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Suppression of Resonance Induced Vibration Because of Wind Load at Bridge Structure by Using Passive Damper

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Abstract: Wind load on flexible bridge structure has various structural effects. Catastrophic effect because of wind load which is called flutter phenomenon will make structural failure rapid. Resonance induced vibration is the other wind load phenomenon which not only includes catastrophic failure but has a long-term effect and discomfort effect because of the structural vibration. Vortex is a typical rotational flow in the wake of an obstacle. The flow fluctuates in such a pattern which is known as Von Karman Vortex trails. If the frequency of vortex fluctuation coincides with one of the flexible structure natural frequency, a resonance phenomenon occurs. The phenomenon is called Vortex Induced Vibration (VIV). Vortex induced vibration depends on the natural frequency of the structure, dynamic wind load, and geometry of the structure. VIV can make the bridge vibrate with large amplitude and it can make the structure failure, if the VIV phenomenon occurs in the long period and the structure cannot withstand the dynamic load. It is very important to reduce the vibration when the VIV occurs in the flexible bridge. This paper presents the use of the Tuned Mass Damper (TMD) to reduce vibration because of vortex induced vibration at a flexible bridge. By using wind tunnel test and finite element analysis, the research shows that passive TMD is effective to reduce the vibration at flexible bridge when the VIV occurs. The highest vibration reduction occurs when the frequency of TMD coincides with the frequency of force vibration.

Keywords: *Aeroelastic, finite element, bridge structure, structure dynamic, resonance induced vibration, tuned mass damper, wind load*

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I. INTRODUCTION

Flexible bridge is very sensitive with dynamics loading especially in dynamics wind load. Dynamics wind load can make the bridge vibrate with higher amplitude. Some phenomenon in structure failure because of wind dynamics loading is Tacoma narrow bridge which collapsed in 1940 at 18 m/s wind speed and Ferrybridge Power Station which had 114 m in height and collapsed at 41 m/s wind speed [1, 2, 3].

VIV are motions induce on bodies by an external flow because of vortex shedding in the surrounding bodies. If the frequency of vortex shedding coincides with one of the flexible structure natural frequency, a resonance phenomenon occurs. Vortex induced vibration is structural vibration induced phenomenon caused by vortex shedding around the building in which its frequency coincides with natural frequency of the structure. Another phenomenon in cross wind direction is lock-in, lock-in occurs, not only at one critical wind velocity but also at several wind velocities [4, 5]. VIV suppression in a low mass damping system is more challenging in practice due to higher amplitude response. VIV can be seen frequently in a multitude of engineering applications such as heat exchanger tubes, cooling towers, bridges, buildings, offshore structures, and nuclear reactors [6]. When the VIV occurs, the bridge structure can vibrate with high amplitude. If the structure cannot withstand the phenomenon then the bridge will be

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a failure because of high displacement vibration on this bridge. Under the dynamic effects from wind induced vibrations, fatigue damage would accumulate and may lead to an eventual collapse of bridges [7]. Environmental influences, changes in load characteristics and random actions accelerate the structural deterioration and can cause damage leading to expensive retrofitting or bridge failure [8].

Numerical solution, experimental, and analytical technique have been used to study about vortex induced vibration. The flow behind the structure and the separation flow could be controlled to decrease the unsteady force on the bluff body structure. Moreover the vibration because of the vortex can be made less than before [9]. With controlling the flow around the bluff body structure where the purpose is to minimize the vibration effect is called aerodynamic modification. Passive flow control techniques are dependent on geometry modifications for the reduction of drag and affecting the vortex shedding formation. The passive devices, such as splitter plates, fairings, helical strakes and small secondary control cylinders, require no external power input and have received much attention [10].

From the wind tunnel experiment by using flow visualizations at circular cylinder with and without strake have different phenomenon regarding the vortex induced phenomenon. The separation points can be changed by the helical strake and refusing the interaction between two shear layers and also minimizing the vortex structure length. By suppressing the vortex structure of wake, VIV control is achievable, therefrom suppressing the lift force and ultimately reducing or controlling the amplitude response [11]. The other study which aims to evaluate the passive control of VIV by small control rods had been done with a Computational fluid dynamic model coupling with a fluid structure interaction method utilized to solve the fluid flow and the motion of cylinder group with varying Reynolds numbers [12].

The other way to reduce the vibration effect because of vortex induced vibration is structural dynamic modification which use damper or modification at structural natural frequency. Another effective approach is to install additive energy dissipating equipment to increase the apparent damping, such as using TMD or Active-Mass-Damper (AMD). Research findings indicated that the tuned liquid column dampers could increase the tower fatigue life [13]. Employing aero- dynamic approaches to change the external force is the most common way [14]. It is very important to reduce the vibration in the flexible bridge in order to make the structure have a long life time and safety for the bridge. The passive TMD is found to be a simple, effective, inexpensive, and reliable means to suppress undesirable vibrations of structures caused by harmonic or wind excitations. Tuned mass damper consists of mass, spring, and damper (optional). A tuned mass damper, or dynamic vibration absorber, consists of a secondary oscillating mass, appended to a primary vibrating structure, and tuned properly on the resonance frequency of the targeted vibration mode of the primary structure [15]. The flexible bridge will be designed with a sectional model with wind tunnel experiment and finite element analysis, because the sectional model is becoming popular in long span bridge design processes. It is convenient to analyze the bridge deck aeroelastic behavior and the model is simple in structure. Wind tunnel testing was used to analyze the VIV phenomenon at sectional bridge wind tunnel model and Tuned mass damper was modeled with finite element by using spring and lumped mass to tune the frequency. Vibration analysis had been done by using frequency response analysis at finite element model.

II. AEROELASTIC WIND TUNNEL MODEL FOR WIND LOAD ON BRIDGE STRUCTURE

Wind tunnel test was used to identify the aerodynamic and aeroelastic characteristics of long span bridge. To determine the aerodynamic characteristics of a long span bridge to wind load can be performed using computational fluid dynamics analysis and aerodynamic testing in the wind tunnel, while to know the aero elastic characteristics of long-span bridges can accurately use wind tunnel testing because of the properties that are unique to every bridge so that the interaction with the wind factor is difficult to predict without testing in wind tunnel [16]. Long span bridge was modeled as sectional deck with rigid structure and eight springs to simulate the structural dynamic effect. Two circle end plates are used to provide the 2D flow condition around the bridge sectional model. The bridge was tested at Laboratory of Industrial Aerodynamic and Wind Engineering Wind Tunnel which has 2.5m x 1.5m test section area and 10m long. The installation of bridge sectional model in wind tunnel is described in Figure 1. The mathematical model can be described by using the differential equations.

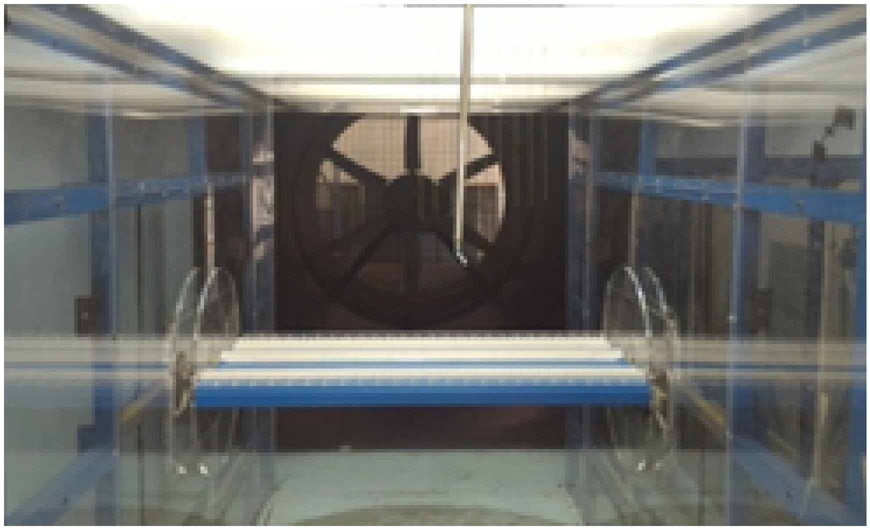

Fig. 1. Installation model at wind tunnel

$$m\ddot{z}+\left[-(-k_1)+k_2+k_3-(-k_4)-(-k_5)+k_6+k_7-(-k_8)\right]z=0 \tag{1}$$

$$I\ddot{a}+\left[-(-k_1)+k_2+k_3-(-k_4)(-k_5)+k_6+k_7-(-k_8)\right]e^2a=0 \tag{2}$$

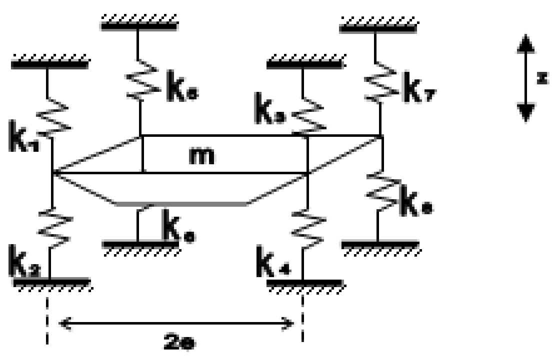

Fig. 2. Schematic model

The schematic mounting of the sectional model is shown in Figure 2. There are 8 springs with the same spring-constant.
Where:
m : density of deck model
I : moment inertia of deck model
$\ddot{m}=\frac{(d^2m)}{dt^2} and \ddot{\alpha}=\frac{(d^2)}{dt^2}$
$k_1,k_2,k_3,k_4,k_5,k_6,k_7,k_8$: spring constant
e : eccentricity , the distance between the point of spring and rotation center point model
To solve the differential equation, we can take the solutions a:

$$z=Z^*cos(\omega t+\phi);\ddot{z}=-\omega^2Z^*cos(\omega t+\phi) \tag{3}$$

$$\alpha=\alpha^*cos(\omega t+\phi);\ddot{\alpha}=-\omega^2\alpha^*cos(\omega t+\phi) \tag{4}$$

Where, ω: angular frequency and ϕ: phase. Then by substituting Equation 3 into Equation 1 is obtained. Then, by substitution of Equation 4 into Equation 2 is obtained;

$$-m\omega^2+(k_1+k_2+k_3+k_4+k_5+k_+k_7+k_8)=0 \quad \omega_H\sqrt{\frac{k_1+k_2+k_3+k_4+k_5+k_+k_7+k_8}{m}} \tag{5}$$

$$-I\omega^2+(k_1+k_2+k_3+k_4+k_5+k_+k_7+k_8)e^2=0 \quad \omega_T\sqrt{\frac{k_1+k_2+k_3+k_4+k_5+k_+k_7+k_8}{I}} \tag{6}$$

If the value of $k_1 = k_2 = k_3 = k_4 = k_5 = k_6 = k_7 = k_8 = k$ it is obtained, the angular frequency for the heaving motion is,

$$\omega_H = \sqrt{\frac{8k}{m}} \tag{7}$$

and the frequency for the torsion angle is

$$\omega_T = e\sqrt{\frac{8k}{I}} \tag{8}$$

The vibration data were recorded with acquisition hardware, software and accelerometer where installed at the model. The accelerometer is used to measure heaving and torsion acceleration because of wind load at the wind tunnel model. Aeroelastic wind tunnel test is designed in such a way to produce the necessary aeroelastic data, particularly for prediction of critical wind speed of excitation on the bridge deck structure by resonance induced vibration, either in bending mode oscillation or torque mode oscillation, Prediction of displacement at each wind speed, and maximum displacement when the resonance induction occurs. The sectional bridge model can vibrate with heaving and torsion mode, the value of the heaving and torsion frequency was 5.5 Hz and 10 Hz. Both frequencies is depend on the value of spring and the eccentricity.

III. FINITE ELEMENT FOR FREQUENCY RESPONSE

For standard engineering tools to analyze VIV is to apply an empirical model for fluid dynamic forces with a FEM based structural model which is the most common approach today. Applying CFD to analyze VIV, especially for larger and more complex problem domain, is hardly seen as it would require a vast amount of computational resources [17].

The dynamic response of the integrated system including sectional bridge wind tunnel model and tuned mass damper is examined by means of finite element simulations. By developing an approach based on the FEM (finite element method) simulations, we will explore the impacts of tuned mass damper regarding the suppression or vibration reduction because of vortex induced vibration which is modeled with frequency response analysis at FEM. FEM software used was MSC Nastran ®.

Frequency response analysis is a method used to compute structural response to steady-state oscillatory excitation. In frequency response analysis the excitation is explicitly defined in the frequency domain. All of the applied forces are known at each forcing frequency. Forces can be in the form of applied forces and/or enforced motions (displacements, velocities, or accelerations).

Frequency response analysis used is modal frequency response analysis. Modal frequency response analysis is an alternate approach to computing the frequency response of a structure. This method uses the mode shapes of the structure to reduce the size, uncouple the equations of motion (when modal or no damping is used), and make the numerical solution more efficient.

The first step in the formulation is to transform the variables from physical coordinates $\{\mu(\omega)\}$ to modal coordinates $\{\xi(\omega)\}$ by assuming.

$$x = [\phi]\{\xi(\omega)\}e^{i\omega t} \tag{9}$$

The mode shapes $[\phi]$ are used to transform the problem in terms of the behavior of the modes as opposed to the behavior of the grid points. To proceed, temporarily ignore all damping, which results in the undamped equation for harmonic motion at forcing frequency (ω).

$$-\omega^2[M]x + [K]\{x\} = \{F(\omega)\} \tag{10}$$

Substituting the modal coordinates in Equation 9 for the physical coordinates in Equation 10 and dividing by $e^{i\omega t}$, the following is obtained:

$$-\omega^2[M][\phi]\{\xi(\omega)\} + [K][\phi]\{\xi(\omega)\} = \{F(\omega)\} \tag{11}$$

Now Equation 11 is the equation of motion in terms of the modal coordinates. At this point, however, the equations remain coupled. To uncouple the equations, pre-multiply by $[\phi^T]$ to obtain:

$$-\omega^2[\phi]^T[M][\phi]\{\xi(\omega)\} + [\phi]^T[K][\phi]\{\xi(\omega)\} = [\phi]^T\{F(\omega)\} \tag{12}$$

Where:
$[\phi]^T[M][\phi]$ =modal (generalized) mass matrix
$[\phi]^T[K][\phi]$ = modal (generalized) stiffness matrix
$[\phi]^T\{P\}$ =modal force vector

In this uncoupled form, the equations of motion are written as a set of uncoupled single degree-of-freedom systems as :

$$-\omega^2 m_i \xi_i(\omega) + k_i \xi() = F_i(\omega) \tag{13}$$

Where:
$m_i = i-th$ modal mass
$k_i = i-th$ modal stiffness
$F_i = i-th$ modal Force
Force frequency (ω) used was the harmonic vibration when the vortex induced vibration phenomenon occurs at wind tunnel testing. VIV is assumed to take place at discrete frequencies that are all Eigen frequencies, but with an added mass that is given by the local flow, The resulting response frequencies will therefore be an adjusted Eigen frequency [17]. The force frequency and the magnitude are the frequency and the magnitude where the lock in phenomenon occurs near the heaving frequency.

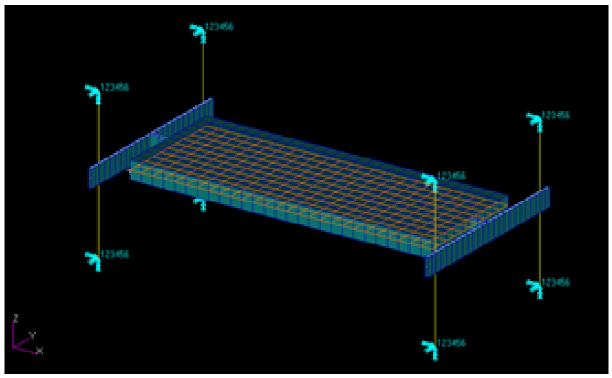

Fig. 3. FEM model with Force frequency

The finite element model of sectional bridge has the same dynamic characteristics with the wind tunnel model which consists of 8 springs with the same spring-constant and the same bridge sectional model mass. The force frequency was applied at the center of the model which has vertical force vibration with single frequency. The FEM schematic model can be seen in Figure 3.

The modal form of the frequency response equation of motion is much faster to solve than the direct method because it is a series of uncoupled single degree-of-freedom systems. Once the individual modal responses $\xi_i(\omega)$ are computed, physical responses are recovered as the summation of the modal responses using.

$$\{x\} = [\phi]\{\xi(\omega)\}e^{it} \tag{14}$$

These responses are in complex form (magnitude/phase or real/imaginary).

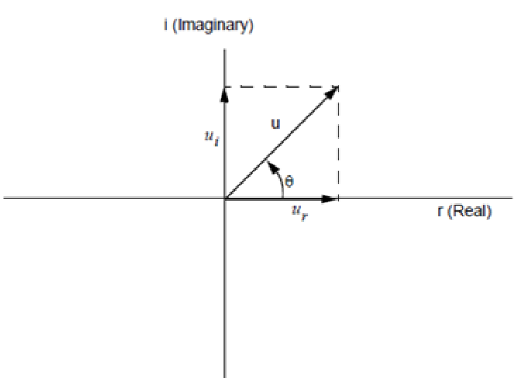

Fig. 4. Imaginary and real coordinate

Where
u = magnitude = $\sqrt{u_r^2 + u_i^2}$
θ = phase angle= $tan^{-1}(u_r u_i)$
u_r = real component = $ucos\theta$
u_i = imaginary component = $usin\theta$

Tuned mass damper was modeled at the side end of the bridge sectional model by using spring element (1-D Element) and lumped mass (Figure 5). The frequency of TMD was tuned at the model heaving frequency, because the purpose is to reduce vibration at heaving resonance.

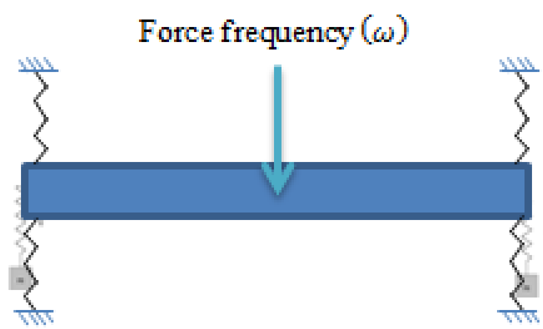

Fig. 5. FEM schematic model with TMD

IV. RESULTS AND DISCUSION

Vortex induced vibration phenomenon can be analyze by doing wind tunnel testing experiment. Sectional bridge wind tunnel model was tested with different wind speed, from lower to higher wind speed with some increasing value of wind speed. Wind tunnel test results are shown as a 3-dimensional plot (waterfall plot) which states the relationship between the amounts of oscillation (amplitude) for a number of frequency spectrums at different wind speeds. By comparing the result with the natural frequency of the model, we can know the vortex induced vibration phenomenon which occurs at the model because of wind load. By rising wind speed gradually from the lowest speed (2 m/s) to the highest value (when the VIV phenomenon at the torque frequency has been reached). Then the vibration amplitude at bridge sectional model was measured at each stage of velocity, to get the magnitude data from the oscillation at the specified frequency range. VIV phenomenon can be seen by processing the vibration data into a frequency domain form at each wind speed in a waterfall graph.

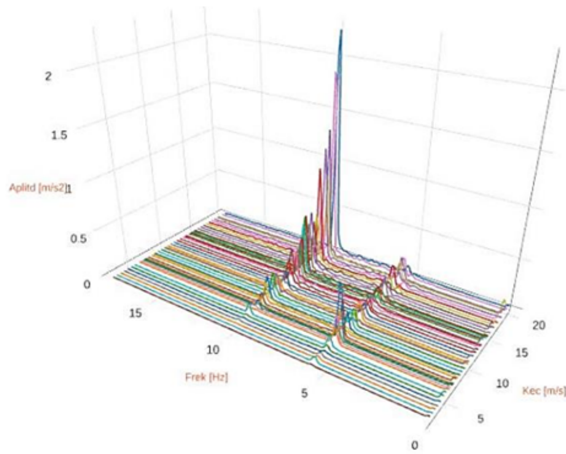

Fig. 6. Waterfall graph TMD

From the wind tunnel test, VIV phenomenon can be seen by analyzing the waterfall plot (Figure 6). Heaving and torsion frequency of the wind tunnel model was exited at various wind speeds. In this research the vibration reduction was focused only for VIV at heaving frequency by using passive tuned mass damper. VIV that exited heaving frequency starts from after the wind speed was 4 m/s until 6 m/s and the maximum amplitude occurs when the wind speed was 5.3 m/s.

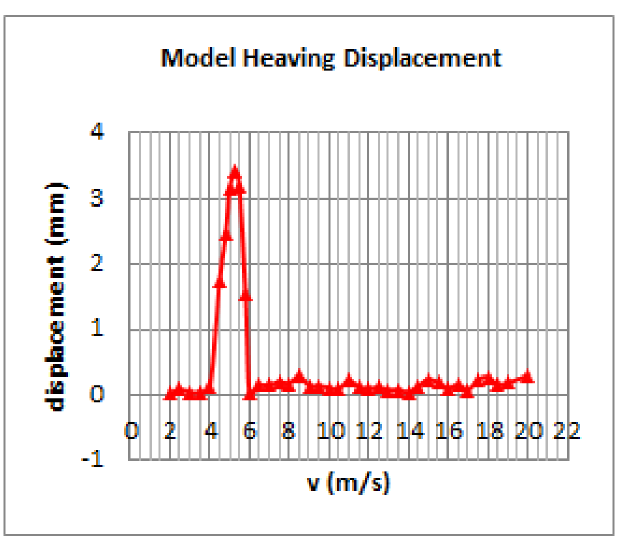

Fig. 7. Displacement amplitude (rms) with several wind speed

Figure 7 shows the variation of VIV amplitude with various wind velocities for the heaving frequency of bridge sectional wind tunnel model. It is seen that the maximum VIV amplitudes for the heaving modes are seen clearly, and the value is around 3.4 mm.

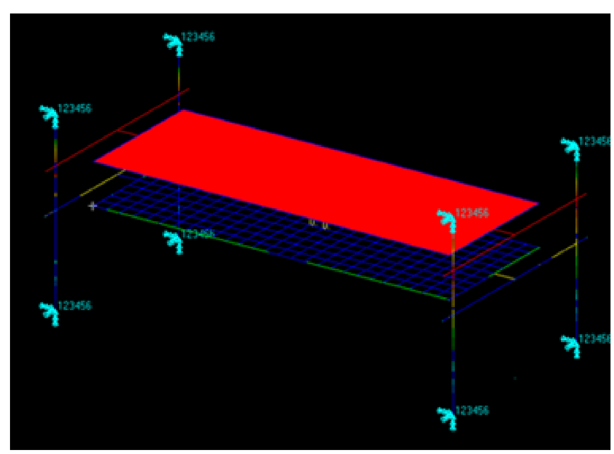

Fig. 8. FEM result without TMD

The structural vibration response from the frequency response analysis with steady-state oscillatory for the sectional bridge model can be seen in Figure 8. The vertical vibration because of force frequency which is represented as vortex induced vibration is described as the red color. The bridge model going up and down with some amplitude depends on the force frequency excitation.

Figure 9 Shows the vertical vibration response of the model with TMD, in which the model almost not moving with the force frequency is equal to the force before using TMD. The vibration response is dominated by the TMD compared with the model. The vibration amplitude of TMD can be seen at the end of the side model.

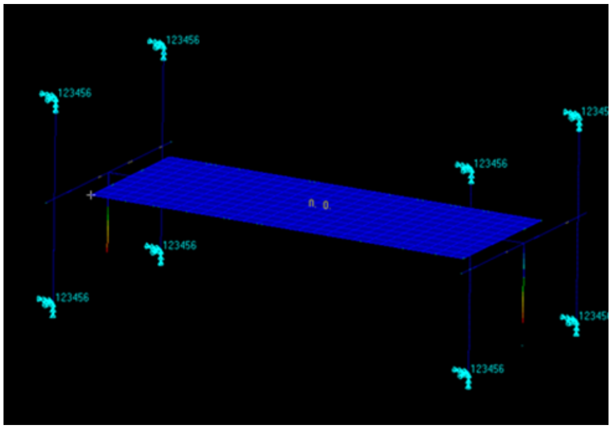

Fig. 9. FEM result with TMD

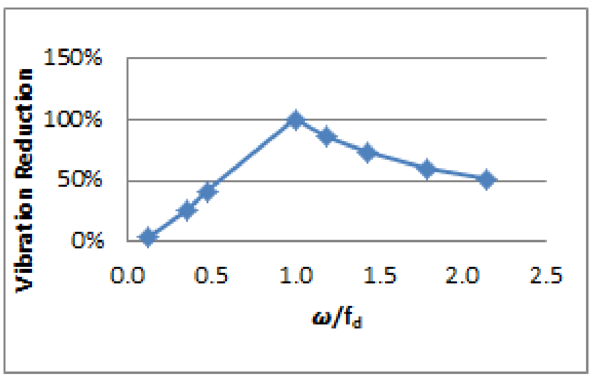

Fig. 10. Vibration Reduction with different ω

The bridge model with TMD had been analyzed with different force frequency excitation as happened in wind tunnel testing near the lock in region at heaving frequency. Graph 1 describes the difference of force frequency excitation (ω) divided by the frequency of TMD (f_d) and the reduction of vibration between before and after using TMD. The passive TMD was effective when the force frequency was equal to the frequency of TMD., because at that point vibration reduction had a high value compared to the other. This result is appropriate with the previous research, where the optimum value of frequency ration between damper and the system is 0.98 (relative to the fundamental frequency) [18].

V. CONCLUSION

The Kármán-vortex shedding and galloping interaction is a major issue in the field of flow-induced vibration, with important consequence on the wind-resistant design of structures [19]. Wind tunnel test for sectional bridge and finite element modelling with frequency response analysis had been done for vortex induced vibration research particularly at heaving frequency and to reduce the vibration because of that by using tuned mass damper. Vortex induced vibration suppression is important to overcome fatigue failure because of the structural vibration. VIV at the long span bridge occurs at certain region of wind speed and had maximum amplitude at some wind speed when the structural natural frequency is exited. Passive TMD which consists of spring and mass and tuned at the natural frequency of the structure can reduce the vibration amplitude. The optimum vibration reduction occurs when the force frequency coincides with the frequency of TMD. However, the writers believe that a lot of work is needed to improve the way to reduce the vibration because of wind load such us galloping, buffeting, vortex shedding, and the other aeroelastic phenomena which occur not only at the one frequency excitation, so the damper must be adjust to the other frequency to reduce the vibration.

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