ENHANCING STRUCTURAL RESPONSE USING INERTER DAMPERS

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Abstract

This paper deals with one kind of dampers which is inerter damper. Inerter is a new mechanical element proposed by Professor Malcolm C. Smith from Cambridge University, which is defined as a mechanical two-terminal, one-port device with the property that the equal and opposite force applied at the terminals is proportional to the relative acceleration between the terminals the principle work of inerter damper is how to convert the linear motion into rotational motion to mitigation the external excitation. Theoretical analysis was presented first part is the analytical study which made modeling for the damping structure proposed and get the equation of motion for the inerter behavior, secondly numerical analysis where the program (ANSYS WORK-Bench 18.2) was adopted, and study the parameters which effected on the damping behavior of inerter structure proposed that is (stiffness, coefficient of friction and mass of flywheel). Where it was found that when the stiffness of the springs increased gradually from (0.2, 0.3, 0.4, 0.6 and 0.8) Kn/mm the amplitude reduced from (25.791, 17.194, 12.896, 8.5974 to 6.4482) mm respectively for each stiffness reading, also the mass of inerter when increased gradually (200,400,600,800 and 1000) g with a constant coefficient of friction and constant stiffness 0.4, 0.6 Kn/mm respectively, the amplitude decrease from 6.3525 to 4.036290. Finally, to study the effect inerter mass on the structures, the mass of inerter increased from (200,400,600,800 to 1000) g gradually to the constant cantilever mass structure equal to 130g. The ratio of the inerter mass to the threshold mass is approximately 1.5 to 7.5 As results obtained from the previous study, the amplitude obtained for each mass (1.0778, 1.069, 1.0509, 0.9514 to 0.872) respectively.

Keywords: Inerter damper, enhancing response, ball-screw inerter.

I. Introduction

The vibration results from external excitation caused damage to the structures and led to destroying them. There are three kinds of inerter damper such as hydraulic, ball-screw and rack and pinion (VI) the inerter proposed is a ball and screw type. The simplest tool (whisk) is used as a ball-screw inerter, which is consisting three parts

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rotational disc, spindle and case part, case part has a guide with an inclined surface and spring element inside it. The inerter proposed employed the friction through its inclined guide in suppressing the vibration. Generally when the cantilever beam structure is subjected to the external excitation firstly with inerter after that without inerter and show the effect of inerter in structures also study the effect of inerter mass on the structures. Figure (1) show the cross-section for inerter used and its parts. Bhaskara Rao [2006] had proposed two numerical models of friction damper to mitigate the seismic response Moreover using lesser dampers at suitable locations could significantly mitigate the seismic response for the combined system, therefore it’s not necessary to connect two adjacent structures at all floors [II]. Marcelo [2017] had been studied the vibration happened in aircraft engine blades which represent an important example of friction dampers, a five control strategies for friction damper was studied using three various hysteresis cycle by using harmonic balance method [V]

![Figure (1) cross-section inerter used](image)

A. Siami [2017] an inerter damper for five degrees of freedom structure had been proposed to protect the famous statues Michelangelo Buonarroti from the external vibration the experimental test was used the impact operation devices such as tuned mass inerter damper and tuned mass damper to mitigate the vibration [I].

**II. Theoretical Analysis**

Previously mentioned the inerter inspired has inside its case part a guide with incline surface, modeling made for its structure and the force applied to it. When the rotating disc subjected to external force, thus led to angular torque which expresses by the relation below:

\[
\tau = I \alpha
\]  

(1)

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The angular acceleration relationship:
\[ \alpha = \frac{a}{R} \]  
(2)

Where, \( I, \alpha, a, R \) moment of inertia, angular acceleration, linear acceleration and radius of curvature respectively. The total torque applied represented summation forces acting on the system by radius.
\[ \tau = \Sigma f_{net} \times R \]  
(3)

From three equations above we conclude:
\[ \Sigma f_{net} \times R = I \times \frac{a}{R} \]  
(4)
\[ \Sigma f_{net} = \text{Total force of weight – normal friction force} \]  
(5)

The inerter proposed in this paper has a normal force and friction force through the inclined surface guide mentioned previously.
\[ I = \frac{1}{2} m R^2 \]  
(6)
\[ \mu = \tan \phi = \frac{p}{2 \pi r_m} \]  
(7)
\[ r_m = \frac{r_i + r_o}{2} \]  
(8)

\( \mu, p, r_m, r_i, r_o \) Coefficient of friction, lead of screw, mean radius of the guide, inner radius of guide and outer radius of guide respectively.
\[ a = R \times \dot{\theta} \]  
(9)
\[ f_{fri} = \frac{1}{2} \mu m R \dot{\theta} \]  
(10)

Equation (8) obtain by assumption that \( \Sigma f_{net} = f_{fri} \) and substituted that with equation (6) and (9) in (4) where \( m, \dot{\theta} \) is mass of disc and angular velocity respectively. When a comparison make between passive dampers and friction dampers, the last have advances such as low cost, powerful energy dissipation capability, simple mechanism and less maintenance [II], the dynamical single degree of freedom model system
\[ I \ddot{\theta} + k \theta = f_{ex}(t) - f_{fri}(t) \]  
[VIII]
(11)

The term of damping which obtains in equation (10) and depended on angular velocity, radius and mass of disc. \( f_{fri}(t) \) represented the term of damping with Coulomb friction. There are two major kinds of friction, “static friction and kinetic friction”. The results of relative displacement and frictional force energy dissipated and our aim how to enhance it, the most important matter in the structure proposed “micro slip” term which
results from a contact surface that prevents slip and this friction caused dissipated energy [III] Coulomb model can be expressed as:

\[ f = f_{fr} \text{ sign } \dot{\theta} \]  

(12)

\[ f = \frac{1}{2} \mu m R \dot{\theta} \text{ sign } \dot{\theta} \]  

(13)

\[ I \ddot{\theta} + \frac{1}{2} m R \mu \text{ sign } \dot{\nu} \dot{\theta} + k \theta = f_{ext}(t) \]  

(14)

It is reasonable to assume the external vibration force that must assume F as a step input. Under the given excitation

\[ f_{ext} = f_0/s \]  

(15)

Let’s named the term of damping which was previously found in equation \( \frac{1}{2} m R \mu \text{ sign } \dot{\nu} \) as \( c \) for ease.

\[ I \ddot{\theta} + c \dot{\theta} + k \theta = f_0/s \]  

(16)

\[ I s^2 \theta(s) + c s \theta(s) + k \theta(s) = \frac{f}{s} \]  

(17)

\[ \theta(s) = \frac{A}{s} + \frac{Bs+D}{Ts^2+Cs+k} \]  

(18)

\[ A = \frac{f}{k} \quad B = -\frac{f_1}{k} \quad D = -\frac{fc}{k} \]  

(19)

For ease assume:

\[ \frac{c}{I} = 2 \quad \frac{k}{I} = 1 \]  

(20)

\[ \theta(t) = \frac{f}{k} L^{-1} \left[ \frac{l}{s} - \frac{(s+2)}{(s+1)^2} \right] \]  

(21)

\[ \theta(t) = \frac{f}{k} \left[ I - \frac{k}{l} e^{-\frac{k}{l} t} + \frac{k}{l} t e^{-\frac{k}{l} t} - \frac{c}{l} t e^{-\frac{k}{l} t} \right] \]  

(22)

linear displacement = angular displacement * raduis of rotation

\[ p = r_o \ast \theta(t) \]  

(23)

\[ f = \frac{p k}{r_o[1 - \frac{k}{l} e^{-\frac{k}{l} t} + \left(\frac{k}{l} - \frac{c}{l}\right) t e^{-\frac{k}{l} t}]} \]  

(25)
III. Numerical Analysis

The solution of complicated problems and modeling in many engineering fields has been developed by finite element method, in this thesis ANSYS Workbench 18.2 used.

III.i. Static Analysis

The “static structural” option is used to explore the static cases for the model proposed

III.ii.a. Connection between elements: there is two connected position in the inerter inspired proposed, so body-ground connection and Body-body connection. The connection detail is shown in figure (2).

Figure (2) connection elements

III.ii.b. Meshing properties: The mesh step make for the structure proposed, the type of meshing used is coarse and several nodes equal to (2257), the element equals to (973) the steps of mesh illustrative below:

Mesh → Sizing → element size → input number. The mesh step is shown in figure (3)
III.ii.c. Boundary condition: the boundary condition for the inerter proposed is fixed from the case part side and a mass will be added to it from the disc side for every mass add a frequency and deflection has been calculated we will obtain a deformation as shown in figure (4)
When a cantilever structure is proposed with an external excitation with and without inerter damper and compare the inerter effected on frequency and deflection. To study the effect of increasing mass on the damping for inerter, a mass of flywheel inerter will increase gradually (200, 400, 600, 800 and 1000) g with a constant mass of the beam, figure (5) show the displacement for each mass step

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III.iii. Model Analysis

To obtain a solution for the structure proposed the model is dragging and connect with transient structure model analysis shown in the following sequence:

Shadow six frequency → create mode shape.

IV. Experimental work

To determine the stiffness magnitude of a spring element that is by the mass-deflection curve for that a structure created shown in the figure (6), deflection record from dial gauge for each mass added

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One of the most important parameters effected on damping is the mass of the flywheel of inerter, experimentally this step complete by added bolts and nuts to the flywheel of the inerter which is inserted with a cantilever beam structure, the latest supply with a hammer for external excitation, amplifier and Oscilloscope devices, figure (7) explain this step. The devices and experiments were made in the university of Baghdad, vibration laboratory.
V. Results and Discussion

This study made theoretical analysis, numerical analysis and experimental analysis and make a comparison between them. Previously mentioned the way to calculated stiffness of spring, table (1) show the result of deflection obtained for three spectra used.

| steps | Mass (g) | Def. (spec.1) mm | Deflection (spec.2) mm | Deflection (spec.3) mm |
|-------|-----------|-------------------|------------------------|------------------------|
| 1     | 200       | 4.52              | 3.82                   | 3.27                   |
| 2     | 400       | 6.55              | 5.15                   | 4.51                   |
| 3     | 600       | 14.2              | 13.06                  | 11.10                  |
| 4     | 700       | 18.85             | 17.3                   | 13.72                  |
| 5     | 1000      | 25.8              | 25.24                  | 21.57                  |

Table (1) mass-deflection results

Sketch (8) show mass-deflection numerically and experimentally results.

Parameters affected on damping of inerter proposed is (coefficient of friction, mass and stiffness), numerically study the behavior of each parameter on amplitude and frequency, first parameter stiffness when increasing the stiffness observe that the decrease the amplitude and increasing the frequency, next to the mass parameter which the amplitude reduces with percentage reach to 36% and reduce the frequency approximately 67%. Figure (9) show the mass parameter effect.

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To study the benefit of increasing mass of inerter damper on the cantilever beam structure that means increase inerter mass from (200,400,600,800 to 1000) g gradually to a constant mass of cantilever beam structure 130g, the rate increasing of inerter mass to the mass of threshold from 1.5 to 7.5 the amplitude reduces from 9.90243 to 3.76055 mm, figure (10) show the effect of increasing mass of inerter to the constant mass of cantilever beam on amplitude.

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VI. Conclusion

- Study the effect of adding masses to the structures on the behavior of vibration, experimental and numerical analysis show that adding mass could reduce the structural response of excitation in a large percentage.

- Numerical and experimental analysis showed the effect of using inerter in reducing the displacement resulting from external excitation that’s good in obtain structure and building safety which subjected to seismic excitation.

- Study the parameters effected on damping in inerter proposed (mass, stiffness and coefficient of friction), and found that when increasing the mass of inerter eight times mass of cantilever beam structure the frequency decrease by 56%.

- Theoretically was obtained the equation of motion for inerter proposed.

Conflict of Interest:

There is no conflict of interest regarding this article.
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