Damping of Wind Induced Galloping Oscillations of Solar Trackers

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Abstract

A solar tracker is a machine that uses a mechanical prime mover to tilt solar photo voltaic panels from east to west during the day to track the sun for maximizing the production of PV power by keeping the incident angle of sun-rays perpendicular to the panel surface. Drag and lift produced by the wind on the surface area of solar panels causes a torsional moment on the tracker structure, and may induce torsional instability in the structure due to wind galloping. The use of hydraulic dampers is recommended to reduce the intensity of galloping and reduce the potential risk of damage to the tracker structure and panels. In this paper, the vibration characteristics of the tracker structure are analyzed (theoretically and numerically) with and without external dampers, using lumped spring-mass-damper approach to identify the suitability of the selected dampers for the application.

Keywords: solar tracker, damping

1 Introduction:

Recent advances in technology, the international consensus on climate change action and relevant changes in national and international policies have made photo voltaic solar energy economical, and by implication the solar industry very competitive. The adoption of solar trackers has increased due to the added gain that the system provides. A solar tracker is an array of solar panels (referred to as modules) mounted on cold formed steel mechanical structures (referred to as table) along with a prime-mover for tracking of modules. Due to the competitive landscape of the solar industry, designers increasingly rely on higher stronger grades of steel to reduce the tonnage of steel in the structure.

This reduced tonnage due to stronger steel allows the system to keep its strength, but results in reduced stiffness of the system. Reduced structural stiffness of the system reduces the modal frequency of the system making it susceptible to excitation in its fundamental modes of vibration.

A common solution used in the industry is to add structural damping elements in the system using hydraulic dampers. There exists no systematic method for examining the suitability of dampers for performing their duty, and thus no method for sizing of dampers for use in solar trackers. Previous studies, such as [1] has focused on stowing logic for reduction of “galloping” in wind, where galloping is commonly referring to the phenomenon of excessive large amplitude torsional movement. An attempt is made in this paper to study the velocity and displacement response of a tracker table under typical forcing with and without the damper. The tracker system is modelled as a lumped torsional spring-mass-damper system. Each of these system components is analyzed individually. A forcing function is approximated based on simplified 2-dimensional CFD model of a tracker structure. Using all the generated data, the vibration response of the structure is simulated and analysed to check for suitability of elected dampers.

2 Tracker Structure and Working:

A typical tracker structure is a cold formed steel structure. Modules are mounted on slender cantilever beams called rails. These rails are in turn mounted on long steel pipes called torque tube. The torque tube is then suspended on vertical steel members using bearings. The vertical posts are grouted through concrete pile foundations in the ground. Figure 1 schematically represents the arrangement of tracker table.

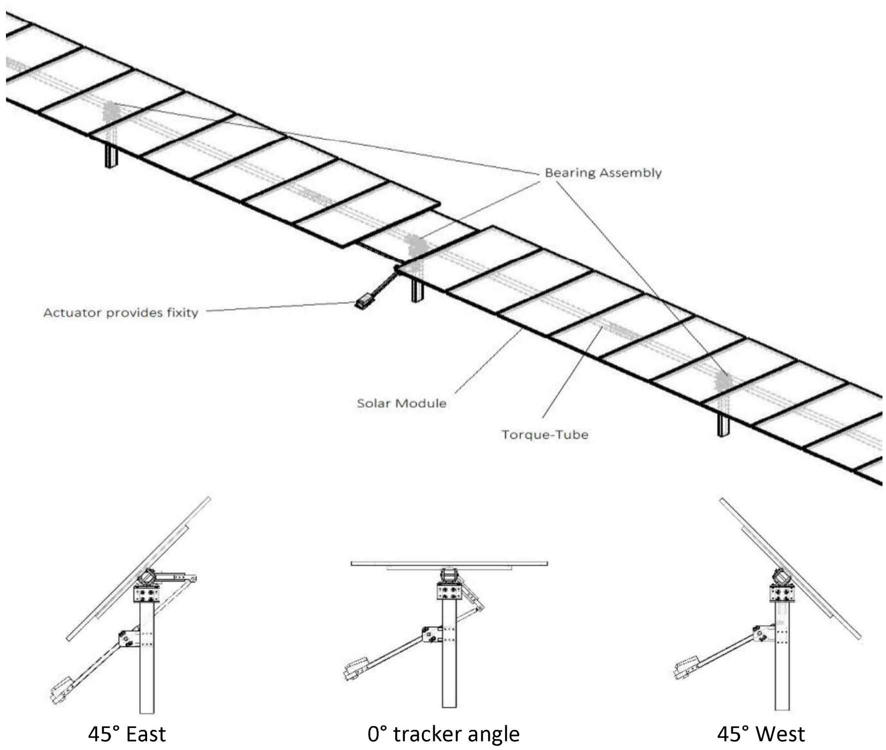


Figure 1: Tracker table solid model and it's configuration at various angles

The torque tube is free to rotate in the bearing and is held in the middle by the linear actuator [2]. The extension and retraction of linear actuator causes the lever-arm coupled to the torque tube to move. Thus, the extension and retraction of linear actuator is used to rotate the torque tube around its longitudinal axis. Modules thus mounted in the torque-tube can track the sun by controlling the of length of linear actuator. Based on the time of day, date and year, astronomical algorithms calculate the ideal azimuth angle to track the sun and execute tracking through electronic control [1].

The load on the system, apart from contact friction in the bearings is due to the self-weight of the system, and moment due to impact of wind on the module surface. Each module contributes to torque which is generated due to exposure to wind and connection to the torque-tube. When analysed as a shaft, the centre post is assumed to be the torsional fixity and the rest of the torque tube is supported in bearings.

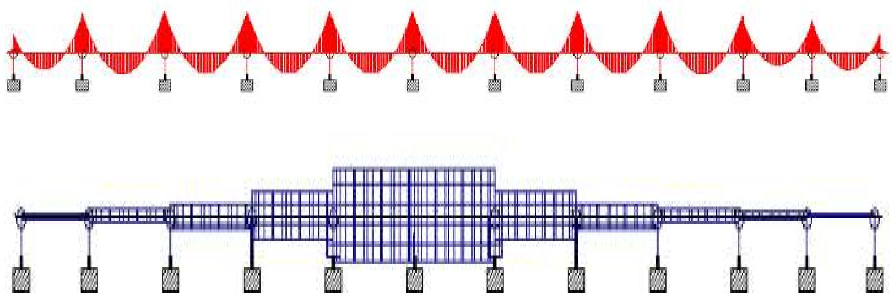


Figure 2: Bending moment diagram of tracker (top) and torque diagram of torque on the torque tube due to wind (bottom). The height of the blue rectangle represents the magnitude of torque. Note that torque keeps on adding in each bay between vertical post and causes maximum torque to concentrate near the centre

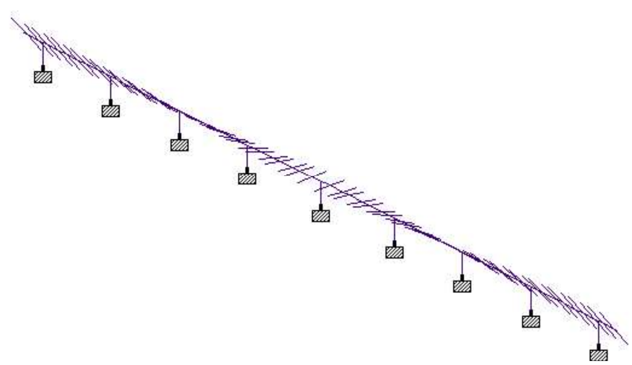


Figure 3: First mode shape in the tracker showing twisting of torque tube that is clamped in the middle and free at one end

The torque tube is modeled as a doubly overhanging continuous beam with supports at every vertical post. The beam thus undergoes loading on its entire span due to the self-weight of the torque-tube, apart from the load due to other members of the payload including rails and modules. Additional load is also due to wind impact on modules. This load may change depending on the wind conditions and angle of attack of the wind on the modules. Simultaneously, this tube is also modeled as a shaft under torsion across its entire span. A simplified model of the torque diagram is given in Figure 2. Through modal analysis done on the structural model, it is found that the first fundamental mode shape is torsional vibration about the torque tube as shown in Figure 3. This is also corroborated from various reports of torsional galloping of structure under load due to wind impact. Hence, in this paper, only this dominant mode of vibration is analysed.

For reducing the magnitude of torsional vibration of the system, hydraulic dampers are added to the system by coupling ends of the dampers to radial levers on the torque tube and other ends fixed to the vertical posts as shown in Figure 5. Thus, if the tracker structure gallops due to wind, the high linear velocity formed because of the damping shall cause a high resultant linear velocity in the damper plunger, resulting in a high damping force from the dampers. This is then resists the vibration and reduces its magnitude.

3 Analysis of Structural Properties:

For analysis of the vibrating structure, a simplified single degree of freedom lumped system model is constructed. The equivalent torsional stiffness of the torque-tube and equivalent mass moment of inertia of the system are calculated for the full suspended system and lumped. The damping torque in the system is calculated based on the geometry of the dampers and mounting.

3.1 Stiffness:

It may be noted that the torque tube spans full length of the tracker. However since the linear actuator in the centre is assumed to provide fixity to the shaft, the suspended system that is free to oscillate in the first torsional mode of vibration is only half of the length of the tracker table.

The torsional stiffness of non-circular hollow rectangular cross-section is given as [**4**]:

$$K_{tube} = \frac{T}{\theta} = \frac{kG}{L} \tag{1}$$

where variable k for non-circular rectangular hollow section is given as:

$$k = \frac{2tt_1(a-t)^2(b-t_1)^2}{at+bt_1-t^2-t_1^2} \tag{2}$$

where a and b are lengths of sides of rectangles and t and $t_1$are the thicknesses of the corresponding sides. In this work, the cross-section of the torque tube is considered to be hollow square with uniform thickness. Thus formula for k reduces to:

$$k = t(a-t)^3 \tag{3}$$

and the torsional stiffness of the torque tube is obtained as:

$$K_{tube} = \frac{t(a-t)^3 G}{L} \quad (4)$$

The value for the given material and section size of a typical torque-tube is calculated to be $6349.6\ Nm/rad$. Parameters used for calculating the value is given in Table *1*.

Table 1: Parameters used for calculating the thickness of torque tube

Parameter	Value	Unit
t	2.5	mm
a	101	mm
G	79.73	GPa
L	30	m

3.2 Inertia:

The rotational inertia of the system is given by the mass moment of inertia of the system about the axis of rotation of the tracker table. Mass moment of inertia calculated for all individual components of the system using solid modelling CAD software. The software, provides the numerical value of the mass moment of inertia about the centre of gravity of the component. Using parallel axis theorem, the value of moment of inertia about the axis of rotation is calculated. The typical value of mass moment of inertia of the system is calculated as $249.6\ kg\ m^2$.

3.3 Damping:

The damping in the system is assumed to be derived only from the hydraulic dampers added. The value of damping for various velocities is ascertained by methods prescribed in [5]. The typical values of damping at various linear plunger velocities is given in Table 2.

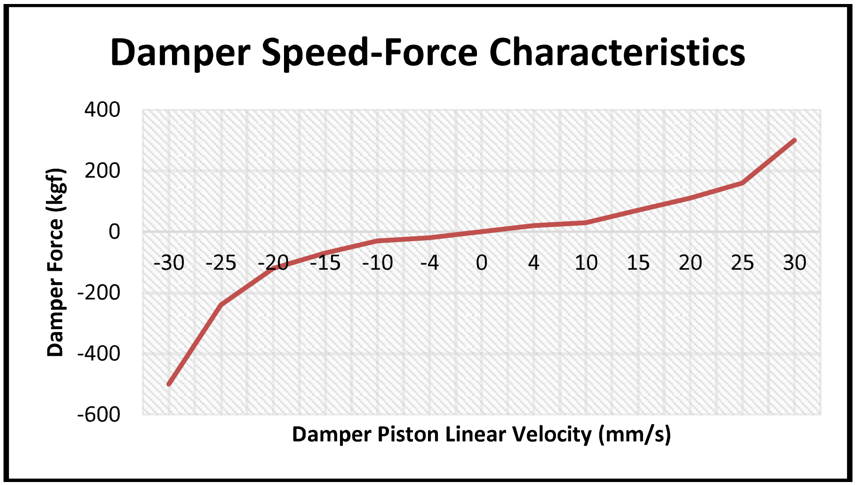


Figure 4: Graph showing damping force versus linear velocity of plunger of damper

Compressive velocity is taken as negative, and extension as positive. A sixth order polynomial is fit through the given data points to obtain the relation between velocity and damping force as shown in Figure 4**.** This gives the response of the damper to linear speed of the plunger.

Table 2: Damping force for various linear plunger velocities

Plunger Velocity *(m/s)*	Force during Extension *(kgf)*	Force during Compression *(kgf)*
4	20	20
10	30	30
15	70	70
20	110	120
25	160	240
30	300	500

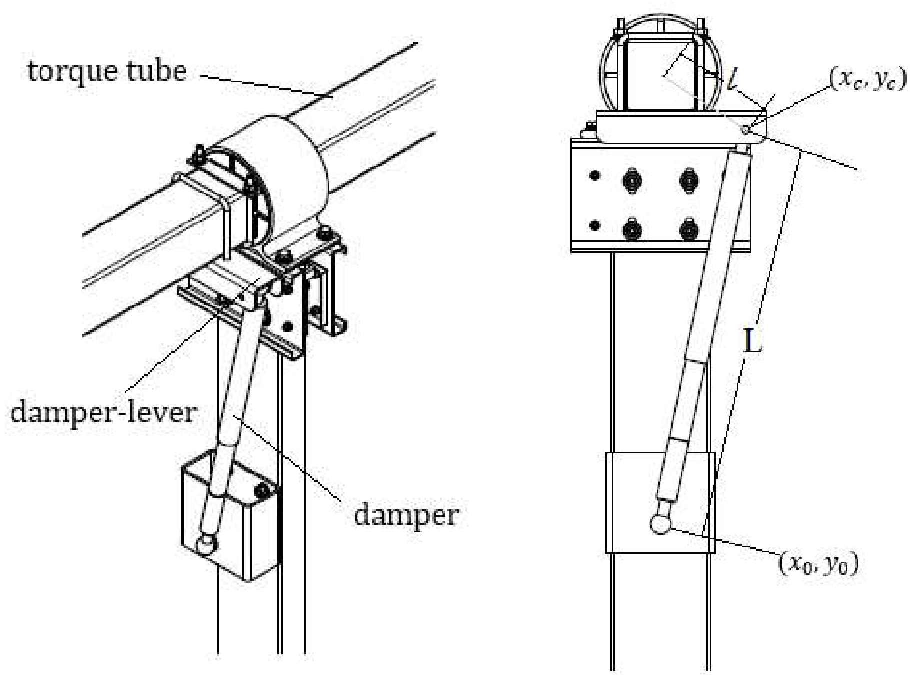


Figure 5: Typical damper mounting done on tracker table

It should be noted that the damper may slope towards the windward side or away from it, as the direction of wind may vary naturally. Based on the geometry of mounting of the damper as shown in *Figure 5*, the linear speed of the damper for the angular velocity of the tracker table is derived by taking the first derivative of the expression for the length of the damper.

$$L^2 = (x_c - x_0)^2 + (y_c - y_0)^2 \tag{5}$$

$$2.L.\dot{L} = 2.(x_c - x_0).(\dot{x_c}) + 2.(y_c - y_0).(\dot{y_c}) \tag{6}$$

Then the value of $(\dot{x_c})$ is simplified as $-\dot{l}.\dot{\theta}.\sin\theta$ and value of $(\dot{y_c})$ as $\dot{l}.\dot{\theta}.\cos\theta$, where θ is the tracker table angle. After simplification, the linear velocity of the plunger, as a function of the angular speed and angular position of the tracker is derived as:

$$\dot{L} = -\frac{l\dot{\theta}}{L}[(x_c - x_0)\, sin\,\theta - (y_c - y_0)\ cos\,\theta] \tag{7}$$

where $\dot{L}$ is the instantaneous linear velocity of the damper plunger at instantaneous damper length L and damper-lever length l which is achieved at tracker table angle θ at angular velocity of tracker table $\dot{\theta}$. Here, (x_c, y_c) are the co-ordinates of the point of coupling of damper-lever and damper end, calculated for the instance from the tracker table angle, while (x_0, y_0) are the co-ordinates of point of coupling of damper with vertical post, which are fixed.

The torque due to damping is calculated by cross-multiplying the damping force to the radial distance of coupling of damper from the centre of rotation. It is noted that the damping torque will always act in the direction opposite to the direction of motion, as it will always resist motion. The value is calculated as:

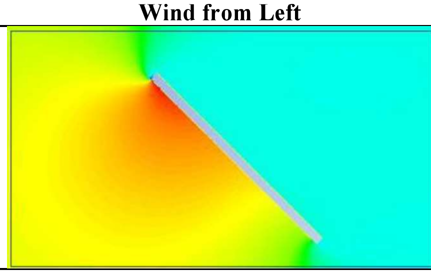
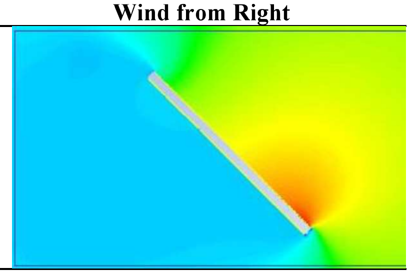
$$\vec{T}_{damp} = \vec{r} \times \vec{F} \tag{8}$$

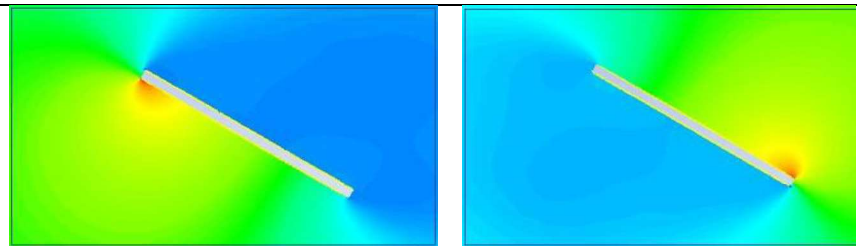
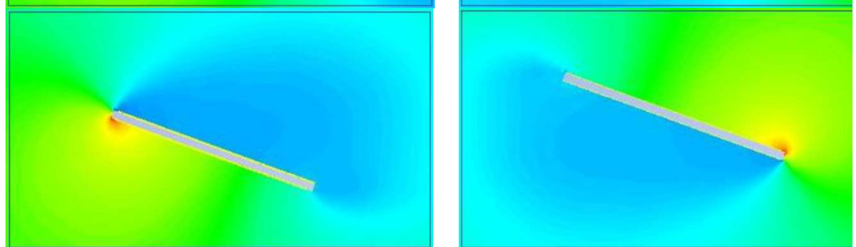
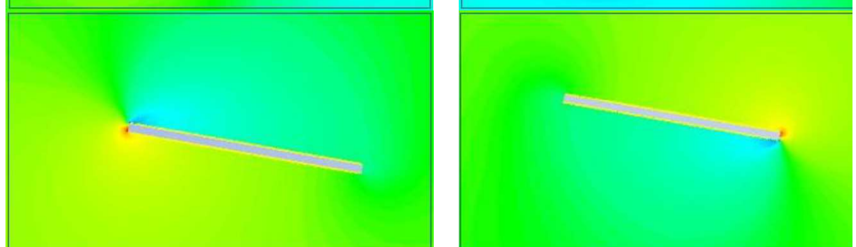
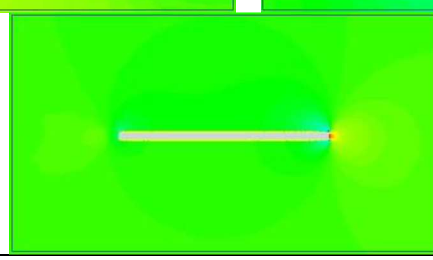
where $\vec{T}_{damp}$ is the damping torque vector, $\vec{F}$ is the damping force vector and $\vec{r}$ is the radius vector from the centre of rotation to the point of coupling of damper and lever. The damping torque is in the direction of the axis of the torque-tube and changes direction based on the direction of the force, and always resists the motion of torque-tube.

4 Force Due to Wind:

The design of tracker is done with compliance to various wind design codes such as [6], [7] and as such may be used to approximate the force and moment caused by wind on the structures. Studies such as [8] have focused on wind moment and force on roof-top structures that typically have small aspect ratios. However, for values of moment that are more relevant to the type of structure under analysis (small height, large aspect ratio), a separate steady state 2 dimensional CFD analysis was conducted for tracker table at different angles to determine the co-efficient of force and centres of pressures at different angles of the tracker table. A typical pressure contours of wind on a flat plate, simulating a tracker is given in Table 3**.**

Table 3: Typical pressure contour plots of wind impact on a flat plate. It is observed that the total pressure on the plate increases with an increase in angle of attack. It is also noted that the centre of pressure always acts on the windward side. The distance of centre of pressure from the leading windward edge increases with an increase in angle. Red areas denote positive pressure, while blue areas denote negative pressure (suction)

Angle	**Wind from Left**	**Wind from Right**
45°		

30°	
20°	
10°	
0°	

The coefficients of force and centre of pressure obtained are given in Table 4. The moment on tracker table is approximated as:

$$M_{t-wind}(v) = \frac{1}{2}\rho_a \, . \, v^2 \, . \, A_{mod} \, . \, C_\alpha . \; (0.5 - p_c) . \, t \tag{9}$$

Where, t is the tributary width, A_{mod} is the area of modules and ρ_a is the density of air.

Table 4: Coefficient of pressure and centre of pressure for various tracker table angles

Angle	Suction		Pressure	
	Suction Co-efficient (C_α)	**Centre of Pressure (p_c)**	**Pressure Co-efficient (C_α)**	**Centre of Pressure (p_c)**
0	-0.14	0.04	0.14	0.04

5	-0.62	0.3	0.65	0.3
10	-0.66	0.3	0.69	0.3
20	-1	0.35	1.1	0.3
30	-1.1	0.4	1.1	0.4
40	-1.24	0.4	1.21	0.4
45	-1.32	0.4	1.29	0.4
50	-1.41	0.4	1.3	0.4
60	-1.53	0.4	1.46	0.4

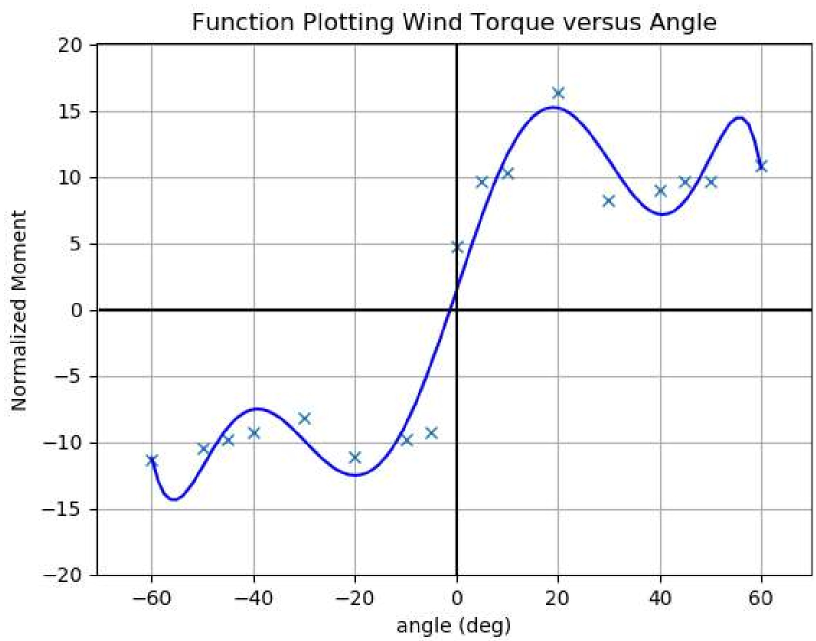


Figure 6: Moment caused by wind at 1 m/s wind speed is calculated as per formula given in equation (7) and plotted with 'x' markers, and a polynomial, bounded in the range of ± 60° is plotted in blue

Figure 6 shows the variation of the normalized wind moment with the angle of attack obtained using above analysis. From the data, an 8th degree curve that closely tracks the data points in Figure 6 for this range is given as below:

$$M_{t-wind}(\theta) = v^2 \,.\, (-1.98104260 \times 10^{-13} \times \theta^8 - 8.71827985 \times 10^{-11} \times \theta^7 + 1.41949619 \times 10^{-9} \times \theta^6 + 6.20715384 \times 10^{-7} \times \theta^5 - 2.89871114 \times 10^{-6} \times \theta^4 - 1.37341678 \times 10^{-3} \times \theta^3 + 8.15112138 \times 10^{-4} \times \theta^2 + 1.149481143\theta + 1.40464709) \quad (10)$$

where the angle θ is given in degrees and velocity v is given in meters per second.

5 Solution of Differential Equation:

The equilibrium equation for linear vibration for single degree of freedom system is given as:

$$I\ddot{\theta} + C_t\,\dot{\theta} + K_t\theta = T(t) \tag{11}$$

However, since the system under consideration does not have linear damping, equation (11) is modified as follows:

$$I\,\ddot{\theta} + T_{damp} + K_{tube}\theta = M_{t-wind}(\theta) \tag{12}$$

To obtain the numerical solution, the initial conditions are assumed to be that of a static slightly positively tilted tracker table, i.e. $\theta = 1°$ and $\dot{\theta} = 0$. The equation is solved numerically using Dormand-Prince method of the Runge Kutta family of ODE solvers.

The wind speed under consideration is taken to be an arbitrary value that is usually faced at site. As an indicative value, a constant wind speed of 17 m/s is assumed. Displacement and velocity response of the undamped system are shown in Figure 7. Similar responses in the presence of damping when the damper is installed such that its slope is towards or away from the windward direction are shown in Figures 8 and 9 respectively.

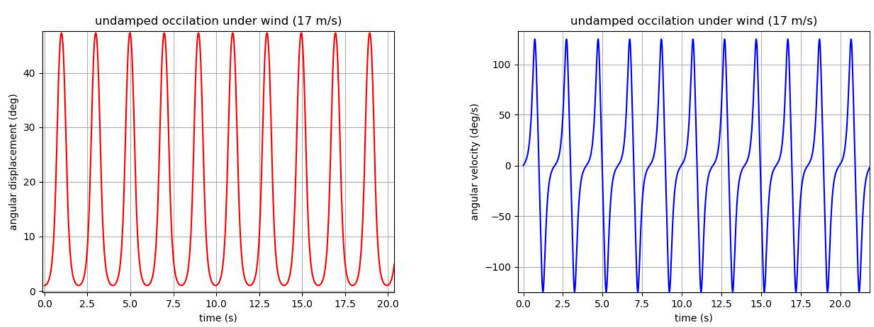


Figure 7: Graphs showing the angular displacement (left) and velocity (right) of tracker table under wind forcing without damping

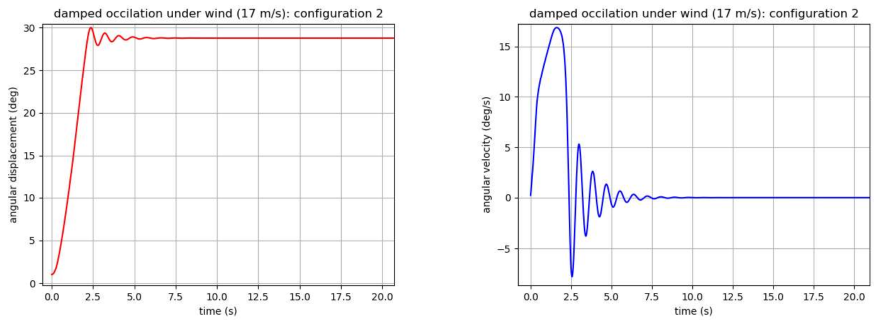


Figure 8: Graphs showing angular displacement (left) and velocity (right) of the tracker table when damper is installed with slope towards the windward side

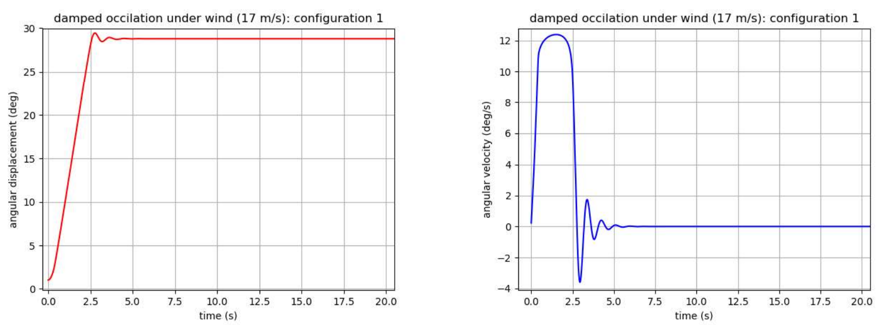


Figure 9: Graphs showing the angular displacement (left) and velocity (right) of the tracker table when the damper is installed with slope away from the windward side

5 Summary:

The tracker structure is a compliant structure under aero-dynamic forcing due to wind. The forcing due to wind is simulated through computational fluid dynamics. The oscillation of the tracker structure is modeled by approximating values of stiffness and inertia and forcing function. The response of the structure is plotted on graphs. It is observed from the graphs generated from simulation, that the dampers chosen are capable of arresting the oscillations of table induced by wind, no matter the direction of wind, in under 10 seconds.

Acknowledgments:

The authors would like express gratitude to Mr. Abhimanyu Sable, Mr. Pankaj Sanap, Mr. Sandeep Bhosale, Mr. Apurav Jain, Mr. Basant Jain and the management of Mahindra Susten for the support and encouragement to carry out this work.

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