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Response surface methodology based multi-objective optimization of tuned mass damper for jacket supported offshore wind turbine

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Abstract. This paper presents a review on getting a Weighted Multi-Objective Optimization (WMO) of Tuned Mass Damper (TMD) parameters based on Response Surface Methodology (RSM) coupled central composite design and Weighted Desirability Function (WDF) to attenuate the earthquake vibration of a jacket supported Offshore Wind Turbine (OWT). To optimize the parameters (stiffness and damping coefficient) of damper, the frequency ratio and damping ratio were considered as a design variable and the top displacement and frequency response were considered as objective functions. The optimization has been carried out under only El Centro earthquake results and after obtained the optimal parameters, more two earthquakes (California and Northridge) has been performed to investigate the performance of optimal damper. The obtained results also compared with the different conventional TMD's designed by Den Hartog's, Sadek *et al.*'s and Warburton's method. From the results, it was found that the optimal TMD based on RSM shows better response than the conventional damper. It is concluded that the proposed response model offers an efficient approach regarding the TMD optimization.

Keywords: weighted multi-objective optimization; tuned mass damper; response surface methodology; weighted desirability function; offshore wind turbine

1. Introduction

Tuned Mass Damper (TMD) is renowned passive vibration absorbing device in the engineering reign. However, the effectiveness of TMD in reducing the earthquake response of structures is still in the row for its vibration controlling phenomena. Despite the bulk of literature on optimization of TMD, till date it's very challenging to the researcher and engineer to finding an optimal TMD. TMD usually consists of mass-spring-damper that will absorb a portion of the energy added to the structure by the live such as dynamic loads. After the first introduction of TMD concept by Frahm (1911), many researchers gave their concentration on TMD device. Some researchers among of them have been successfully designing the TMD. Ormondroyd (1928) and Brock (1946) has been discussed the tuned mass damper parameters. Afterward, the Warburton (1981) design the parameters energy absorber to find an optimum one for minimizing vibration response of the structure. After some years, Den Hartog (1985) has discussed the mechanical vibration reducing device to mitigate the seismic response of the structure. To determine the optimum parameters of single tuned mass damper, a methodology has been discussed by the Sadek *et al*. (1997) for a single degree of freedom and multiple degrees of freedom structures subjected to a number of earthquake excitations. Also, an optimal design theory has been studied by the Lee *et al*. (2006) for structures implemented with tuned mass dampers. Salvi and Rizzi (2014) derived the closed-form optimum tuning formulas for passive TMD device and tuned the TMD parameters through a nonlinear gradient-based optimization algorithm. Zhou *et al*. (2015) investigated the optimization of multiple tuned mass dampers (MTMD) for large-span roof structures subjected to win loads and developed a practical method for the design of MTMD according to the characteristics of structures. Pourzeynali *et al*. (2016) investigated the robust multi-objective optimization design of semi-active tuned mass damper (STMD) system using genetic algorithms and fuzzy logic to consider the uncertainties which may exist in the system.

The response surface methodology (RSM) is one of the most widely-used statistical approach that is useful for analyzing the data and optimizing the processes. Soto-Pérez (2015) applied this to the optimization of cement paste mix design. Khan *et al*. (2016) investigated multi-objective optimization to optimize the cost effective mix proportioning of high strength self-compacting concrete by approximating material model and cost model by means of RSM.

Like other engineering problem, TMD design is multi-objective optimization problem. Thus, TMD design have to optimize multiple objectives simultaneously. In most real engineering problem, all objectives may have the respective relative importance.

This paper has concerns about the multi-objective

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optimization with relatively weighted objectives of TMD based on RSM coupled central composite design (CCD) and desirability function considering the relative importance of each objective. The multi-objective optimization of TMD system would be difficult due to the different functions having different units and different orders of magnitude. Thus, it needs to make these objective functions be on the same scale by applying desirability function. In addition to this, each of different objective functions must have a different importance in designing TMD parameters depending on applications, requirements and so on. The multi-objective optimization problem is structurally similar with multi-criteria decision making (MCDM) process dealing with the problem of choosing an option from a set of alternatives, which are characterized in terms of their attributes. One of the most outstanding multi-criteria decision making (MCDM) approaches is the analytical hierarchy process (AHP) developed by Saaty (1990), which has its roots in obtaining the relative weights among the factors and the total values of each alternative based on these weights. This study constructed the relative weight of two objective functions by the AHP.

The proposed optimization method is also expected to find more accurate optimum properties of TMD and overcoming the drawbacks of previous TMD optimization related works. To find an optimal TMD, the frequency ratio and damping ratio of the TMD has been considered as design variables while the response of the structure has been taken as the objective function. The optimization of TMD is configured with an El Centro earthquake. In this review, offshore wind turbine (OWT) has been considered to apply the optimal TMD. After finding the optimal TMD, the OWT model has been equipped with the optimal TMD and then simulated under three earthquake loads such as El Centro, California and Northridge earthquakes. To compare the effectiveness of optimal TMD, the OWT model has been also analyzed with the different conventional TMD's designed by Den Hartog's, Sadek *et al*.'s and Warburton's method.

2. Proposed optimization scheme

2.1 Weighted multi-objective optimization

2.1.1 Response surface methodology (RSM)

The response surface methodology (RSM) is one of the good approaches to approximate the observed data. Therefore, the RSM is convenient for developing, improving and analyzing problems and consists of data collection, modeling, and optimization (Myers *et al*. 2016). It investigates the relationship between the design variables and response variables. Determination of optimum condition of TMD required instantaneous consideration of more responses, which is defined as a multi-response or multi-objective problem (Khuri 1996).

Suppose that there are $\boldsymbol{R}$ responses, $\mathbf{y}=(y_1, \ldots, y_l)$, which are determined by the input variables, $\mathbf{x}$. A multi-objective optimization (MOO) problem is defined in Eq. (1).

$$\text{optimize} \quad \{\hat{y}_1(\boldsymbol{x}), \hat{y}_2(\boldsymbol{x}), \ldots, \hat{y}_l(\boldsymbol{x})\}, \text{ subject to } \quad \boldsymbol{x} \epsilon \boldsymbol{\Lambda}, \quad (1)$$

where $\hat{y}_l(\boldsymbol{x})$ is the *i*th estimated response model and $\boldsymbol{\Lambda}$ is the region of experiment. Based on these, this work focused on finding an optimal TMD by the optimization process based on RSM with weighted desirability function to be explained below.

2.1.2 Central composite design (CCD)

The central composite design (CCD) is one of the design of experiment for numerical calculation of multi-objective nonlinear model for the optimization process of variables (Sadhukhan *et al*. 2016). The CCD has been applied in this study to determine the optimum variables of TMD. Also, the CCD has been used for fitting a second-order model which requires a minimum number of experiments/run for modeling (Myers *et al*. 2016). The total number of analysis point is considered by $K = 2^{\mathrm{k}} + 2k + c$ where k is factors numbers and c is center point replication number. The gap between the axial point and center point in a CCD is defined by the $\alpha = (2^k)^{\frac{1}{4}}$ value.

Usually, the optimization process requires the designed experiments, coefficients of a statistical model, and predicting the response of output variable and checking the adequacy of the model. An experimental model has been developed based on a second order quadratic model for optimal TMD to correlate the response of structure and that is given by Eq. (2).

$$\hat{y}_i = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i{}^2 + \sum_{i=1}^{k-1} \sum_{j>1}^{k} \beta_{ij} x_i x_j + \varepsilon \quad (2)$$

where $\hat{y}_i$ is the response variable; β_o is the intercept, $\beta_i, \beta_{ii}, \beta_{ij}$ is the coefficients of the linear effect, double interactions; x_i, x_j are the response variables and ε is error.

2.1.3 Weighted composite desirability function

The concept of desirability function analysis (DFA) has been popularized by Derringer and Suich (1980), for the simultaneous multi-response optimization problems. In the DFA, each estimated response (e.g., the ith estimated response $\hat{y}_i$ is transformed into a scale-free value, called individual desirability function (denoted as di $(\hat{y}_i)$) that are then amalgamated into a composite or overall desirability function. The composite desirability *D*, combined the individual desirability values. The value of individual or composite desirability remain between 0 and 1. When the response is out of acceptable limit, the corresponding desirability value will be 0. When the response is in acceptable limit, the desirability will be 1 or closer to 1. The response in acceptable means it can be minimum, maximum or target. In this paper, the response will be minimum and the TMD will be optimum for the application.

If the value of the response variable is expected to be minimum-the-best (MTB)-type, the individual desirability function as follows

$$d_{i,min}(\hat{y}_i) = \begin{cases} 1 & \text{if } \hat{y}_i(\mathrm{x}) \leq y_{min} \\ \left(\frac{\hat{y}_i(\mathrm{x}) - UV_{y_i}}{y_{min} - UV_{y_i}}\right)^{o_i} & \text{if } y_{min} \leq \hat{y}_i(\mathrm{x}) \leq UV_{y_i}, \mathrm{o}_i \geq 0 \\ 0 & \text{if } \hat{y}_i(\mathrm{x}) \geq UV_{y_i} \end{cases} \quad (3)$$

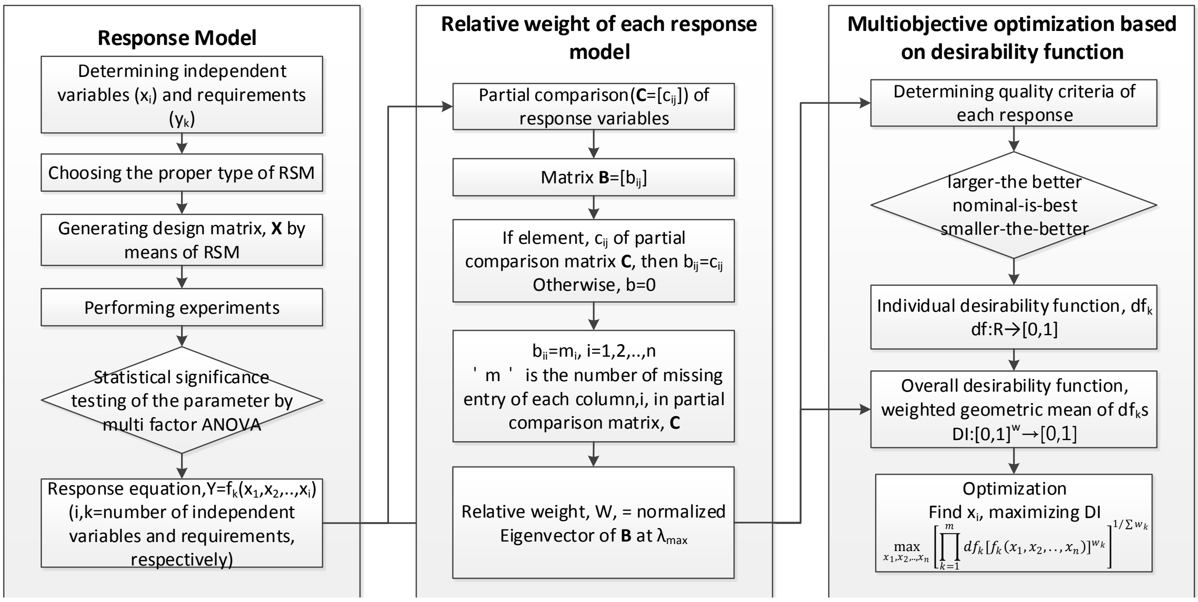


Fig. 1 Proposed RSM based weighted multi-objective optimization procedure

where UV_{y_i} is the upper value of response variable.

When the response variable is expected to be maximum-the-best (MaTB)-type, the individual desirability function as follows

$$d_{i,max}(\hat{y}_i) = \begin{cases} 1 & \text{if } \hat{y}_i(\mathrm{x}) \ge y_{max} \\ \left(\dfrac{\hat{y}_i(\mathrm{x}) - LV_{y_i}}{y_{max} - LV_{y_i}}\right)^{o_i} & \text{if } y_{max} \ge \hat{y}_i(\mathrm{x}) \ge LV_{y_i}, \mathrm{o}_i \ge 0 \\ 0 & \text{if } \hat{y}_i(\mathrm{x}) \le LV_{y_i} \end{cases} \quad (4)$$

where LV_{y_i} is the lower value of response variable and

When the response variable is expected to be nominal or target-the-best (NTB)-type, the individual desirability function as follows

$$d_{i,nominal}(\hat{y}_i) = \begin{cases} 1 & \text{if } y_{max} \le \hat{y}_i(\mathrm{x}) \le y_{min} \\ \left(\frac{\hat{y}_i(\mathrm{x}) - UV_{y_i}}{y_{min} - UV_{y_i}}\right)^{m_i} & \text{if } y_{min} \le \hat{y}_i(\mathrm{x}) \le UV_{y_i},\ m_i \ge 0 \\ \left(\frac{\hat{y}_i(\mathrm{x}) - LV_{y_i}}{y_{max} - LV_{y_i}}\right)^{n_i} & \text{if } y_{max} \ge \hat{y}_i(\mathrm{x}) \ge LV_{y_i}, n_i \ge 0 \\ 0 & \text{if } LV_{y_i} \ge \hat{y}_i(\mathrm{x}) \ge UV_{y_i} \end{cases} \quad (5)$$

where $\hat{y}_i(\mathrm{x})$ is the value of the individual response value and m_i, n_i and o_i are, user specified or calculated weight of the response and that allow changing the shape of $d_i(\hat{y}_i)$. Z

If $m_i\ (or\ n_i\ or\ o_i) = 1$, the shape will be linear; if $m_i\ (or\ n_i\ or\ o_i) > 1$, convex; and if $0 < m_i\ (or\ n_i\ or\ o_i) < 1$, concave (Jeong and Kim 2009). A weighted geometric mean has been applied in this paper, which proposed by G. C. Derringer (1994), $D = (({d_1}^{w_1})\ ({d_2}^{w_2}) \dots ({d_I}^{w_I}))^{1/\Sigma w_I}$. The weight values of this equation were determined from the analytic hierarchy process below.

2.1.4 Estimating the relative weight of objective functions using Analytic Hierarchy Process

The analytic hierarchy process (AHP) known as a multi-attribute modeling methodology that is widely used for solving complex decision-making problem. The AHP is generally involved in multiple criteria decision making problem. The AHP has been applied for estimating the relative weight of the objective function corresponding with individual desirability.

Let $C(i)$, i=1, 2, … ,n be the set of criteria and let quantified judgments on a pair of criteria $C(i)$, $C(j)$ be represented by the following matrix

$$\mathrm{B} = \begin{bmatrix} b_{11} = 1 & b_{12} & \cdots & \mathrm{b}_{1n} \\ 1/b_{12} & \mathrm{b}_{22} = 1 & \cdots & \mathrm{b}_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ 1/\mathrm{b}_{1n} & 1/\mathrm{b}_{2n} & \cdots & \mathrm{b}_{nn} = 1 \end{bmatrix} \quad (6)$$

The weights would be given by the following

$$\mathrm{w}_i / w_j = b_{ij} \ \ (\text{for } i, j = 1, 2, \dots, n) \quad (7)$$

The above formulation reduces to the following

$$\mathrm{w}_i = \frac{1}{n} \sum_{j=1}^{n} b_{ij}\, w_j \quad (\text{for } i, j = 1, 2, \dots, n) \quad (8)$$

For the existence of a unique solution, the above formulation can further be reduced to the following

$$\mathrm{B}' \cdot w' = \lambda_{\max} \cdot w' \quad (9)$$

where B'= pairwise comparison matrix between criteria, w'=eigenvector of B' and $\lambda_{\max}$=largest eigenvalue of the matrix B'.

The analytic hierarchy process is briefly summarized into two steps like (1) constructing a pairwise comparison matrix and (2) estimating the value of the eigenvector that reflects the relative weights of the criteria, and that the weight has been used to the desirability function.

2.2 Proposed AHP weighted multi-objective optimization

2.2.1 Developing of RSM model

Response surface methodology coupled CCD has been

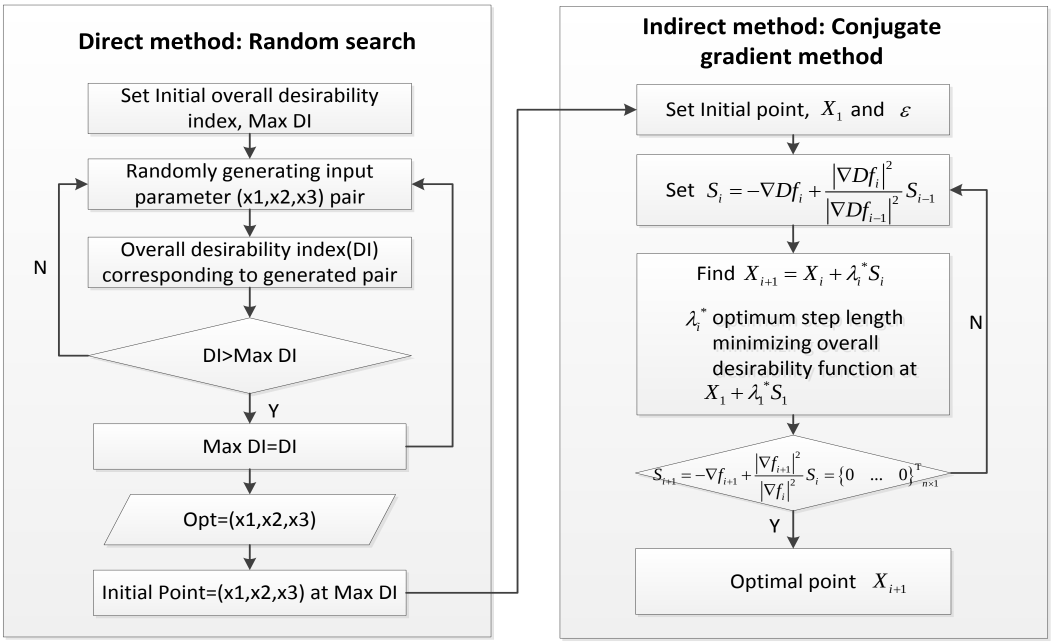


Fig. 2 Composite desirability function for multi-objective optimization

used to optimize the parameters of TMD. The objective function $(\hat{y}_i)$ has been to minimize both the maximum magnitude of the frequency response and the tower top displacement of wind turbine by assuming the frequency ratio and damping ratio of TMD as design variables (x_i). In very cases, the design matrix has been created by extreme vertices method of design and analysis of structure under El Centro Earthquake. Using analysis of variance (ANOVA), the significance of input parameters has been evaluated. The quality criteria of each response have been checked by modal adequacy which is determined by value of R-square (R^2). To get the optimal point the target should be determine, it can be larger, smaller or nominal is better. Individual and overall desirability also checked to check the effectivity of a group variables fulfill the targets for predefined responses. Mathcad 15 has been used to establish the design matrix, to analyze the experimental data and to get the optimal point.

The proposed approach for optimization based on the planned experimental works (within the domain of required characteristic performance) and statistical analysis of the data generated, which would reduce the number of trial batches needed. The Proposed RSM based weighted multi-objective optimization approach consists several steps. The flow charts in Fig. 1 illustrates the proposed RSM based weighted multi-Objective optimization approach.

2.2.2 Finding optimal value of multi-objective optimization by weighted desirability function

The multi-objective optimization problem of this study using weighted desirability function can be formulated as follows

$$arg \max_{\mathrm{X}} D(\mathrm{X}) = [d_1^{\;w_1}\left(y_1(X)\right), d_2^{\;w_2}\left(y_2(\mathrm{X})\right), \cdots, d_m^{\;w_m}(y_m(\mathrm{X}))]^{\frac{1}{\Sigma W}} \tag{10}$$

where, X *is independent variables in each interest region*
$\mathrm{W} = w_1 + w_2 + \cdots w_m = 1$
and w_m *are relative weights of each inidividual desirabilit*

This composite desirability function $(D(X))$ derived from combination of multiple response models is definitely nonlinear and constrained. Finding an optimal point from this function is to solve a constrained nonlinear optimization problem in n dimensions. The steepest descent method that most commercial DOE (design of experiment) software like Minitab, Design Expert adopts is known to converge slowly in case objective function is complex and high nonlinear. The Fletcher-Reeves method can modify the steepest descent method. In order to efficiently find an optimal point maximizing the composite desirability function this study comprises two parts as shown in Fig. 2.

Overall procedure finding an optimal point of the objective function expressed by composite desirability function has been described in Fig. 2. Left box in Fig. 2 shows a process to find an optimal point from which conjugate gradient method starts iterating to find an optimal point. The process to find an optimal point by Fletcher-Reeves algorithm of conjugate gradient method is described in right box of Fig. 2.

3. Offshore wind turbine numerical model

3.1 Equation of motion of structure with the TMD

The offshore wind turbine (OWT) structure that is shown in Fig. 3, has been assumed as a lumped mass system at each degree of freedom and the governing equation of motion can be written as

$$M\ddot{x} + C\dot{x} + Kx = -M\ddot{x_g} \tag{11}$$

where x, $\dot{x}$, $\ddot{x}$ and $\ddot{x_g}$ respectively represents the displacement, velocity, acceleration and ground acceleration vectors of the system relative to the base point.

The dimension of the matric can be presented as $(N+1) \times 1$. M, C and $K,$ are the mass, damping and stiffness matrices respectively. Where the matrix dimension is $(N+1) \times (N+1)$.

M, C and $K,$ are as follows

$$M = \begin{bmatrix} M_{s\,N\times N} & 0_{N\times 1} \\ 0_{1\times N} & m_{d\ 1\times 1} \end{bmatrix}_{(N+1)\times(N+1)}$$

$$C = \begin{bmatrix} C_{s\,N\times N} & 0_{N\times 1} \\ 0_{1\times N} & c_{d\ 1\times 1} \end{bmatrix}_{(N+1)\times(N+1)}$$

$$K = \begin{bmatrix} K_{s\,N\times N} & 0_{N\times 1} \\ 0_{1\times N} & k_{d\ 1\times 1} \end{bmatrix}_{(N+1)\times(N+1)}$$

where, M_s, C_s, and $K_s$are the mass, damping and stiffness matrices of the wind turbine structure respectively, having a matric dimension of $N \times N$. In addition, m_d , c_d and k_d are the mass, damping and stiffness, of the TMD respectively.

3.2 Eigenvalue analysis and model validation

The eigenvalue analysis of the uncontrolled structure has been carried out to get the natural frequencies, mode shapes, and effective modal masses. The modal properties especially natural frequency from OpenSees has been checked with the FAST model. Fig. 4 shows the mode shape of an uncontrolled offshore wind turbine with jacket structure. The natural frequencies of OpenSees model are quite match with FAST model, which is given in Table 1.

The gravitational force is also checked for verification of model. It is found that all the reaction forces of the jacket support structure are 18.657 MN force at fixed supports without giving any other loads which are matched with FAST model.

Table 1 Natural Frequency of FEM of jacket support structure of offshore wind turbine

Mode	FAST (Hz)	OpenSees (Hz)
1st fore-aft mode	0.3190	0.32734
1ST Side-Side mode	0.3190	0.32734
2nd fore-aft mode	1.1944	1.1743
2nd Side-side mode	1.1944	1.1743

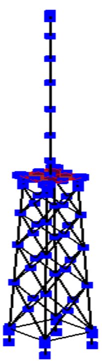
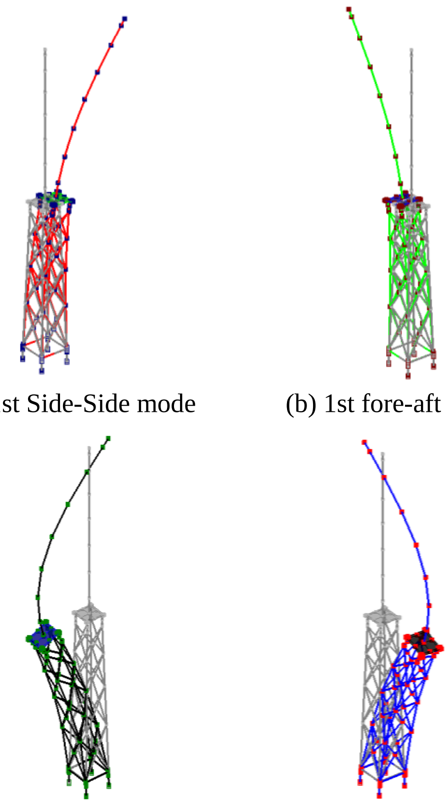


Fig. 3 Structural Model of Jacket supported offshore wind turbine



(a) 1st Side-Side mode (b) 1st fore-aft mode

(c) 2nd Side-side mode (d) 2nd fore-aft mode

Fig. 4 Mode shape of uncontrolled jacket supported an offshore wind turbine

3.3 Applied load and structural model property

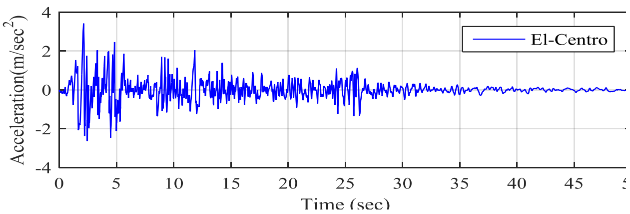
For evaluating and comparing the performance of the proposed optimized TMDcontrol system withttt, the considered structure has been analyzed with the consideration of El Centro, California, and Northridge earthquake. Fig. 5, shows the earthquake signal of (a) El Centro, (b) California, and (c) Northridge in the form of acceleration.

All of the accelerations were executed as a time history. The motive for applying several earthquakes is at different earthquakes contain various distinctive frequencies. The application of ground motion and its PGA in 'g' scale, and the time interval of signals have been given below in Table 2.

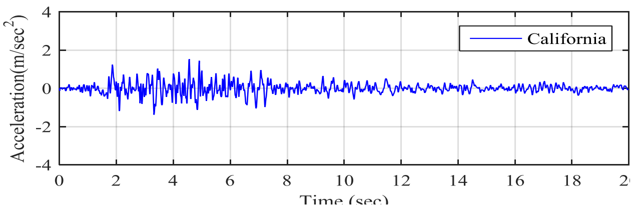
Here, the El Centro earthquake load have been applied for optimization and the others loads for check the adequacy and acceptance. After finding the optimum tuning frequency (α_d) and the optimum damping ratio (ξ_d) of TMD, the natural frequency $(\omega_d = \alpha_d \omega_{s1})$, stiffness$(K_d = m_d \omega_d^2)$, and damping $(C_d = 2\xi_d m_d \omega_d)$ properties of tuned mass damper has been determined, where,m_d and ω_{s1} is the mass of TMD and structural natural frequency of first mode. The stroke length has been calculated by using the following equation: $= \frac{gT^2}{4\pi^2}$.

3.3.1 Structural model property

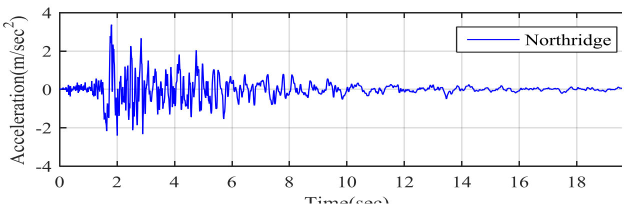
In this study, a model that is shown in Fig. 3, has been



(a) Accelerogram of El Centro Earthquake



(b) Accelerogram of California Earthquake



(c) Accelerogram of Northridge Earthquake

Fig. 5 Applied ground motions

Table 2 Time history data of ground motion

Variables	El Centro Earthquake	California Earthquake	Northridge Earthquake
Load steps	2500	2000	2000
Time interval (sec)	0.02	0.01	0.01
PGA(g)	0.348	0.158	0.343

developed following by the NREL 5 MW-OC4 jacket supported offshore wind turbine which has been developed by National Renewable Energy Laboratory (NREL). The whole structure consists of a tower, transition piece, and jacket structure. The tower has consisted of nine elements with a different section. And its height has been 68 m. The transition piece (TP) is considered as a rigid body where it is present among the baseline turbine and the jacket structure. Moreover, the jacket structure had 4 levels of X-braces, mud braces, 4 legs and a transition piece. Also, it had 64 nodes and 112 forced beam-column elements. The three-forth portion of it's situated beneath the water, where the height of jacket structure is 65.65 m. The whole structure is resting on 4 central piles. The masses of rotor nacelle assembly (RNA) with hub has been considered as rigid body where the masses are a lump at top of the structure. Others properties of FEM of OWT structure are given in Table 3.

3.3.2 Design variables and optimum parameters of TMD

To minimize both the maximum displacement and frequency response of tower top of the OWT structure, the frequency ratio and damping ratio of the TMD were configured as design variables whereas the mass of TMD has been taken 1% of the total structural mass.

After finding the optimum TMD by the optimization, we can obtain the value of frequency response amplitude (dB) and displacement of the structure. The structural response has been optimized under the applied El Centro earthquakes. After getting optimal parameters of TMD for different earthquakes also applied for validation of RSM approach for optimizing TMD parameters. The objectives function can be defined as follows

$$O_1 = min \parallel \max(dB_{tt}) \tag{12}$$

$$O_2 = min \parallel max\ (D_{tt}) \tag{13}$$

where dB_{tt} denotes the frequency response of tower top and D_{tt} is the displacement of tower top.

4. Preparation of response models with design variable of TMD

4.1 Analysis points and structural responses

The design of experiment has been configured based on response surface methodology coupled with central composite design to investigate the effect of factors on responses. For optimal TMD, frequency ratio and damping ratio were considered as the independent variable and

`Table 3 Jacket support of offshore wind turbine structure properties

Parameter	Diameter (m)	Thickness (m)	
Tower top outer diameter	4	0.03	
Tower base outer diameter	5.6	0.032	
Jacket ‘X’ braces and Mud braces	0.8	0.02	
Leg	1.20	0.05 (up to the 1st bay), 0.035-0.04 (TP)	
Pile	2.08	0.491(upper level),0.069 (lower level)	
Tower Length (m)	68 m	Tower Mass (ton)	230
Mass density (kg/m^3)	7850	Poisson’s ratio	0.3
		Poisson’s ratio of TP	0.18
Shear Modulus (N/m^2)	8.08e+10	Young Modulus (N/m^2)	2.1e+11
Transition piece Dimension, TP (m^3)	9.6×9.6×4	Mass density for TP (kg/m^3)	1807
Jacket Mass (ton)	655.83	RNA Mass (ton)	350
Total structural Mass (ton)	1901.83	Transition piece Mass (ton)	666

Table 4 Analysis point and corresponding structural responses

Analysis Point Type	Coded Unit		Actual Unit		Responses	
	α_d	ξ_d	α_d	ξ_d	dB_{tt}	D_{tt}
F	-1.00000	-1.00000	0.90000	0.100000	6.287	24.01
A	0.00000	-1.41421	0.95000	0.068934	5.592	23.75
F	1.00000	1.00000	1.00000	0.250000	2.920	18.04
A	1.41421	0.00000	1.02071	0.175000	3.651	19.90
F	1.00000	-1.00000	1.00000	0.100000	4.009	22.13
F	-1.00000	1.00000	0.90000	0.250000	4.011	20.68
A	-1.41421	0.00000	0.87929	0.175000	5.401	23.10
C	0.00000	0.00000	0.95000	0.175000	3.864	20.37
A	0.00000	1.41421	0.95000	0.281066	3.028	17.99

Table 5 Quadratic model summary to check the adequacy

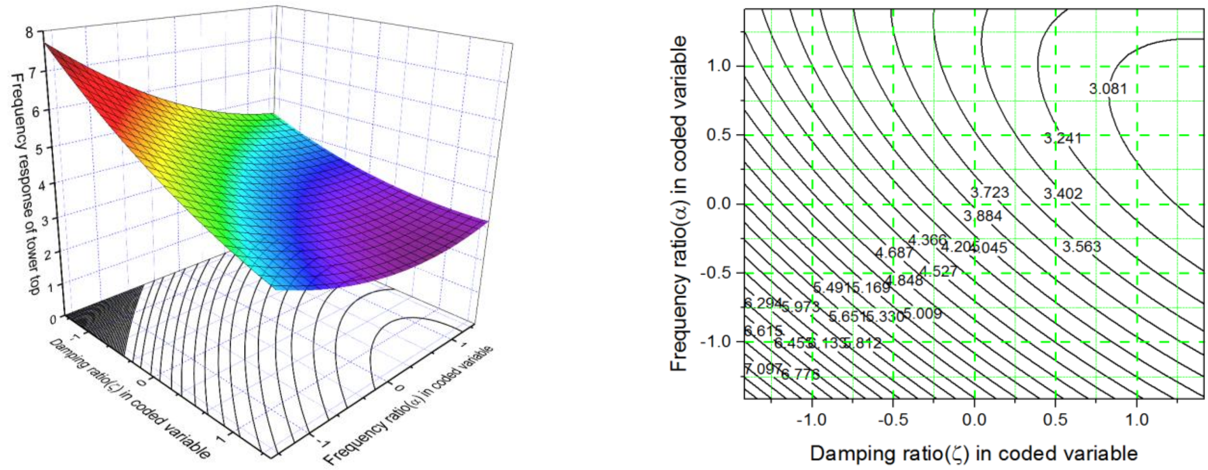
Responses	TMD		
	Model Equation with coded coefficient	R^2(%)	R^2_{adj}(%)
dB_{tt}	$3.864 - 0.7305(\alpha_1) - 0.8739(\xi_1) + 0.303(\alpha_1{}^2) + 0.195(\xi_1{}^2) + 0.297(\alpha_1\xi_1)$	98.80	96.81
D_{tt}	$20.37 - 1.1307(\alpha_1) - 1.9457(\xi_1) + 0.5725(\alpha_1{}^2) + 0.2575(\xi_1{}^2) - 0.19(\alpha_1\xi_1)$	99.84	99.57

frequency response, and displacement of the tower has been considered as desired response. A design point has been created based on the CCD with constrained for frequency ratio and damping ratio of TMD, and the design point were 0.9 to 1.0 and 0.1 to 0.25 respectively. The design of experiment (DOE) has been made at total 9 experimental points composed of 4 factorial points, 4 axial points, and 1 center points. To complete these optimizations, the analysis has been performed for nine times. The derived model would be acceptable for a comprehensive TMD parameter. Analysis point and structural responses for each TMD are illustrated in Table 4.

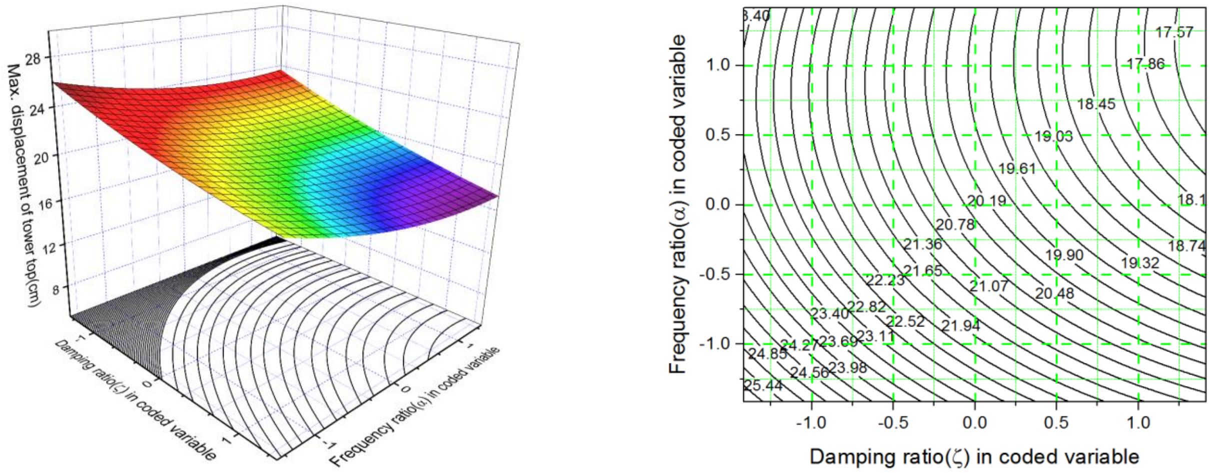
4.2 Model adequacy and analysis of variance

The coefficient of determination of *R*-squared (R^2) for multiple regression is a measure of how close the data are to the fitted regression line. Usually, a model fits the data well if the deviations between the measured data and the predicted data are small and impartial. Table 5 shows R^2 and R^2_{adj} for a full quadratic model of the TMD response variables.

In this study, it is found that the R^2 and R^2_{adj} values are significantly high i.e., it shows a high correlation of dependent variables and thus the model can be considered



(a) 3D response surface and contour plot of frequency response of tower top (dB_{tt})



(b) 3D response surface and contour plot of tower top displacement (D_{tt})

Fig. 6 Response surface and contour plots of response variable

Table 6 ANOVA result of full quadratic model of TMD parameter

Response	Unit	Sources	Sum of squares	DOF	Mean Square	F-value	P-value
dB_{tt}	dB	Model	10.9979	5	2.1995	49.54	0.004
		Residual error	0.1332	3	0.0444		
		Sum	11.1311	8			
D_{tt}	cm	Model	41.6606	5	8.3321	377.68	0.000
		Residual error	0.0677	3	0.0221		
		Sum	41.7268	8			

Table 7 Parameter configuration for individual desirability function

Response	Goal	Target	Upper limit	Relative weight
dB_{tt} (dB)	Minimum	2.92	6.287	0.56
D_{tt} (cm)	Minimum	17.99	24.01	0.44

Table 8 Optimal design point for proposed criteria and composite desirability

Optimal point		Individual desirability (d) at optimal point		Composite desirability (D) at optimal point
Frequency ratio	1.0207	dB_{tt}	0.9944	0.9972
Damping ratio	0.2811	D_{tt}	1.0000	

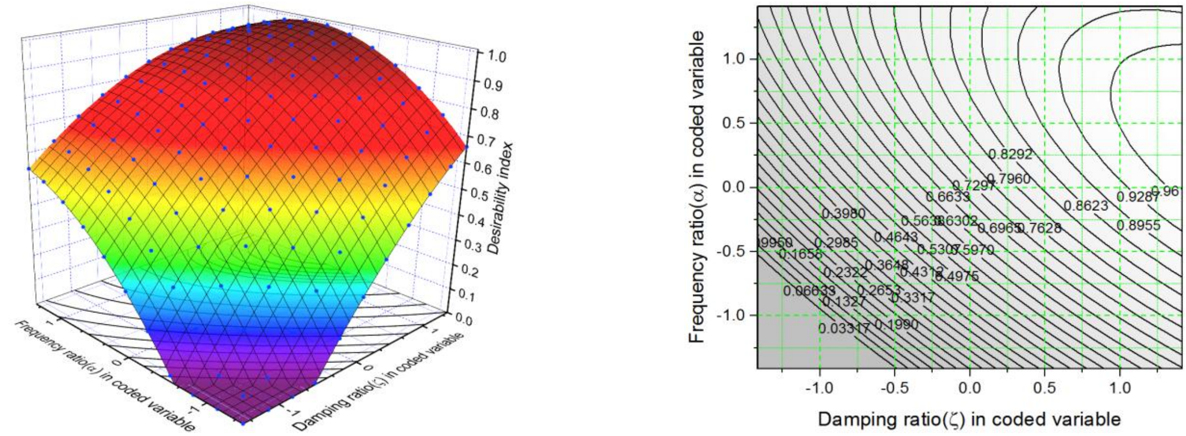
as adequate. An Analysis of variance (ANOVA) has been carried out to find whether the effect of factors on responses is statistically significant or not. The p-values for displacement and frequency response for a second-order polynomial were measured. The result of ANOVA is presented in Table 6 (TMD).

4.3 Response surfaces depending on design variable

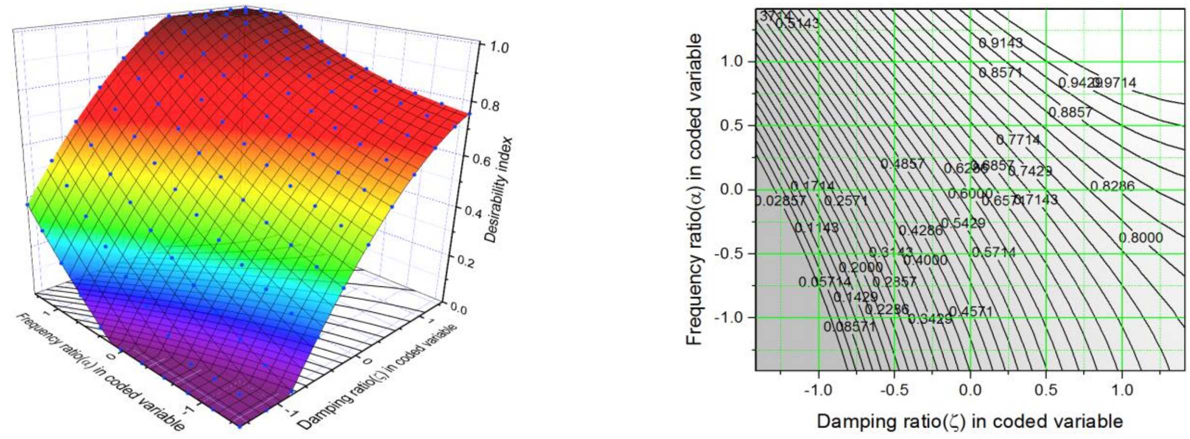
A surface plot displays three-dimensional view that provides a clear understanding of the response surface. It helps to visualize how the response changes with the different combination of factors. Fig. 6 illustrate the 3D response surface plot and contour with design points of frequency response amplitude of tower top and maximum tower top displacement under El Centro earthquake respect to the frequency ratio and damping ratio of optimal TMD.

4.4 Estimation of relative weight of objective fucntion and the desirability fuction

To estimate the relative weight of objective function in this study, pairwise comparison matrix has been prepared through a questionnaire asking the relative importance of frequency amplitude compared with a maximum displacement of wind turbine with TMD. The relative weights of frequency amplitude and maximum



(a) Individual desirability distribution of frequency amplitude of tower top



(b) Individual desirability distribution of maximum displacement of tower top

Fig. 7 Desirability distribution of individual response

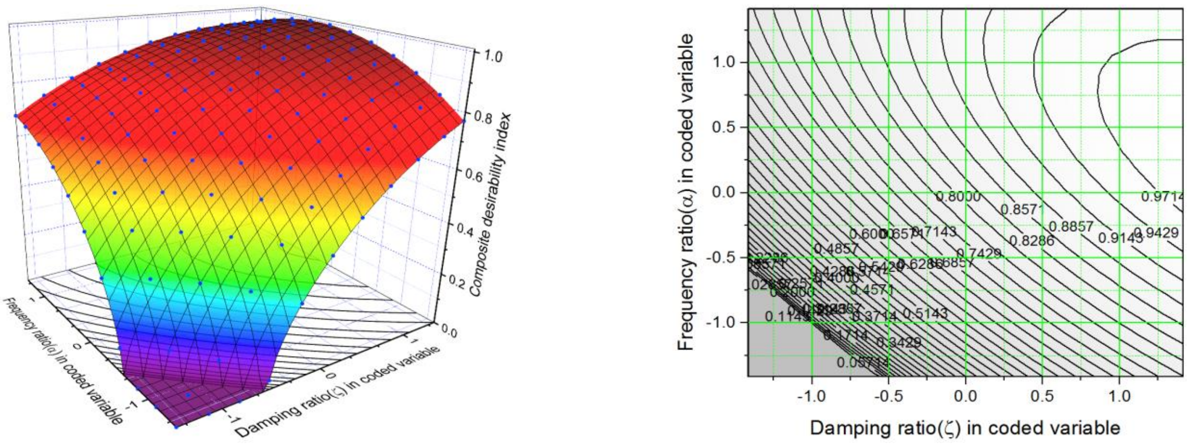
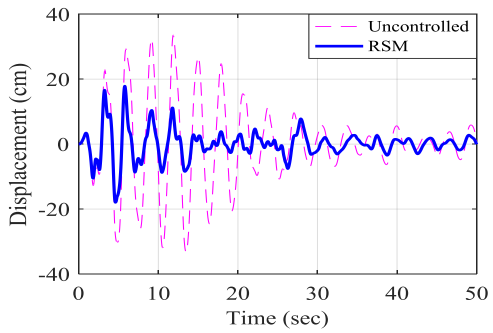
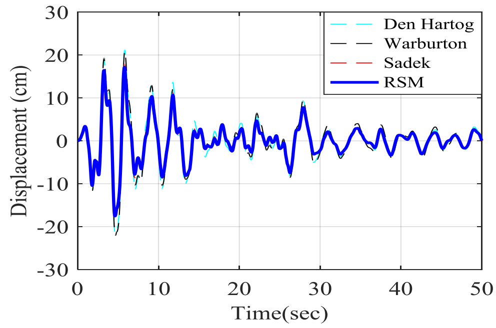


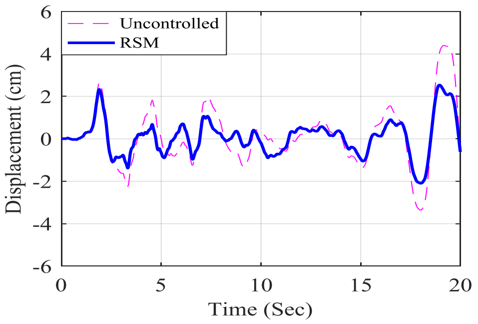
Fig. 8 Composite desirability distribution of combined response



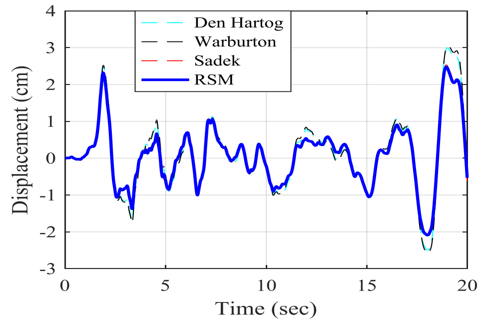
(a) Displacement with/without optimal TMD under El Centro earthquake



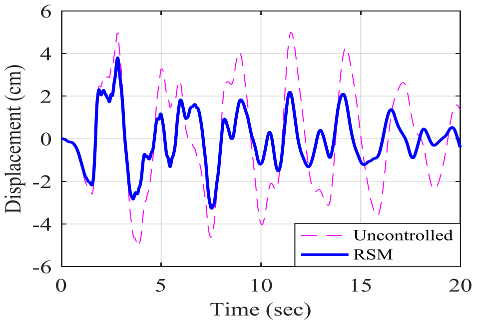
(b) Displacement with conventional and optimal TMD under El Centro earthquake



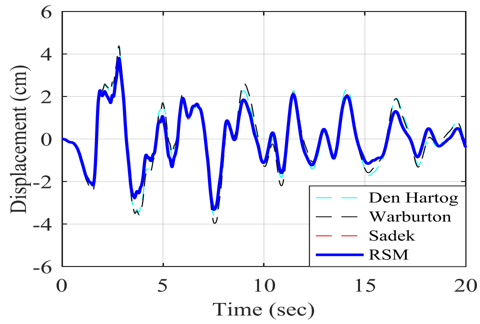
(c) Displacement with/without optimal TMD under California earthquake



(d) Displacement with conventional and optimal TMD under California earthquake



(e) Displacement with/without optimal TMD under Northridge earthquake



(f) Displacement with conventional and optimal TMD under Northridge earthquake

Fig. 9 Dynamic displacement response of OWT under different earthquakes

displacement has been estimated to be 0.45~0.68 and 0.32~0.55 in 95% confidence interval, respectively. The mean relative weights of these two input variables were 0.56 and 0.44.

These relative weight values were used for assigning the relative importance of objective function to composite desirability function. The multiple performance optimizations of TMD parameters has been carried out using multi-objective optimization based on desirability function approach reflecting the relative weight of objective function of TMD. The optimization analysis has been carried out using a series of random search method and conjugate gradient method prepared by engineering software for numerical analysis, Mathcad15. In this study, desirability function has been used to optimize response. For the TMD parameter optimization cases, tower top maximum displacement, frequency response, is targeted to minimize. The response goal of optimization and parameter limits for different responses of TMD is given in Table 7.

Figs. 7 and 8 are plotting the desirability index depending on design variables based on individual and composite desirability function corresonding the parameters in Table 6, respectively. Here, two responses are competing for each other on the basis of two design variables of frequency ratio and damping ratio for TMD. The optimal design point for proposed criteria and local and composite desirability values are presented in Table 8.

The predicted values of responses as displacement 17.574 cm and frequency response 3.78 dB along with the individual desirability of 0.9944, and 1.0 respectively for TMD parameter. To optimize all responses at the same time composite desirability is required which ascertain how it optimizes the set responses together. In this study, the composite desirability is found 0.9972 for TMD parameter which is close to 1 (one), point out that settings are favorable for all responses as a whole. Therefore, it can be said that for the minimum top displacement, frequency response, parameter settings for frequency ratio and damping ratio is 1.0207 and 0.2811 respectively for optimum TMD.

Fig. 8 illustrates the composite distribution on reflecting the relative weight of displacement and frequency response depending on input variables. The analyze value have been found for the displacement and frequency response as 18.12cm and 3.82dB respectively under the El Centro earthquake analysis with the optimal TMD.

5. Dynamic responses of offshore wind turbine with the optimized TMD

The offshore wind turbine (OWT) has been analyzed with the optimal TMD and conventional design by Den-Hartog, Warburton, and Sadek. The responses of RSM based optimal TMD has been compared with different conventional TMD design approaches which are based on Den-Hartog, Warburton, and Sadek, in terms of tower top displacement and frequency response. The responses of structure can be shown from the Figs. 9-11.

The response reduction rates by RSM based optimal TMD of top displacement are 47.77%, 42.86% and 24.75% under El Centro earthquake, California earthquake, and Northridge earthquake respectively with respect to uncontrolled response and frequency response decreasing rates are 79.70%, 49.16% and 70.07% consequently.

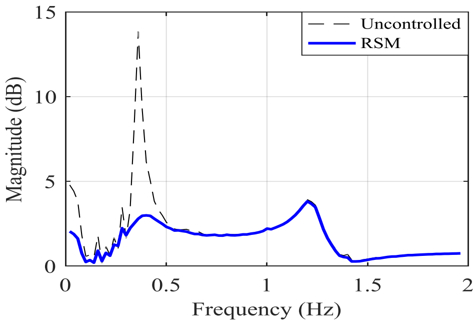
Inner to check the efficiency of the optimal TMD by RSM, the dynamic responses of OWT were compared with others TMD design methods performance. From the Fig. 10, we can observe the kinematic response in terms of displacement under the applied seismic loads. In details, the Figs. 10(a)-(b) shows the displacement response with respect to the uncontrolled and controlled structure under the El Centro earthquake. The uncontrolled displacement for the El Centro earthquake is 32.58 cm, whereas the controlled structure displacement is 17.54 cm, 21.63 cm, 17.93 cm and 22.02 cm with TMD design by RSM, Den-Hartog, Warburton, and Sadek respectively. The OWT structure with RSM based optimal TMD alleviates 12.19%, 1.17%, and 13.35% more than the conventional TMD based on Den-Hartog, Warburton, and Sadek.

Figs. 10(c)-(d) shows the uncontrolled and controlled displacement response of the structure for the California earthquake. The uncontrolled top tower displacement under California Earthquakes is 4.40 cm whereas the controlled displacement with TMD by RSM, Den-Hartog, Warburton, and Sadek is 2.48 cm, 3cm, 2.50 and 3.05 correspondingly. RSM based design TMD is able to control more top tower displacement than TMD design by Den-Hartog, Warburton, and Sadek which is 11.83%, 0.46% and 12.96 % separately.

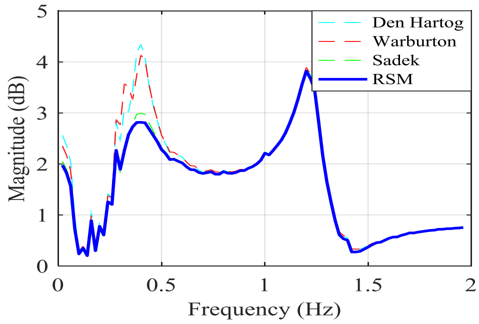
Figs. 10(e)-(f) shows the uncontrolled and controlled displacement response of the structure for the Northridge earthquake. The uncontrolled and controlled displacement with RSM based TMD of tower top of OWT structure are 5.05 cm and 3.8 cm respectively. The controlled displacements with conventional TMD by Den-Hartog, Warburton and Sadek are 4.28 cm, 3.9 cm, and 4.39 cm respectively. The OWT structure with optimal TMD by RSM mitigates 9.51%, 1.98%, and 11.69% more response than TMD design by Den-Hartog, Warburton and Sadek respect to the dynamic displacement response.

The frequency response of OWT is also checked. TMD design has been carried out considering the first modal frequency of the uncontrolled structure. The dynamic frequency response of the structure is presented in Fig. 12 for the applied seismic loads. Figs. 11(a)-(b) shows the maximum frequency response with respect to the uncontrolled and controlled structure with optimal TMD under the El Centro earthquake. The uncontrolled frequency response amplitude of the first mode under El Centro Earthquake has been obtained 13.84dB whereas the frequency response amplitude controlled structure with TMD by RSM, Den-Hartog, Warburton and Sadek are 2.84dB, 4.35dB, 3.82dB, and 4.14dB correspondingly. RSM based design TMD is able to control more top tower displacement than TMD design by Den-Hartog, Warburton, and Sadek which is 11.14%, 7.31% and 9.62 % separately.

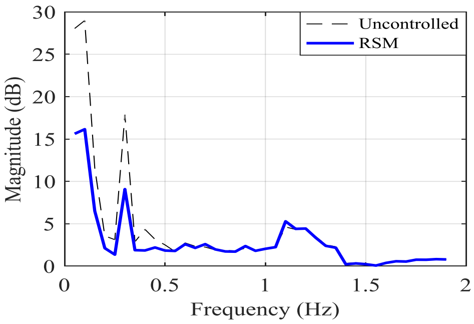
Figs. 11(c)-(d) shows the uncontrolled and controlled frequency response curve of the structure for the California Earthquake. The uncontrolled and controlled with RSM based TMD frequency response amplitude of the first mode of OWT structure are 17.86dB and 9.08dB respectively. The controlled frequency amplitude with conventional TMD by Den-Hartog, Warburton and Sadek are 12.32dB, 12.50dB and 13.15dB respectively. The OWT structure with optimal TMD by RSM mitigates 18.15%, 19.15%, and 13.15% more response than TMD design by Den-Hartog, Warburton



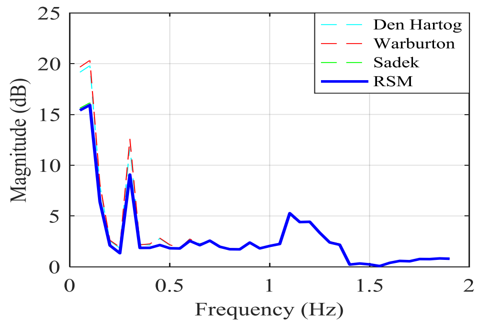
(a) Frequency response with/without optimal TMD under El Centro earthquake



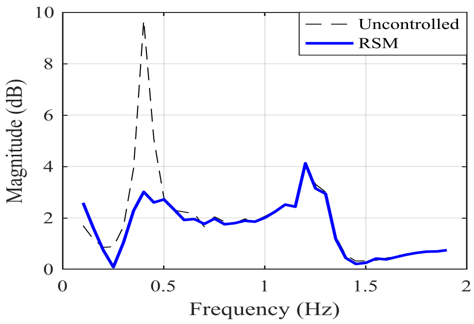
(b) Frequency response with conventional and optimal TMD under El Centro earthquake



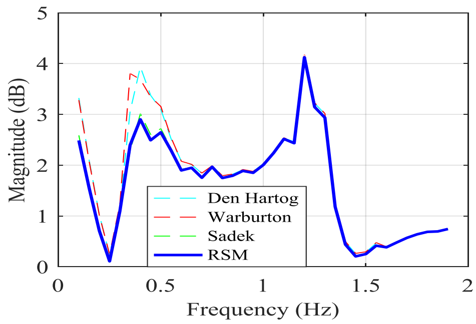
(c) Frequency response with/without optimal TMD under California earthquake



(d) Frequency response with conventional and optimal TMD under California earthquake



(e) Frequency response with/without optimal TMD under Northridge earthquake



(f) Frequency response with conventional and optimal TMD under Northridge earthquake

Fig. 10 Dynamic frequency response of tower top of OWT under applied earthquakes

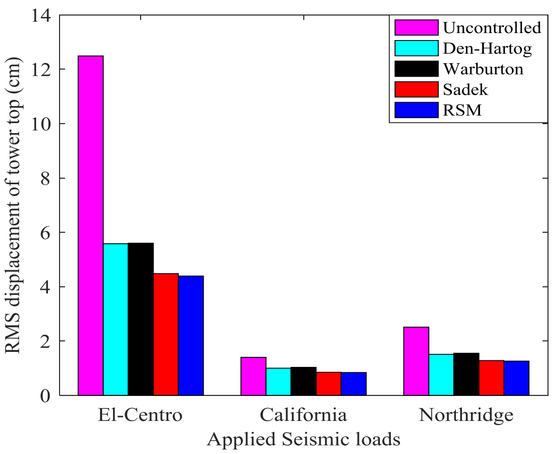


Fig. 11 Seismic response in terms of root mean square displacement of OWT structure

and Sadek respect to the dynamic frequency response amplitude.

Moreover, the Figs. 11(e)-(f) the frequency response amplitude of the first mode with respect to the uncontrolled and controlled structure under Northridge earthquake. The uncontrolled frequency response amplitude is 9.69dB, whereas the controlled structure displacement is 2.90dB, 3.98dB, 2.98dB and 3.97dB with TMD design by RSM, Den-Hartog, Warburton, and Sadek respectively The OWT structure with RSM based optimal TMD alleviates 11.15%, 1.03%, and 11.05% more response than the conventional TMD by Den-Hartog, Warburton, and Sadek.

Furthermore, the root means square displacement (RMSD) of tower top of OWT structure is considered with or without TMD. The RMSD of the uncontrolled and controlled structure is shown in Fig. 11. The uncontrolled RMSD of OWT is 12.49 cm, while the controlled RMS displacement of OWT is 5.58 cm, 5.6 cm, 4.48 cm, and 4.39 cm respectively with the conventional and optimal TMD. The controlled responses are respect to the Den Hartog, Warburton, Sadek *et al* and RSM based TMD. The above response is found under the applied El Centro earthquake. Similarly, the RSMD of tower top of OWT structure has been checked under the California earthquake. The uncontrolled RMSD of OWT is 1.4 cm, while the controlled RMSD of OWT with the conventional and optimal TMD were 1.0 cm, 1.03 cm, 0.85 cm, and 0.84 cm respectively. Moreover, the RSMD of tower top of OWT under the Northridge earthquake is checked. The uncontrolled RMSD of OWT is 2.51 cm, while the controlled RMSD of OWT with the conventional and optimal TMD were 1.51 cm, 1.55 cm, 1.28 cm, and 1.26 cm respectively. From the above results, it is found that the structural displacement and frequency response suppressed effectively with the use of RSM based AHP weighted optimal TMD.

6. Conclusions

The optimization scheme that utilizes the response surface methodology based on the weighted multi-objective optimization to find an optimum TMD that was applied to the OWT and to trade off the conflicting between two objective functions depending on the design variables of frequency ratio and damping ratio.

The following conclusion can be drawn from this study.

The reduction rate of displacement and frequency response with the RSM based optimal TMD under the El Centro earthquake has been found 47.77% and 79.70% respectively respect to uncontrolled structure. Also, the RSM based optimized damper has been found 12.19% and 11.14%; 1.17% and 7.31%; 13.35% and 9.62% more efficient than the Den Hartog, Sadek and Warburton designed conventional TMD.

Also, the reduction rate of displacement and frequency response with the RSM based optimal TMD under the California earthquake has been found 43.64% and 49.16% respectively respect to uncontrolled structure. Also, the RSM based optimized damper has been found 11.83% and 18.15%; 0.46% and 19.15%; 12.96% and 22.79% more efficient than the Den Hartog, Sadek and Warburton designed conventional TMD.

And, the reduction rate of displacement and frequency response with the RSM based optimal TMD under the Northridge earthquake has been found 24.75% and 70.07% respectively respect to uncontrolled structure. Also, the RSM based optimized damper has been found 9.51% and 11.15%; 1.98% and 1.03%; 11.69% and 11.05% more efficient than the Den Hartog, Sadek and Warburton designed conventional TMD.

In conclusion, optimization of TMD by the weighted multi objective optimization based on RSM has been found as rational and beneficial. Also, it shows the comparative advantage to improve the dynamic response compared with conventional design.

Acknowledgments

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