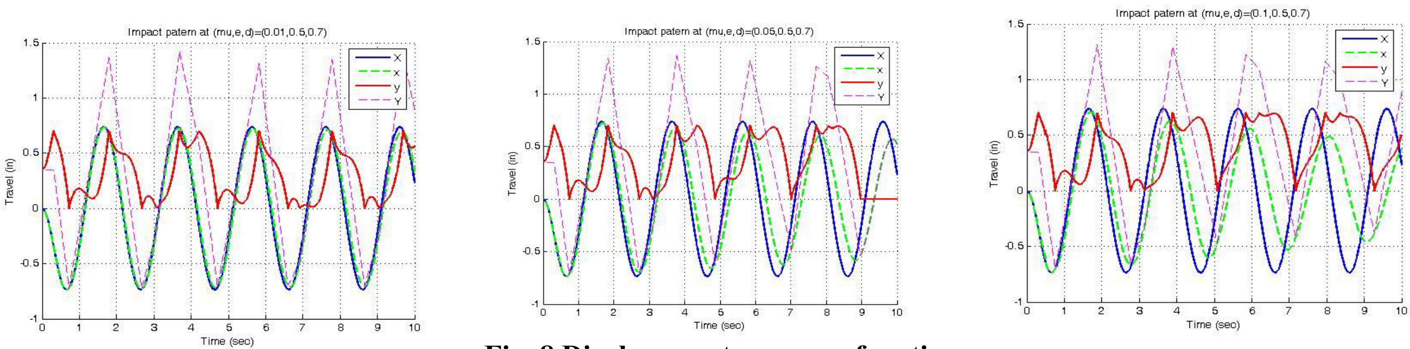

Fig. 8 Displacement response function

with $\mu = 0.01$ 0.05 0.1 $e = 0.5,$ $d = 0.7$

for impulsive excitation

If the force of friction exists, it also contributes to the reduction in the velocity while the particle is in motion. As the mass is increased beyond a certain value, its relative velocity immediately following the impact does not allow it to overcome the friction force while in motion. It then comes to rest relative to the system before approaching the other wall. At that point, if the system resumes its motion in the same direction and its acceleration is large enough to overcome the force of friction, the particle starts traveling in the opposite direction relative to the system. If a similar situation arises before approaching the container boundary, the particle reverses its direction again. Therefore, it is possible for the particle to be suspended between the container's boundaries while the system goes through several cycles of motion before making the next impact. Since the number of impacts decreases with an increase in mass, the overall effect of the damper stabilizes. Here it must be noted that the relative acceleration of the particle is independent of its mass and depends only upon the coefficient of kinetic friction; therefore, a heavier particle does not slow anymore rapidly than a lighter one does.

The coefficient of restitution "e" which is the ratio between the relative velocity immediately following the impact to the relative just before impact determines the rebound velocity of the particle and. It depends on the type, shape, and surface area of the materials coming in contact. At low values of the coefficient of restitution, the particle's rebound velocity does not allow it to escape from the wall on which it makes an impact. In the absence of any friction, the particle breaks free at the instant the velocity of the system decreases. (Figs. 9 and 10)

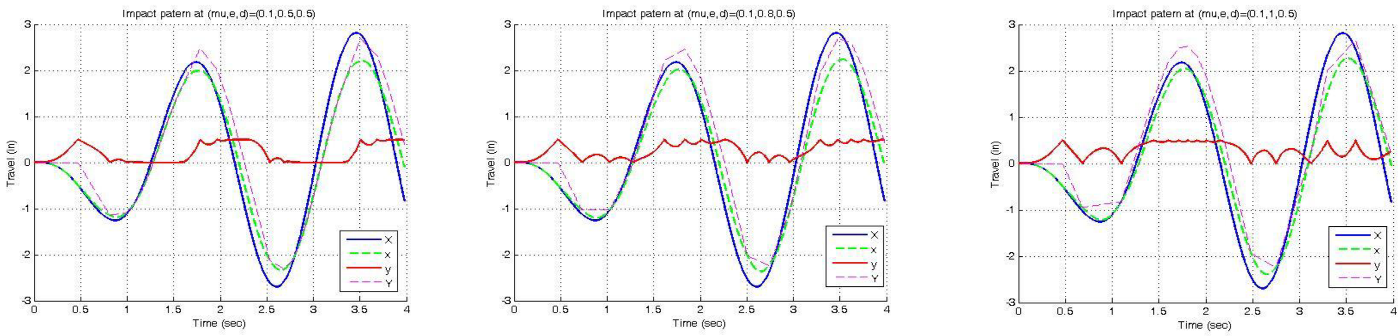

Fig. 9 Displacement response function
with $\mu = 0.1 \quad e = 0.5, \quad 0.8 \quad 1.0 \quad d = 0.5$
for harmonic excitation

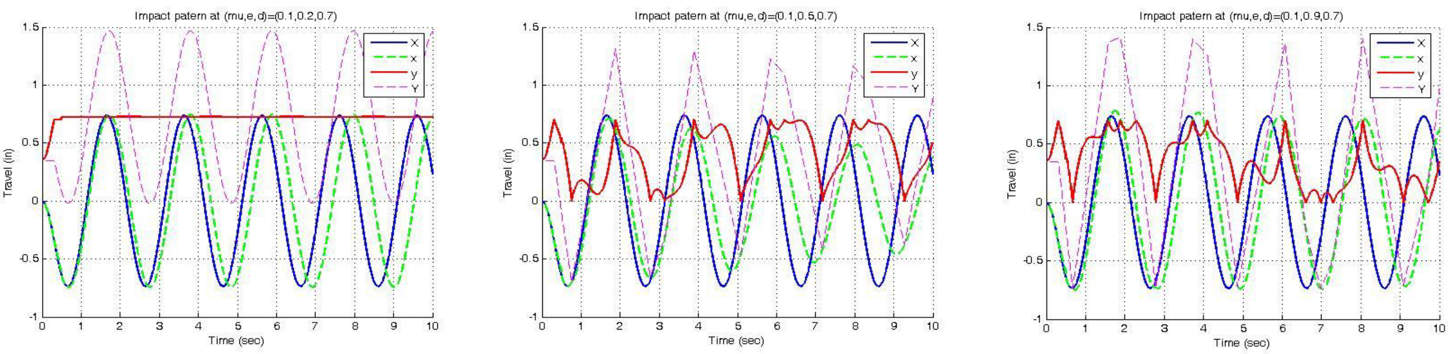

Fig. 10 Displacement response function
with $\mu = 0.1 \quad e = 0.2, \quad 0.5 \quad 0.9 \quad d = 0.7$
for impulsive excitation

If an impact pattern exists such that each impact decreases the velocity of the system, then an increase in the coefficient of restitution will further decrease the system's amplitude. This is due to an increase in the velocity of the particle at impact. At high values of the coefficient of restitution, the particle may reach the other wall of the container too quickly because of a high relative velocity. Then, the impact pattern of two impacts per cycle will not exist. However, the situation can be remedied by increasing the gap, which will allow the particle to travel further before making the impact. At a certain value of the gap, the impact pattern will return to two impacts per cycle.

6. Conclusions

The following conclusions are drawn from the study reported here in.

(i) In this paper was showed that impact damper can serve as an efficient damper to investigate SDOF system vibration under harmonic and impulsive excitations.
(ii) It was investigated that the system's parameters such as mass, gap and coefficient of restitution are the main factors to reduce the vibration amplitude.
(iii) When an impact damper is attached to a damped driven system, it is observed that the response of the system varies with small changes in the particle's mass, the coefficient of restitution and particle's clearance. There are specific values of mass, gap and coefficient of restitution which improve damping.
(iv) For harmonic and impulsive excitations, damp of the system will be improved by increasing of mass ratio, (regarding to Figures, range of 5% to 10% is more reasonable).
(v) In impulsive excitation there is a specific value of d which is efficient for the system, and any decreasing or increasing will not help to the system, (based on the results from the Figs.: $0.7<d<1.3$).
(vi) Coefficient of restitution in impulsive excitation has also a specific value to reduce vibration amplitude (Figs. show the best value is $0.2<e<0.9$).

References

[1] B. F. Spencer Jr., S. Nagarajaiah, (2003), "State of the Art of Structural Control", Journal of Structural Engineering, July 2003, pp.845-856.
[2] Aamir S. Butt and Fred A. Akl, (1997), "Experimental Analysis of Impact-Damped Flexible Beams", Journal of Engineering Mechanics, April 1997, pp 376-383.
[3] S. F. Masri, (1973), "Steady-State Response of a Multidegree System with an Impact Damper", Journal of Applied Mechanics, March 1973, pp 127-132.
[4] Ranjit K. Roy and Richard D. Rocke and J. Eari Foster, (1975), "The Application of Impact Dampers to Continuous Systems", Journal of Engineering for Industry, Nov. 1975, pp1317-1324.
[5] Akl and Butt (1994), Application of Impact Dampers in Vibration Control of Flexible Structures, NASA report, Structures and Mechanics Division, August 1994.
[6] R. Chalmers and S. E. Semercigl, (1991), Impact Damping the Second Mode of a Cantilevered Beam, Journal of Sound and Vibrations, (1991), Vol. 146, pp157-161.
[7] Aamir S. Butt and Fred A. Akl, (1997), "Experimental Analysis of Impact-Damped Flexible Beams", Journal of Engineering Mechanics, April 1997, pp 376-383.
[8] R.D. Nayeri and S.F. Masri and J.P. Caffrey, (2007), Studies of the Performance of Multi-Unit Impact Dampers Under Stochastic Excitation", Journal of Vibration and Acoustics, April 2007, Vol. 129, pp239-251.
[9] S.F. Masri, (1973), "Steady-State Response of a Multidegree System with an Impact Damper", Journal of Applied Mechanics, March 1973, pp 127-132.
[10] R.D. Nayeri, S.F. Masri, J.P. Caffrey (2007), "Studies of the Performance of Multi-Unit Impact Dampers", Journal of Vibration and Acoustics, Vol.129, pp 239- 251.
[11] Aamir S. Butt, (1994), "Dynamics of an Impact-Damped Harmonic Oscillator", Developments in Theoretical and Applied Mechanics, Vol17, pp 298-308.