NON-LINEAR SMA-SDOF SYSTEM – AN OPTIMALITY STUDY, SOFT COMPUTING AND STATISTICAL PERSPECTIVE

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ABSTRACT

The ground motion due to earthquake is quite significantly different from that of the blast induced ground motion (BIGM). Even for the design of many facilities like ammunition storage, oil and water storage caverns the effect of ground shock vibration due to blast has to be taken into consideration. So the engineers in the field of mining and construction are quite concerned about such effects of blast. In this paper the structures are subjected to ground acceleration due to underground blast. The non-linear models of the SMA damper have also been considered in this context. An optimality study on non-linear SMA-single-degree-of-freedom (SDOF) systems has been carried out. Lastly the paper entails the soft computing and statistical perspective on non-linear SMA-SDOF system.

Key Words: *Shape Memory Alloy (SMA), Blast Induced Ground Motion (BIGM), Single-degree-of-freedom (SDOF) system, optimality, soft computing.*

INTRODUCTION

Underground blast load is an essential factor which is to be taken into consideration for all the civil structures located in the close proximity of underground mines and construction activities. The main characteristic features of the ground motion caused by underground blast are the waves of large amplitude and high frequency which behaves like an impulse load. It depends on several parameters such as the properties of the soil media, detonation time and also on the nature and geometry of the explosion. The shock resulting from underground blast includes two phases of vibration i.e. the forced-vibration phase and the free vibration phase. In the forced vibration phase high frequency modes with smaller displacement and large acceleration is the response characteristic, representing very high inertial shear force. However, the response in the free vibration phase is characterized by lower modes of frequency with larger displacement but the acceleration being smaller. When a structure is subjected to strong ground motion due to underground blast it might experience a sudden shear failure in the forced vibration phase. Even if the structure is strong enough to resist this sudden shear failure it may be damaged after the ground shock in the free vibration phase due to larger displacement and smaller acceleration caused by lower modes of frequency. So both the initial acceleration as well as the large displacement is needed to be controlled to prevent structural collapse. A two dimensional one storey framed structure is modeled as a single degree of freedom (SDOF) system. The mass of the structure is considered to be lumped and is simplified as a linear spring dash-pot model. The differential equation of motion of a SDOF system is taken into account and when the damping force arising from the SMA damper is incorporated in the equation, it makes the differential equation of motion non-linear in nature. This differential equation of motion is solved by using the 4th order Runge-kutta (R-K) method in Matlab R2008a and the displacement time-history analysis is done. Furthermore an optimality study considering various cross-sectional area of the damper is also carried out.

MATHEMATICAL FORMULATION

Let us consider a linear SDOF structural system subjected to a horizontal ground acceleration ($\ddot{u}_g$) due to underground blast. A SMA damper is installed as diagonal bracing in the structure. Let $u(t)$, $\dot{u}(t)$ and $\ddot{u}(t)$ respectively denote the horizontal displacement, velocity and acceleration along the DOF of the structure relative to the ground. The equation of motion of DOF may be written as

$$m\ddot{u}(t)+c\dot{u}(t)+ku(t)=-m\ddot{u}_g-F_{SMA} \tag{1.1}$$

where m, c, k and F_{SMA} denote the mass, damping , stiffness of SDOF system and the damping force transmitted from the SMA damper to the structure.

On rearranging Eq.(1.1) we obtain

$$m(\ddot{u}(t)+\ddot{u}_g(t))+c\dot{u}(t)+ku(t)+F_{SMA}(t)=0 \tag{1.2}$$

Normalizing Eq.(1.2) by m and considering $\frac{c}{m}=2\zeta\omega$ & $\frac{k}{m}=\omega^2$ we get

$$\ddot{u}(t)=-\ddot{u}_g-2\zeta\omega\,\dot{u}(t)-\omega^2 u(t)-\frac{F_{SMA}}{m} \tag{1.3}$$

Now,

$$s(t)=u(t)\cos\theta \tag{1.4}$$

and

$$€_{\text{SMA}}=\frac{f(s(t))}{L_{SMA}} \tag{1.5}$$

where

$s(t)$ =axial deformation of the SMA damper bracing

θ = angle between the SMA damper and the framed structure

€ = strain in the SMA damper bracing and

L_{SMA} =Length of the SMA damper bracing.

Now, the F_{SMA} versus €$_{\text{SMA}}$ is defined as the non-linear typical hysteretic loop for super elastic Nitinol SMA. The loop is defined in Matlab R2008a and each time the governing differential equation of motion is solved by using the 4th order Runge-kutta (R-K) method.

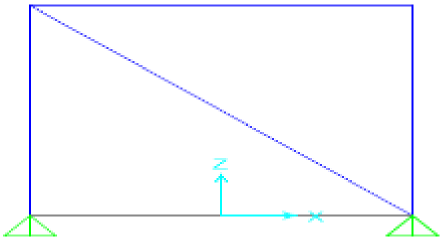

Fig. 1.1 Single storey frame with SMA damper modeled as SDOF system

Results and Discussions

The structural damping ζ is taken as 2% for structural steel and E_{steel} as 2×10^5 MPa. The displacement time-histories for the uncontrolled bare frame and the frame with SMA damper bracings comprising of 20 numbers of NiTi wires each of diameter 1 mm are presented in Fig. 1.2. The input BIGM is for R = 50m and Q = 100tons. The results of the simulation study showing the values of peak frame displacement for varying charge intensity Q and the distance R are tabulated in Table 1.1

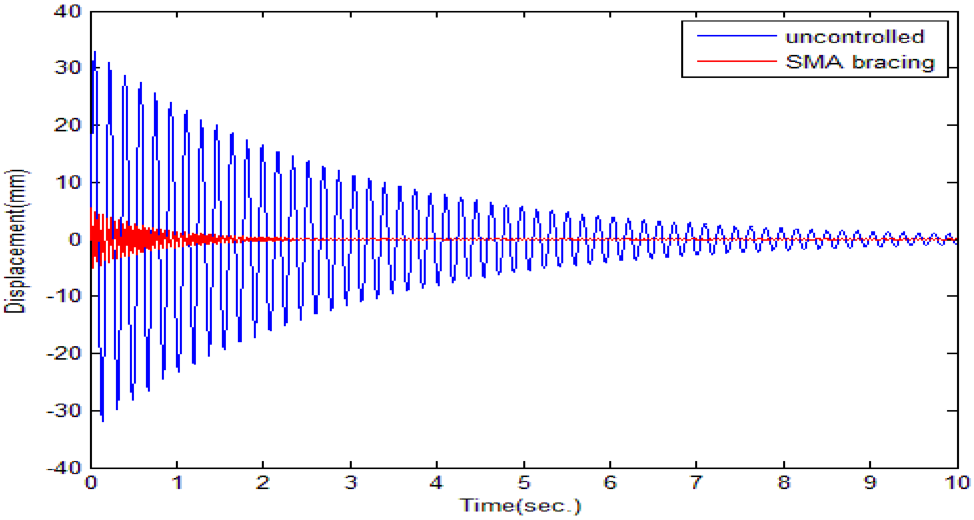

Fig. 1.2: Displacement time-history for the uncontrolled as well as the controlled frame with SMA damper

Table- 1.1: Simulation study showing the peak displacement values for varying Q and R

R (m)	Q(tons)	Uncontrolled frame(mm)	Frame with SMA damper (mm)
50	10	9.56	1.8
100	10	5.56	0.9
50	100	31.25	6.1
100	100	14.23	2.25

Next, a numerical optimization study is carried out by varying the cross-sectional area of the SMA damper. Again, the BIGM corresponds to that for R = 50m and Q = 100 tons. Fig.1.3 shows the variation of percentage reduction in displacement response for various cross-sectional areas of the damper.

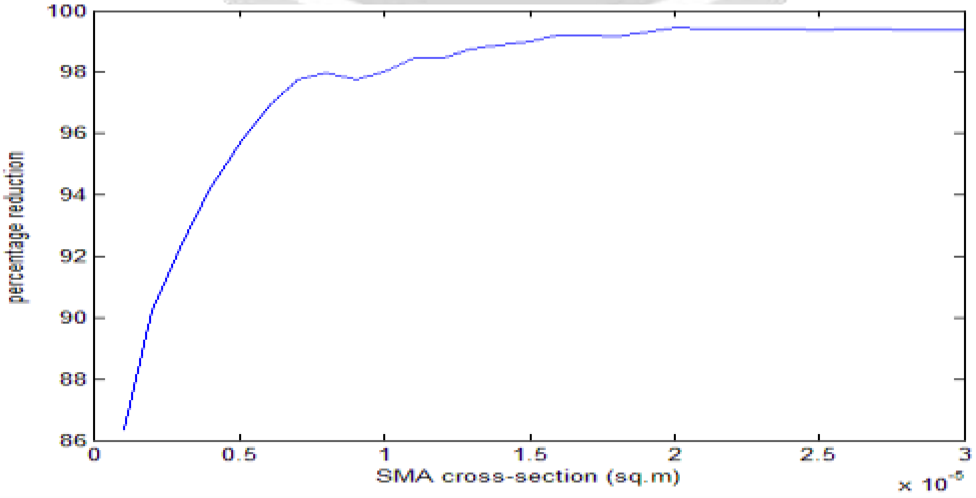

Fig. 1.3: Variation of percentage reduction with cross-section of damper

The figure shows that even with a fairly low cross-sectional area of the SMA damper brace, there is substantial response reduction. The performance of the SMA damper brace increases sharply with increase in cross-sectional area, but after about 10 mm^2, the further improvement in performance is marginal. The value of 20 mm^2 may be taken as the optimal value of cross-sectional area of the damper in this case.

SOFT COMPUTING AND STATISTICAL PERSPECTIVE

A.Neuro-fuzzy Model

Due to underground blast, the reduction in blast intensity plays a pivotal role. The significant parameters (Carvalho E.M.L. ,Batista R.C.,2003) include peak particle velocity, propagation velocity of wave in the rock , distance in meters measured from charge centre, TNT charge weight in kilogram , volume of charge chamber in cubic meter.

The quantified reduction percentage of blast intensity as per the neuro-fuzzy model is $I_B = \sum_{i=1}^{n} p_i \times w_i + \beta$

where I_B = reduction percentage of blast intensity

p_i = fuzzy value of ith parameter,

w_i = associated weight of ith parameter,

n = total number of parameters

and β = unit positive bias value.

B. Analysis of blast event occurrence in the light of group theory

The probabilistic analysis of occurrence of blast events maintais a proper co-ordination between present with past and present with future event.

Let us assume $T_E(€_t)$ be the time-stamp of blast event occurrence,

$T_E(€_{t-1})$ be the time-stamp of previous blast event occurrence with respect to present event

and $T_E(€_{t+1})$ be a probabilistic estimate of time-stamp of future blast event occurrence with respect to present event.

The entire time-stamps of realizing the past, present and future events can be represented by Abelian Group (G,+) where $T_E(€_{t-1}, €_t, €_{t+1}) = \{0, \pm1, \pm 2, \ldots \pm\infty\}$,the identity element ‘0’ being $T_E(€_t)$.

The sets representing correlation of past and future events with respect to present are

$$T_E(€_{t-1},€_t) = \{ (-1,0),(-2,0),\ldots.(-\infty,0)\}$$

and $$T_E(€_t,€_{t+1}) = \{ (1,0), (2,0),\ldots..(\infty,0) \}$$

C. Temporal fuzzy logic based analysis

Let $\mu_E(x, t_i)$ denote time-variant membership function of decay of amplitude of the response under the action of blast load

and $\mu_D(x,t_i)$ denote time-variant membership function of stability of restoration.

$R(\mu_E(x, t_i))$ ¢ $F(\mu_D(x, t_i))$ and $F(\mu_E(x, t_i))$ ¢ $R(\mu_D(x, t_i))$,

where ¢ is the concurrence temporal fuzzy symbol , $R(\mu_A(y, t_i))$ is rare fuzzy value of $\mu_A(y, t_i)$ and $F(\mu_A(y, t_i))$ is frequent fuzzy value of $\mu_A(y, t_i)$.Diagnosis of event (decay or restoration) can be investigated at specific timing instants for futuristic trend analysis as follows –

$$\beta\ [\ X^{a}\ \mu_{E}(x,t_{i})\ W^{b}X^{a+1}\ \mu_{E}(x,t_{m})]$$

where $\beta\ \mu_A(x,\ t_i)$ signifies validity of $\mu_A(x,\ t_i)$ at next timing instant ,

$X^a\ \mu_E(x,t_i)$ stores grade of membership $\mu_E(x,t_i)$ in location a

and $W^bX^{a+1}\ \mu_E(x,t_m)$ means wait for b consecutive intervals and then calculate next calculate grade of membership $\mu_E(x,t_m)$ thereby storing in location (a+1)

CONCLUSIONS

Through this work, the applicability of SMA as a structural vibration control device for framed structures subjected to underground blast induced ground motion has been investigated. An optimality study on non-linear SMA-SDOF system is conducted. Besides dissipating energy, SMAs also possess re-centering capability which enables the structure to return to its original position after the blasting effect. Economically feasible solutions can be attained with Nitinol-based SMAs if they are used in small devices or judiciously applied to selected regions of a structure. Also extra fabrication costs can be avoided as SMA device has a straightforward design. So it is definitely concluded that if the SMAs are utilized in the right manner they have a great potential in controlling the structural response due to underground blast induced support motions of structures. The work has also been analysed in the light of neuro-fuzzy model, Abelian group theory and temporal fuzzy logic.

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