JCARME

ISSN: 2228-7922

SRTTU

Journal of Computational and Applied Research in Mechanical Engineering
Vol. 3, No. 2, pp. 85- 94, Spring 2014
http://jcarme.srttu.edu

Optimal design of a vibration absorber for tremor control of arm in Parkinson's disease

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Article info:
Received: 17/05/2013
Accepted: 30/11/2013
Online: 03/03/2014

Keywords:
Parkinson's disease,
Vibration absorber,
Random vibrations,
Imperialist competitive algorithm,
Multi-objective optimization.

Abstract

Because the underlying physiology of pathological tremor in a Parkinson's patient is not well understood, the existing physical and drug therapies have not been successful in tremor treatment. Different mathematical modeling of such vibration has been introduced to investigate the problem and reduce the existing vibration. Most of the models have represented the induced vibration as a sinusoidal wave for mathematical simplification. In this study, a more realistic model based on random vibration was used to attack the problem of tremor suppression. A simple approach for suppressing the tremor associated with Parkinson's disease was presented. This paper was concerned with a multi-objective approach for optimum design of linear vibration absorber subject to random vibrations. Analytical expressions, for the case of non-stationary white-noise accelerations, were also derived. The present approach was different from conventional optimum design criteria since it was based on minimizing displacement as well as accelerating variance of the main structure responses without considering performances required against discrepancy in response. In this study, in order to control the tremor induced on biomechanical arm model excited by non-stationary based acceleration random process, multi-objective optimization (MOO) design of a vibration absorber was developed and performed using modern imperialist competitive optimization algorithm for multi-objective optimization. The results demonstrated importance of this method and showed that multi-objective design methodology provided significant improvement in performance stability and giving better control of the design solution choice.

1. Introduction

Since the 1817 descriptions of 'shaking palsy' by James Parkinson [1], the concept of clinical entity Parkinson's Disease (PD) has been established. The most prominent tremor in Parkinson's disease is rest tremor (i.e. when voluntary muscle activity is absent). Tremors

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are characterized in terms of frequency, amplitude and waveform. Frequency of PD tremor varies from 2 to 10 Hz [2]. Because the underlying physiology of pathological tremor is not well understood, the existing physical and drug therapies have not been successful in tremor treatment. In this paper, a passive control tremor in Parkinson's disease was studied. Dynamic parameters were applied to a biomechanical arm model and vibration absorption system parameters were obtained using multi-objective optimization.

There are essentially two main approaches to forced vibration control: vibration isolation and vibration absorption. The vibration isolation system is designed to isolate source of vibration from the system of interest or isolate the device from the source of vibration [3]. Vibration absorbers, however, are normally used to absorb or extract vibrations from an oscillatory system by adding a physical spring-mass-damper system to the structure [4-5]. By changing the absorber's characteristics, the added absorber's natural frequency can be tuned so that the structure does not feel the transmitted force. Theoretically, natural frequency of the vibration absorber can be tuned such that the amplitude of vibration is minimized at the frequency of vibration. Spring of the vibration absorber transfers vibration energy to the added mass. This issue results in substantial motion of the added mass. A viscous damper is used to dissipate energy of the vibration [6]. In PD tremor, different patients have individual tremor frequencies (from 2 to 12 Hz) [7]. Since tremor suppression is a broadband vibration control problem, it is necessary for the proposed vibration absorber to be tuned to suppress tremor at a specific frequency.

Problems of vibration absorber analysis for control of arm in PD and designing are still present in scientific papers. For example, Teixeira et al. studied an approach to PD tremor suppression based on a self-tunable dynamic vibration absorber (DVA) and addressed two configurations, which were different by a damping element during the research [8]. As'arry et al. examined an active control technique to lessen severity of tremors and presented an online method of a hybrid proportional–integral control with active force control strategy for tremor attenuation [9]. Verstappen et al. provided results of applying repetitive control to overcome or lessen effects of this tremor by regulating level of artificially induced electrical stimulation applied to a person's limb to cause muscle contraction [10].

All the methods proposed for seismic device optimization have been based on the minimization of a single OF (objective function) that quantifies the protected systems' response reduction with respect to the unprotected configuration. Moreover, the OFs are expressed in terms of covariance and the main limitation is lack of information about final structural performance, which is unknown when expressed in terms of reliability. The present work focused on the structural optimum design criterion that directly involved a performance based design in the random vibrating structural problem. Without loss of generality, the optimum design of a vibration control device was analyzed as a case study regarding structures subject to seismic actions. Here, in contrast to conventional optimization which involves single OF, several OFs were involved in design decisions. These functions are often in conflict with each other and it is not possible for them to define a universally approved criterion for "optimum" design as occurs in SOO (single objective optimization). For this reason, Pareto dominance and Pareto optimality constitute every important notions in MOO problems because they not only could furnish a single defined optimal solution (as in SOO), but also could give a set of possible optimal satisfying solutions at the same time. In this work, an MOO procedure was adopted for the optimum design of seismic devices for linear two-DOF model of arm subject to random seismic loads in Parkinson's disease. This procedure adopted 2DOF vector that was defined using both standard deterministic costs and structural survival probability indices. An example was developed with the first OF element assumed as a deterministic device mass that was proportional to the patient comfort and the second one was probability of the response discrepancy. The discrepancy is defined as the

first crossing out of an admissible domain of one structural response during all seismic actions.
Reliability evaluation was developed using the state space covariance analysis and the Poisson hypothesis was adopted to evaluate mean threshold crossing rate for the safe domain. A single vibration absorber located at the forearm of a two degree of freedom (DOF) linear model of the arm was analyzed. The base acceleration representing seismic actions were modeled by a non-stationary filtered white-noise that could yield a realistic seismic load model. In the optimization problem, the design vector was the collection of vibration absorber's mechanical parameters including frequency, mass ratio and damping ratio. The main innovation of the proposed approach was adaptation of the performance based seismic design in an MOO problem for the optimum design of a vibration absorber in accordance with modern seismic technical codes. The proposed approach could give pre-design information which is extremely useful in initial designer decisions. Using the MOO proposed in this work, the designer could control performances and patient comfort in different Pareto front locations and defines solution types to be adopted according to sensibilities and decisions. The novelty of the proposed method was in using multi-dimensional criterion for the design. In these situations, the designer had to select the design variables, meeting all the objectives.
This work was performed using the modern imperialist competitive optimization algorithm that had good performance in solving complex optimization problems. Imperialist competitive algorithm (ICA) is a novel global search heuristic that uses imperialism and imperialistic competition process as a source of inspiration.

2. Biomechanical arm model

Dynamic modeling of the arm is vital for understanding the muscle activation related to arm movement. A brief survey of the literature reveals that human arm has been commonly modeled as a double-jointed, two-dimensional dynamic system [11-13]. The joints have been modeled as ideal, frictionless kinematic joints with strictly fixed axes or centers of rotation. In the lumped-mass planar model developed by JACKSON and JOSEPH (1978), motion in the sagittal plane was studied, in which the upper arm and the forearm were represented by straight, pivoted rods. The Lagrangian method was adopted to derive dynamic mathematical model. In this case, once muscular torques, resistive torques and accelerations of the shoulder were available, motion of the arm (forward mechanism) could be determined. The body's trunk was considered to be fixed and connections were made at the shoulder joint and elbow joint. This model described planar motion: flexion/extension in the shoulder joint and elbow joint. It was consisted of two rigid segments and two joints, representing the shoulder and elbow. The forearm and hand were considered to be one segment. Assuming small angular displacements and neglecting the higher-order terms, non-linear equations of motion could be liberalized in the neighborhood of the point of stable equilibrium (i.e. here, θ_1=45° and θ_2=90°).

$$[M]\{\ddot{\theta}\}+[C]\{\dot{\theta}\}+[K]\{\theta\}=\{F\}\sin(\omega t) \quad (1)$$

$$M=\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$

$$K=\begin{bmatrix} K_1+K_3 & K_3 \\ K_3 & K_2+K_3 \end{bmatrix} \quad (2)$$

$$C=\begin{bmatrix} C_1+C_3 & C_3 \\ C_3 & C_2+C_3 \end{bmatrix}$$

$$\begin{aligned} M_{11} &= (I_1+m_1a_1^2)+(I_2+m_2a_2^2) \\ &+m_2l_1^2+m_b(l_1^2+l_2^2)+m_3(l_1^2+l_3^2) \\ M_{12} &= (I_2+m_2a_2^2)+m_bl_2^2+m_3l_3^2 \\ M_{21} &= M_{12} \\ M_{22} &= (I_2+m_2a_2^2)+m_bl_2^2+m_3l_3^2 \end{aligned} \quad (3)$$

I_1 and I_2 are moments of inertia at the centre mass of the upper arm and forearm, m_1 and m_2 are masses of the upper arm and forearm,

l_1, l_2, l_3, l_a are lengths of the upper arm and forearm and distances from the absorber's center of gravity and joint to the elbow joint, respectively, $a_1$and a_2 are distances from the proximal joint to the centre of mass of the upper arm and forearm, $F_1$and $F_2$are external torques acting at the shoulder and elbow joints, respectively, θ_1 and θ_2 represent angles of flexion at the shoulder and elbow and K_i and C_i are the net stiffness and damping coefficients of muscles. Figure 1 shows schematic diagram of the arm model.

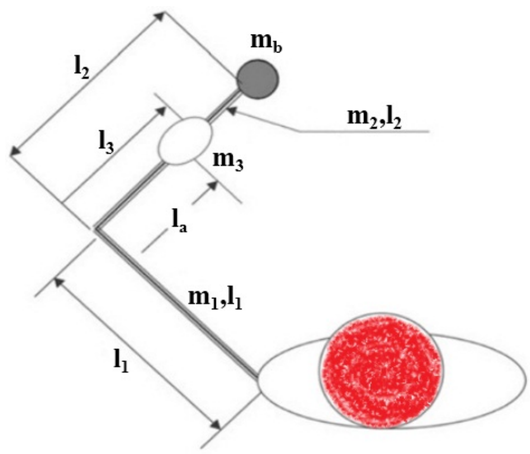

Fig. 1. Schematic diagram of arm model.

3. Multi-objective stochastic optimization of random vibrating systems

For a generic linear *n* DOF system excited by a forcing vector ***f(t)*** whose related stochastic process is Gaussian with null mean value stochastic vector ***F***(*t*), well-known differential matrix motion equation is:

$$\mathrm{M}\ddot{\theta}(\mathrm{t})+\mathrm{C}\dot{\theta}(\mathrm{t})+\mathrm{K}\theta(\mathrm{t})=\mathrm{f}(\mathrm{t}) \quad (4)$$

where ***M***, ***C*** and ***K*** are deterministic mass, damping and stiffness matrices, respectively and $\ddot{\theta}, \dot{\theta}$ and θ are angular acceleration, velocity and displacement vectors, respectively. The motion Eq. (4) can be written as a first order differential matrix equation by introducing the space state vector $z(t)=(\theta(t)\dot{\theta}(t))^T$ under the hypothesis of zero mean Gaussian input (as commonly assumed for natural phenomena). The stochastic response is completely described by state space covariance matrix knowledge ***R***(*t*) and it can be evaluated by means of Lyapunov covariance matrix equation [14] shown below:

$$\dot{R}(t)=AR(t)+R(t)A^T+B(t) \quad (5)$$

where the matrix $B(t)=\left\langle \hat{f}+z^T \right\rangle + \left\langle z\hat{f}^T \right\rangle$, and the system matrix and input vector are

$$A=\begin{bmatrix} 0 & 1 \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \quad (6)$$

$$\hat{f}(t)=\begin{Bmatrix} 0 \\ M^{-1}f(t) \end{Bmatrix} \quad (7)$$

4. Optimization criteria

The optimization problem could be formulated as selection of a set of design variables collected in the above so-called DV***b*** over a possible admissible domain Ω_b. With reference to SOO problem, optimal DV can minimize a given OF and satisfy the assigned constraint conditions. Deterministic-based optimization is aimed to minimize weight or volume subject to given deterministic constraints generally referred to as general stresses and/or displacements. An additional probabilistic constraint is considered in the case of reliability-based design, which is related to structural performance. Reliability theory is afterwards introduced into structural engineering and structural optimization in order to consider all the existing sources of uncertainty in a more rational way. MOO provides the opportunity for the designer to evaluate a set of possible solutions that satisfy more than one index, but with different performances. The definitions of these solutions are usually known as the Pareto dominance and

Pareto optimality criterion and constitute a fundamental point in MOO problems. Essentially, defining the generic "efficiency" index, $OF_i(\boldsymbol{b})$, as a typical minimization-based MOO problem, is assumed as

$$\min\left\{OF_1(\bar{b}), OF_2(\bar{b}), \ldots, OF_M(\bar{b})\right\} \tag{8}$$

Given two candidate solutions b_j و b_k in the domain Ω_b, if

$$\begin{aligned} &\forall i \in \{1,\ldots,M\}, OF_i(b_j) \le OF_j(b_k) \\ &\exists i \in \{1,\ldots,M\}, OF_i(b_j) \le OF_i(b_k) \end{aligned} \tag{9}$$

and defining the two objective vectors

$$v(b_j) = \{OF_1(b_j),\ldots,OF_M(b_j)\} \tag{10}$$

$$v(b_k) = \{OF_1(b_k),\ldots,OF_M(b_k)\} \tag{11}$$

Vector $\boldsymbol{v}(\overline{b_j})$ is said to dominate vector $\boldsymbol{v}(\overline{b_k})$. If no feasible solution $\boldsymbol{v}(\overline{b_k})$ exists that dominates solution $\boldsymbol{v}(\overline{b_j})$, $\boldsymbol{v}(\overline{b_j})$ is classified as a non-dominated or Pareto optimal solution.
Unfortunately, the Pareto optimum does not almost always give a single solution, but rather a set of solutions; it cannot proceed in an analytical way. The collection of all Pareto optimal solutions is known as the Pareto optimal set or Pareto efficient set. The corresponding objective vectors are instead described as the Pareto front or trade-off surface.

5. Optimization algorithm

Evolutionary optimization methods, inspired by natural processes, have shown good performance in solving complex optimization problems. The method, proposed in this work, used socio-political evolution of human as a source of inspiration for developing a powerful optimization strategy. Specifically, this algorithm considered imperialism as a level of human's social evolution and, by mathematically modeling this complicated political and historical process, harnessed it as a tool for evolutionary optimization. Since its recent inception, this novel method has been widely adopted by researchers to solve different optimization tasks. This method has been used to design optimal layout for factories, adaptive antenna arrays, intelligent recommender systems, optimal controller for industrial and chemical possesses [15-16].
ICA is a novel global search heuristic that uses imperialism and imperialistic competition process as a source of inspiration. Since its inception, this algorithm has been used to solve many optimization tasks. A big picture of the proposed algorithm is shown in Fig. 2.

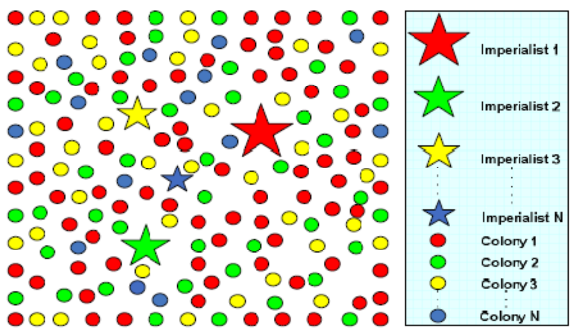

Fig. 2. Big picture of the proposed algorithm [17].

Figure 3 shows the pseudo-code for this algorithm. This algorithm starts with some initial countries. Some of the best countries are selected to be the *imperialist states* and all other countries form *colonies* of these imperialists. The colonies are divided among the mentioned imperialists based on their power [18]. After dividing all colonies among imperialists and creating the initial empires, these colonies start moving toward their relevant imperialist state. This movement is a simple model of assimilation policy that has been pursued by some imperialist states. Figure 4 demonstrates movement of a colony towards the imperialist. In this movement, θ and *x* are random numbers with uniform distribution and *d* is distance between colony and the imperialist.

Total power of an empire depends on both power of the imperialist country and power of its colonies. In this algorithm, this fact is modeled by defining total power of an empire by the power of imperialist state plus a percentage of the mean power of its colonies.

1) Select some random points on the function and initialize the empires.

2) Move the colonies toward their relevant imperialist (assimilating).

3) If there is a colony in an empire which has lower cost than that of imperialist, exchange the positions of that colony and the imperialist.

4) Compute total cost of all empires (related to the power of both imperialist and its colonies).

5) Pick the weakest colony (colonies) from the weakest empires and give it (them) to the empire that has the most likelihood to possess it (imperialistic competition).

6) Eliminate the powerless empires.

7) If there is just one empire, stop; otherwise, go to step 2.

Fig. 3. Pseudo code for the proposed algorithm [16].

In imperialistic competition, all the empires try to take possession of colonies of other empires and control them. This competition gradually brings about a decrease in the power of weaker empires and an increase in the power of more powerful ones. This competition is modeled by just picking some (usually one) of the weakest colonies of the weakest empires and making a competition among all empires to possess the colony (colonies). Figure 5 shows a big picture of the modeled imperialistic competition. Based on their total power, in this competition, each of empires will have some likelihood of taking possession of the mentioned colonies. The more powerful an empire is, the more likely it will possess these colonies. In other words, these colonies will not be certainly possessed by the most powerful empires; however, they will be more likely to possess them [17-18].

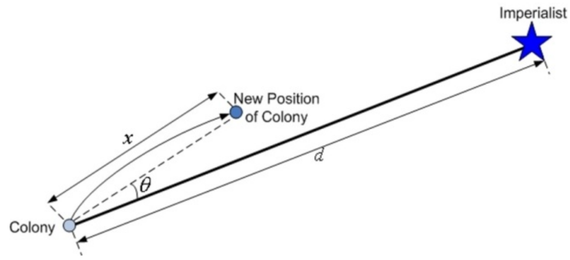

Fig. 4. Motion of colonies toward their relevant.

Any empire that is not able to succeed in imperialist competition and cannot increase its power (or at least prevent decreasing its power) will be eliminated. The imperialistic competition will gradually result in an increase in the power of great empires and a decrease in the power of weaker ones. Weak empires will lose their power gradually and they will collapse ultimately. Movement of colonies toward their relevant imperialists along with competition among empires and also collapse mechanism will cause all the countries to converge to a state in which there exists just one empire in the world and all other countries are its colonies. In this ideal new world, colonies have the same position and power as the imperialist [19].

6. Optimization formulation of the system

A standard way in modeling vibration absorber was carried out by a mass-dashpot-spring system (the secondary system) attached to the top of a linear single DOF system. The main scope was to reduce unacceptable vibrations in the main system; i.e. damage level and failure probability. In this specific case, the base excitation acting on the arm was treated as a non-stationary filtered stochastic process. It is quite important to represent evolutionary nature of response processes, given the effect of this characteristic on structural reliability.
Simplicity and less computing cost could be obtained by treating the process as a stationary one; but, it could overestimate the real final

reliability so that the engineering decision based on the optimization criteria could be strongly different from the real physical phenomenon.

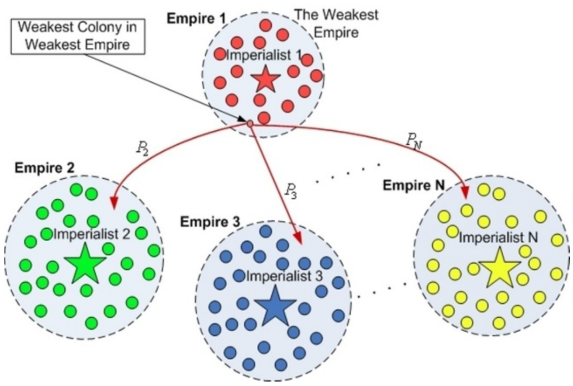

Fig. 5. Imperialistic competition: The more powerful an empire is, the more likely it will possess the weakest colony of the weakest empire [17].

Therefore, a time-modulated input process was adopted for base acceleration description and the motion equations of the system in Fig. 6 were

$$\ddot{\theta}(t)+C\dot{\theta}(t)+K\theta(t)=-Mr\ddot{\theta} \tag{12}$$

where ***M***, ***C*** and ***K*** are, respectively, deterministic mass, damping and stiffness *(n+1)×(n+1)* matrices. **n** represents the number of degrees of freedom in the system. Since in this work n=1 was used, the vectors $\theta=(\theta_1,\theta_2,\theta_A)^T$, $\dot{\theta}=(\dot{\theta}_1,\dot{\theta}_2,\dot{\theta}_A)^T$ and $\ddot{\theta}=(\ddot{\theta}_1,\ddot{\theta}_2,\ddot{\theta}_A)^T$ collected the displacements, velocities and accelerations of the arm and of the vibration absorber relative to the arm and finally r = $(1,1)^T$. For higher DOF systems, n as well as rank of $\theta,\dot{\theta},\ddot{\theta}$ and r grew.

The vibration absorber's mechanical characteristics were described by parameters M_A, K_A and C_A, respectively, as mass, stiffness and damping of the vibration absorber. Introducing the space state vector $Z=(\theta,\theta_f,\dot{\theta},\dot{\theta}_f)^T$,the system matrix ***A*** would be

$$A=\begin{bmatrix}0^{(n+2)(n+2)} & I^{(n+2)(n+2)}\\ -H_K & -H_C\end{bmatrix} \tag{13}$$

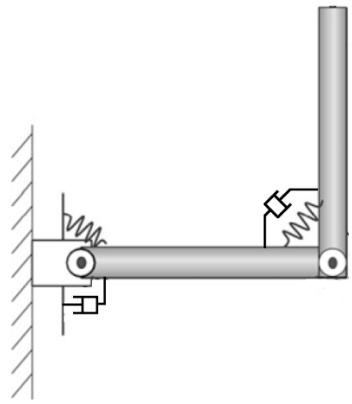

Fig. 6. Schematic arm model equipped with a vibration absorber.

in which the two sub-matrices (*n*+2)(*n*+2) H_K and H_C are respectively

$$H_K=\begin{bmatrix} & & \omega_f^2\\ (M^{-1}K)^{(n+1)(n+1)} & & \cdots\\ & & \omega_f^2\\ 0 & \cdots \quad 0 & -\omega_f^2\end{bmatrix} \tag{14}$$

$$H_C=\begin{bmatrix} & & 2\xi_f\omega_f\\ (M^{-1}C)^{(n+1)(n+1)} & & \cdots\\ & & 2\xi_f\omega_f\\ 0 & \cdots \quad 0 & -2\xi_f\omega_f\end{bmatrix} \tag{15}$$

To describe the stochastic acceleration, the non-stationary Kanai-Tajimi (K-T) stochastic seismic model [20] was used in this work. This model has found wide application in random vibration analysis of arm because of providing a simple way for describing motions characterized by a single dominant frequency. It is an interesting fact of life that many naturally occurring random vibrations have the well-known Gaussian probability distribution [21]. So, the model was excited by Gaussian distribution by a simple white-noise linear filter which treated the vibrations as a steady random phenomenon.

Following the above considerations, total acceleration $\ddot{\theta}_b(t)$ acting on the basis of the structure was obtained by summing contribution of inertial force $\ddot{\theta}_f(t)$ of the K-T filter and the time-modulated white-noise excitation $\varphi(t)w(t)$ as follows:

$$\begin{cases} \ddot{X}_b(t) = \ddot{X}_f(t) + \phi(t)w(t) \\ \ddot{X}_f + 2\xi_f\omega_f\dot{X}_f(t) + \omega_f^2 X_f(t) = -\phi(t)w(t) \end{cases} \quad (16)$$

where $\boldsymbol{X}_f(t)$ is displacement response of the K-Tfilter, ω_f is K-T filter natural frequency and ξ_f is K-T filter damping coefficient. Regarding the modulation function $\varphi(t)$, different formulations have been proposed in the literature. In this paper, the one proposed by Jennings [22] was used which had the following form:

$$\varphi(t) = \begin{cases} (t/t_1)^2 & t < t_1 \\ 1 & t_1 < t < t_2 \\ e^{-\beta(t-t_2)} & t > t_2 \end{cases} \quad (17)$$

where $t_d=t_2-t_1$ is time interval and the peak excitation is constant. Parameters are assumed as t_1=3 s, t_2=15 s and β=0.4 s^{-1}.
Intensity constant S_0 of power spectral density (PSD) can be related to the standard deviation $\sigma_{\ddot{x}_b}$ of ground acceleration [23] by means of the following relation:

$$S_0 = 2\xi_f\sigma_{\ddot{x}_b}^2 / \left[\pi(1+4\xi_f^2)\omega_f\right] \quad (18)$$

where γ_m, the mass ratio, is defined as vibration absorber mass with respect to the structure one.

$$\gamma_m = m_a / \sum_{i=1}^{n_f} m_i \quad (19)$$

and $P_f(\boldsymbol{b}, x_{adm}, T)$ is structure failure probability at time T; it is assumed that the conventional structural failure takes place when the structure lateral displacement x_L crosses a fixed threshold value x_{adm}. This performance index (or its complementary reliability $r(\boldsymbol{b}, x_{adm}, T)=1-P_f$), with respect to the first exceeding of a threshold value x_{adm} must be evaluated. Giving the assumption $r(\boldsymbol{b}, x_{adm}, 0)=1$ at the beginning of the seismic action, the approximate Poisson formulation of the exact Rice's formula [24] for a symmetric barrier provides

$$P_f(b, x_{adm}, T) = 1 - \exp\{-2\int_0^T v^+(b, x_{adm}, \tau)d\tau\} \quad (20)$$

Possible strategy that could be adopted for the structural optimization of vibration absorber's mechanical parameters is minimization of γ_m and of the system failure probability. The MOO problem is hence defined by collecting both deterministic cost index and reliability measure in an OF vector so that the multi-objective optimal criteria could be stated as find $b \in \Omega_b$ which minimizes

$$\overline{OF}(b, T) = \{\gamma_m, P_f(b, T)\} \quad (21)$$

7. Numerical results

Optimal design of a vibration absorber for vibration control of a 2 DOF arm was considered. Mechanical characteristics are shown in Table 1.

Table 1. Mechanical characteristics of the arm.

	Mass(kg)	Stiffness(N/m)
Shoulder	1.45	180
Elbow	2.18	250

Also $c_1=0.001k_1$ and $c_2=0.002k_2$ [25].
In this problem, n=2 for all proven relations. In solving the original problem, the Pareto optimal set was obtained. Figure 7 shows the Pareto set for the possibility of 2 mm displacement. X axis represents the minimized mass ratio and y axis represents the minimum failure probability. Other parameters of the optimal design of the vibration absorber such as ω_T, ξ_T are dipicted in Figures 8 and 9, respectively. Therefore, for a specific P_f, optimum solution $\mathbf{b}^{opt}$ which minimized γ_m and satisfied the desired objective would be achieved. It is clear that, with increasing mass ratio, the failure probability decreased; but, an extra mass was imposed on the patient. So, a balance between failure probability and mass ratio had to be made.

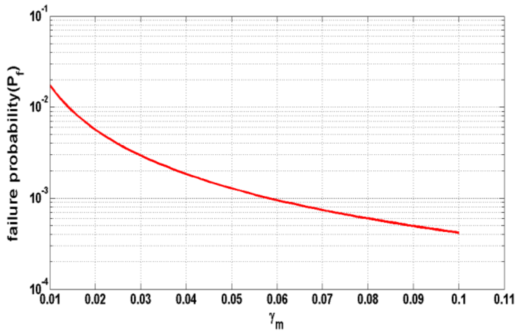

Fig. 7. Parato set for 2 mm displacement.

In Fig. 8 x axis represents mass ratio γ_m and y axis represents optimum frequency ratio. For each mass ratio, an optimum frequency of operation will exist based on which the system configuration is.

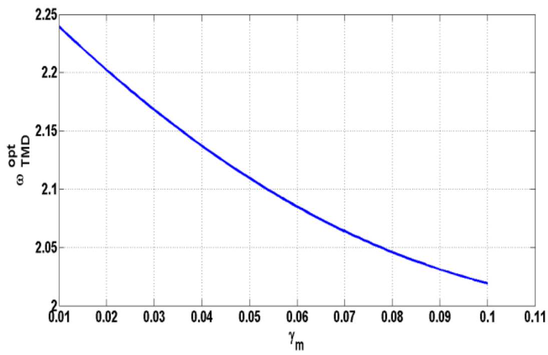

Fig. 8. Optimum frequency ratio.

In Fig. 9, x axis represents mass ratio γ_m and y axis represents optimum damping ratio ξ_{TMD}. For each mass ratio, an optimum damping ratio existed that led to optimum performance of the system.

8. Conclusions

In this paper, a multi-objective approach was studied for optimum design of linear vibration absorber subject to random vibrations. Analytical expressions for the case of non-stationary white-noise accelerations were also derived. The present approach was different from conventional optimum design criteria since it was based on minimizing displacement as well as acceleration variance of the main structure responses without considering performances required against discrepancy in

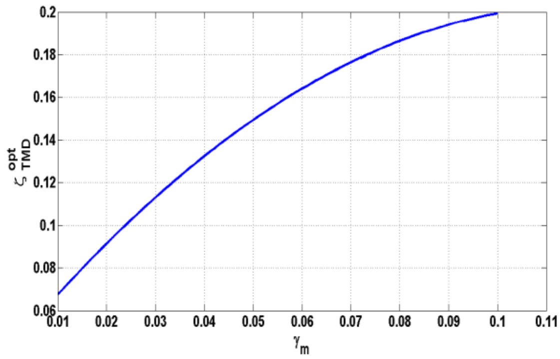

Fig. 9. Optimum damping ratio.

response. In this study, in order to control the tremor induced on biomechanical arm model excited by non-stationary based acceleration random process, multi-objective optimization (MOO) design of a vibration absorber was developed. A numerical example of a vibration absorber for a two degree of freedom arm was developed and the generated results were compared with those of similar investigations.

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