Analysis study the used of Tuned Mass Damper (TMD) on an existing train bridge due to high speed train with moving mass load approach

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Abstract. As the need of the train speed increased, the existing bridges need to be evaluated, especially in dynamic responses, which are deformation and acceleration. In this study, Cisomang Bridge is modeled and analyzed due to the high-speed train SJ X2 in varying speeds, 50 km/h, 100 km/h, 150 km/h, and 200 km/h. The used of tuned mass damper also will be varied on its setting and placing. The tuned mass dampers setting be varied based on the first or second natural frequency and the placing of tuned mass damper be varied based on maximum deformation of the first or second mode. Moreover, the tuned mass damper ratio will be varied 1% and 1.6%. For all speed variations, dynamic responses of structure without TMD still fulfil the Indonesian Government Criterion based on PM 60 – 2012 but do not meet requirement of comfort criteria based on DIN-Fachbericht 101. Furthermore, only for the speed train 50km/h dynamic responses of structure fulfil safety criteria based on Eurocode EN 1990:2002, whereas the other speed variations do not meet that requirement. In the use of TMD 1% mass ratio, the structure fulfils the safety criteria for all speed variations. In the use of TMD 1.6% mass ratio, all the structure fulfils the safety and comfort criteria except 100 km/h speed which only fulfils the safety criteria.

1 Introduction

The high demand traffic triggers the development of high speed train in Indonesia, even new infrastructure will be built to accommodate “high speed train Jakarta-Bandung” by Indonesian Government. However, the construction of new infrastructure will be cost and time consuming. Cisomang Railway Bridge is one of existing bridges located in Jakarta-Bandung Line. It is interesting to evaluate whether high speed trains are able to go through the existing Cisomang Railway Bridge.

Zhang et al [9] have studied that train speed increase bridge acceleration, whereas some provisions state that bridge must fulfils safety and comfort criteria based on its acceleration [4 5]. The excessive vibration might be happened to the existing Cisomang Railway Bridge which was not designed for high speed train previously. Some works [6 7] have studied the reducing structural responses with the use of TMD. Kwon et al [6] studied three-span bridge under TGV train whereas Wang et al [7] studied simply supported bridge under three various trains: French T.G.V., German I.C.E, and Japanese S.K.S. In this study, Cisomang Railway Bridge will be analysed under high speed train SJ X2. Dynamic responses of Cisomang Railway Bridge will be evaluated, which are structure’s displacement and acceleration. If the structure’s responses exceed the limit, TMD will be used to reduce them. This study aimed to analyse the existing structure’s responses due to high speed train before and after the used of TMD. The location and setting properties of TMD installation will be varied in several structural modes. The mass ratio

of TMD also will be varied. All variation is made to find which one is the most effective.

2 Case Study

The bridge to be analysed is 244.3m Cisomang Railway Bridge located above Cisomang River, Purwakarta, West Java as shown in Figure 1 and Figure 2. The bridge has 16 supports which are 8 fixed supports located on truss piers, 4 pinned supports located on abutment and 4 pinned supports located on the arch as shown in Figure 3. The bridge has various truss pier height dimension that can be shown in Figure 4.

Fig. 1. Cisomang Railway Bridge

Fig. 2. Plan Layout Cisomang Railway Bridge

Fig. 3. The Supports of The Bridge

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Fig. 4. Truss Pier Height Dimension

There are 2 variations of TMD mass, which are 1% and 1.6%, 2 variations of TMD setting, which are first and second structure's mode frequencies, and 2 variations of TMD location, which are first and second structure's mode maximum deformations. So, there are 8 models in total as described in Table 1.

Table 1. Model Case study

1 % Mass Ratio of TMD		Location	
		Max Deformation of First Mode	Max Deformation of Second Mode
Setting	Frequency of First Mode	Model 1	Model 3
	Frequency of Second Mode	Model 2	Model 4
1.6 % Mass Ratio of TMD		Location	
		Max Deformation of First Mode	Max Deformation of Second Mode
Setting	Frequency of First Mode	Model 5	Model 7
	Frequency of Second Mode	Model 6	Model 8

The material used for Cisomang Railway Bridge is steel with material specifications S355J0 and S235J0. Material properties of S355J0 can be seen in Table 2 and S235J0 material properties can be seen in Table 3.

Table 2. S355J0 Material Properties

Nominal thickness (t) (mm)	Minimum yield strength (MPa)	Tensile strength (MPa)
$t \leq 16$	355	479 - 630
$16 < t \leq 40$	345	479 - 630
$40 < t \leq 63$	335	479 - 630
$63 < t \leq 80$	325	479 - 630
$80 < t \leq 100$	315	479 - 630
$100 < t \leq 125$	295	479 - 630

Table 3. S235J0 Material Properties

Nominal thickness (t) (mm)	Minimum yield strength (MPa)	Tensile strength (MPa)
$t \leq 16$	235	360 - 510
$16 < t \leq 40$	225	360 - 510
$40 < t \leq 63$	225	360 - 510
$63 < t \leq 80$	215	360 - 510
$80 < t \leq 100$	215	360 - 510
$100 < t \leq 125$	195	360 - 510

The sections used for Cisomang Railway Bridge are IWF (Figure 5a) listed on Table 4, hollow section (Figure 5b) list on Table 5, and tapered section (Figure 5c) listed on Table 6.

Fig. 5. Section used for Cisomang Railway Bridge

Table 4. IWF Section Properties

IWF Section	H (mm)	B (mm)	tw (mm)	tf1 (mm)	tf2 (mm)
2022x500	2022	500	20	57	60
1200x700	1200	700	20	40	40
924x400	924	400	20	25	25
283x300	283	300	7.5	10.5	10.5

Table 5. Box Hollow Section Properties

Hollow Section	H (mm)	B (mm)	tw (mm)	tf1 (mm)	tf2 (mm)
VB 1	500	460	36	18	18
VB 2	500	1000	70	25	25
VB 3	486	650	45	18	18
VB 4	500	650	60	45	45
VB 5	520	1420	20	35	35
Arch	600	520	55	35	35

Table 6. Tapered Box Section Properties

Tapered Section	H (mm)	B (mm)	tw (mm)	tf1 (mm)	tf2 (mm)
Arch - 1	600 - 1300	520	55	35	35
Arch - 3	600 - 1000	520	55	35	35

2.1. Dynamic Load on Bridge

Dynamic load changes over time. There are 3 different types of dynamic load for bridge: moving load (Figure 6a), moving mass without stiffness and damping (Figure 6b) and moving mass with stiffness and damping (Figure 6c) as discussed in [3].

Fig. 6. Three types of Dynamic Load on Bridge [3]

Dynamic load used in this study is moving mass with stiffness and damping, so that the train load is calculated first which follow SDOF model as shown in Figure 7. Bridge resist train load f_T which follows equation (1).

Fig. 7. Train Load Model [1]

$$f_T = ku + c\dot{u} \quad (1)$$

Where :

f_T : force transferred to bridge (N)

k : stiffness (N/m)

c : damping ratio (N.s/m)

u : displacement (m)

$\dot{u}$: velocity (m/s)

Displacement and velocity are derived from SDOF equation

$$m \cdot \ddot{u} + c \cdot \dot{u} + k \cdot u = p_o \quad (2)$$

Which has the solution $u(t)$

$$u(t) = e^{-\xi \omega t} (A_1 \cos \omega_D t + A_2 \sin \omega_D t) + \frac{p_o}{K} \quad (3)$$

And the solution $\dot{u}(t)$

$$\begin{aligned} \dot{u}(t) = e^{-\xi \omega t} (-A_1 \omega_D \sin \omega_D t + A_2 \omega_D \cos \omega_D t) \\ + (-\xi \omega) e^{-\xi \omega t} (A_1 \cos \omega_D t + A_2 \sin \omega_D t) \end{aligned} \quad (4)$$

So that in the end, we can get train load function F_t as shown in Figure 8

Fig. 8. F_t Load Function

F_t load function (Figure 8) must be applied to specific node on the bridge span. The load is concentrated load from the weight of train wagon which has distance as shown in Figure 9. So, in this model train load will be applied to 24 nodes on the bridge span as shown in Figure 10, which has distance approximately 10 m between nodes. F_t load function (Figure 8) is applied on the specific node from those 24 nodes so that the new function must be derived which represent load function for each node. To derived load function for specific node, train time arrival at that specified node must be determined first. Train time arrival at specified node depends on speed of the train. There will be 24 load functions for 1 speed train for 1 bridge model. Because there are 4 speed variations, in the end there are 96 load functions in total. As an example, the load calculation for node 1210 which is located at the middle of the span will be shown in Table 7 (for 50 km/hour), Table 8 (for 100 km/hour), Table 9 (for 150 km/hour), and Table 10 (for 200 km/hour). The functions shown in Figure 11 to 14 will be applied to node 1210.

Fig. 9. Train's Wagon Distance

Fig. 10. Twenty Four Nodes to be Applied Train Load

Table 7. Load Calculation for Node at The Middle of The Span (Speed of Train 50 km/hour)

Nodal 1210	Distance (m)	Time (s)	Load (kN)
Wagon 11	144.88	10.43	325.12
Wagon 12	162.58	11.71	324.24
Wagon 21	170.83	12.30	324.78
Wagon 22	188.53	13.57	325.07
Wagon 31	196.78	14.17	324.93
Wagon 32	214.48	15.44	325.31
Wagon 41	222.73	16.04	325.10
Wagon 42	241.01	17.35	325.33
Wagon 51	248.68	17.90	325.22
Wagon 52	266.38	19.18	325.34
Wagon 61	274.63	19.77	325.27
Wagon 62	292.33	21.05	325.32
Wagon 71	300.58	21.64	325.29
Wagon 72	318.28	22.92	325.31

Fig. 11. Load Function for Node at The Middle of The Span (Speed of Train 50 km/hour)

Table 8. Load Calculation for Node at The Middle of The Span (Speed of Train 100 km/hour)

Nodal 1210	Distance (m)	Time (s)	Load (kN)
Wagon 11	144.88	5.22	345.46
Wagon 12	162.58	5.85	304.27
Wagon 21	170.83	6.15	309.57
Wagon 22	188.53	6.79	337.76
Wagon 31	196.78	7.08	336.80
Wagon 32	214.48	7.72	318.33
Wagon 41	222.73	8.02	317.32
Wagon 42	241.01	8.68	329.18
Wagon 51	248.68	8.95	330.60
Wagon 52	266.38	9.59	323.66
Wagon 61	274.63	9.89	321.93
Wagon 62	292.33	10.52	325.87
Wagon 71	300.58	10.82	327.35
Wagon 72	318.28	11.46	325.27

Fig. 12. Load Function for Node at The Middle of The Span (Speed of Train 100 km/hour)

Table 9. Load Calculation for Node at The Middle of The Span
(Speed of Train 150 km/hour)

Nodal 1210	Distance (m)	Time (s)	Load (kN)
Wagon 11	144.88	3.48	320.39
Wagon 12	162.58	3.90	271.62
Wagon 21	170.83	4.10	280.82
Wagon 22	188.53	4.52	334.37
Wagon 31	196.78	4.72	353.19
Wagon 32	214.48	5.15	350.40
Wagon 41	222.73	5.35	334.59
Wagon 42	241.01	5.78	305.62
Wagon 51	248.68	5.97	304.35
Wagon 52	266.38	6.39	322.06
Wagon 61	274.63	6.59	331.90
Wagon 62	292.33	7.02	337.99
Wagon 71	300.58	7.21	333.37
Wagon 72	318.28	7.64	319.96

Fig. 13. Load Function for Node at The Middle of The Span
(Speed of Train 150 km/hour)

Table 10. Load Calculation for Node at The Middle of The Span (Speed of Train 200 km/hour)

Nodal 1210	Distance (m)	Time (s)	Load (kN)
Wagon 11	144.88	2.61	371.34
Wagon 12	162.58	2.93	410.28
Wagon 21	170.83	3.07	399.21
Wagon 22	188.53	3.39	338.17
Wagon 31	196.78	3.54	307.66
Wagon 32	214.48	3.86	272.20
Wagon 41	222.73	4.01	274.32
Wagon 42	241.01	4.34	309.53
Wagon 51	248.68	4.48	328.29
Wagon 52	266.38	4.79	356.95
Wagon 61	274.63	4.94	358.93
Wagon 62	292.33	5.26	341.74
Wagon 71	300.58	5.41	328.95
Wagon 72	318.28	5.73	307.46

Fig. 14. Load Function for Node at The Middle of The Span
(Speed of Train 200 km/hour)

2.2 Tuned Mass Damper

2.2.1 Tuned Mass Damper Mechanism

The purpose of adding the mass damper is to limit the motion of the structure with the mechanism is represented in Figure 15 [2].

Fig. 15. TMD Mechanism in SDOF [2]

$$\omega^2 = \frac{k}{m} \quad (5)$$

$$c = 2\xi\omega m \quad (6)$$

$$\omega_d^2 = \frac{k_d}{m_d} \quad (7)$$

$$c_d = 2\xi_d\omega_d m_d \quad (8)$$

And defining $\bar{m}$ as the mass ratio,

$$\bar{m} = \frac{m_d}{m} \quad (9)$$

The governing equations of motion are given by

$$\text{Tuned mass } \ddot{u}_d + 2\xi_d\omega_d\dot{u}_d + \omega_d^2 u_d = -\ddot{u} \quad (10)$$

$$\text{Primary mass } (1 + \bar{m})\ddot{u} + 2\xi\omega\dot{u} + \omega^2 u = \frac{p}{m} - \bar{m}\ddot{u}_d \quad (11)$$

2.2.2 Tuned Mass Damper Planning

Dimension of tuned mass damper used in this study refers to manufacturer as shown in Table 11. Selection of tuned mass damper is limited by the distance between upper structure (beam) and the arch which are 1.3 m length. Mass, stiffness and damping of TMD become the input into the structural modelling. TMD 1500 kg is used in 1% mass ratio model and TMD 2000 kg is used in 1.6% mass ratio model.

Table 11. Tuned Mass Damper Dimension [8]

Tuned mass (kg)	Length (mm)	Width (mm)	Height (mm)
250	620	200	635
500	870	200	735
750	1020	200	905
1000	1220	200	935
1500	1420	240	1005
2000	1620	240	1085
2500	1750	250	1185
3000	1870	250	1285
4000	2120	280	1585
5000	2320	280	1705
6000	2520	280	1785

3 Results and Discussion

Table 12 shows the periods of the structure and Figure 16 to 17 show the structural mode shape.

Table 12. Periods of Structure

Mode	Frequency (rad/sec)	Frequency (cycle/sec)	Period (sec)
1	3,2698	0,5204	1,9215
2	6,5598	1,0440	0,9578

Fig. 16. First Mode Shape of Structure

Fig. 17. Second Mode Shape of Structure

The whole mass of the bridge including the arch is taken into account while planning TMD because the arch also deformed (not a rigid body). Figure 18 shows the structure's deformation due to static load.

Fig. 18. Deformation of Structure due to Static Load

3.1 Dynamic Responses of Structure without TMD

Dynamic responses which are under reviewed in this study are displacement and acceleration.

3.1.1 Displacement

In this study, displacement of structure at the middle of the span is being concerned. Speed of the train influences displacement of the structure. Table 13 and Figure 19 shows the displacement value for each train's speed.

Table 13. Maximum Displacement for each Speed of Train

Speed of the Train (km/hour)	Displacement (m)
50	-0,00419
100	-0,00689
150	-0,0071
200	-0,00917

Fig. 19. Maximum Displacement for each Speed of Train

According to PM 60 2012 "Persyaratan Teknis Jalur Kereta Api" [10], maximum deflection limit is $L/1000$ which is $244.3 \text{ meter}/1000 = 0.244 \text{ meter}$. Maximum deflection of structure is less than the limitation so it can be concluded that the structure is acceptable in deformation.

3.1.2 Acceleration

Based on its maximum acceleration, structure must fulfil safety level and serviceability level. Structure is acceptable safe if its acceleration is less than 3.5 m/s^2 based on Eurocode EN 1990:2002 [5] and acceptable in serviceability comfort level if its acceleration is less than 2 m/s^2 based on *DIN-Fachbericht 101 Einwirkungen auf Brücken* [4]. Figure 20 shows maximum structure's acceleration for each speed of train. Structure fulfil both of the safety and serviceability level only for 50 km/hour speed of train.

Fig. 20. Maximum Acceleration for each Speed of Train

The structure is not safe for 100 km/hour, 150 km/hour and 200 km/hour speed of train. Because the acceleration of structure exceeds the maximum limit of safety due to high speed train, tuned mass damper will be used to reduce it.

3.2 Dynamic Responses of Structure with TMD

Generally, for all variations, TMD is proven reduce Cisomang Railway Bridge's response. As an illustration, Figure 21 shows how significance 1.6% TMD reduce Cisomang Railway Bridge's response when it is placed in max deformation of second mode and set to first mode frequency.

Fig. 21. TMD Reduces Cisomang Railway Bridge's Acceleration

Furthermore, as described before in Chapter 2, TMD will be varied to find which one is the most effective. TMD will be placed at maximum deformation of first mode for Model 1, 2, 5, 6 as shown in Figure 22 and placed at maximum deformation of second mode for Model 3, 4, 7, 8 as shown in Figure 23. Furthermore, TMD will be varied in mass and frequency setting.

Fig. 22. TMD Location for Model 1, 2, 5, 6

Fig. 23. TMD Location for Model 3, 4, 7, 8

3.2.1 The used of TMD 1 % Mass Ratio

For 1% mass ratio, 12 TMD are installed which have properties follow Table 14. In this sub chapter (1% mass ratio of TMD), Model 1 until 4 are under reviewed.

Table 14. Properties of TMD 1 % Mass Ratio

	First Mode Natural Frequency	Second Mode Natural Frequency	
M_T	1,337	1,337	ton
K_T	14,152	56,9585	kN/m
D_T	0,53144	1,0661	kN. s/m

From these variations, it can be concluded that TMD reduce the structure's acceleration. Previously, structure is safe if only the speed of the train 50 km/hour. After the used of 1% mass ratio of TMD, structure becomes safe for 50 km/hour, 100 km/hour, 150 km/hour and 200 km/hour. But, all the structures still not fulfil serviceability comfort level. This can be summarized in Figure 24 and 25.

Fig. 24. The Effect of The Used of TMD 1% Mass Ratio Placed at The Maximum Deformation of First Mode on Structure's Acceleration (Model 1 and 2)

Fig. 25. The Effect of The Used of TMD 1% Mass Ratio Placed at The Maximum Deformation of Second Mode on Structure's Acceleration (Model 3 and 4)

3.2.2 The used of TMD 1.6 % Mass Ratio

For 1.6% mass ratio, 13 TMD are installed which have properties follow Table 15. In this sub chapter (1.6% mass ratio of TMD), Model 5 until 8 are under reviewed.

Table 15. Properties of TMD 1.6 % Mass Ratio

	First Mode Natural Frequency	Second Mode Natural Frequency	
M_T	1,9747	1,9747	ton
K_T	20,7757	83,6185	kN/m
D_T	0,9879	1,981	kN. s/m

Once again, from these variations, it can be concluded that TMD reduce the structure's acceleration. Previously, all the structures do not satisfy serviceability requirement in the used of 1% mass ratio of TMD. After the used of 1.6% mass ratio of TMD, structure meet the requirement for 50 km/hour, 150 km/hour and 200 km/hour but still not satisfy for 100 km/hour. This can be summarized in Figure 26 and 27.

Fig. 26. The Effect of The Used of TMD 1.6% Mass Ratio Placed at The Maximum Deformation of First Mode on Structure's Acceleration (Model 5 and 6)

Fig. 27. The Effect of The Used of TMD 1.6% Mass Ratio Placed at The Maximum Deformation of First Mode on Structure's Acceleration (Model 7 and 8)

3.2.3 The Effectiveness of Tuned Mass Damper

How significance TMD reduces the structure's responses is summarized in Figure 28. The used of 1.6% TMD mass ratio gives the best result. And the best effective is given by the used of TMD which is tuned to the first mode. The largest decrease in structure's acceleration is when the bridge crossed by the train which has velocity 150 km/hour.

Fig. 28. The Effectiveness of TMD

3.2.4 Dominant Frequency Analysis using Fast Fourier Transform

The data used for FFT is structure's acceleration without TMD. The acceleration graphs from FFT will be shown only the natural frequency part to find out the most dominant natural frequency. From Figure 29 and Table 16, amplitudes of first natural frequency always larger than the second natural frequency. So, it can be concluded that first mode is more dominant than second mode. It is the reason why TMD tuned to first mode is more effective than to second mode. Moreover, amplitudes from FFT analysis for 150km/hour speed of train are largest than the other speed of train. It is the reason why the largest decrease in structure's acceleration is when the bridge crossed by the train which has velocity 150 km/hour.

Fig. 29. Acceleration Graph from FFT Analysis for Each Speed of The Train (a) 50 km/hour (b) 100 km/hour (c) 150 km/hour (d) 200 km/hour

Table 16. Amplitude Vs Natural Frequency

	Amplitude	
	1 st Natural Frequency	2 nd Natural Frequency
50 km/hr	2.273	1.983
100 km/hr	2.769	1.733
150 km/hr	7.819	0.567
200 km/hr	6.32	4.231

3.2.5 Resonance Checking

Resonance will occur if the structure frequency same as the load frequency. Resonance may cause collapse to structure. From Table 17, the natural frequency of structure different to the load frequency so that it can be concluded that resonance does not occur.

Table 17. Resonance Checking

Natural Frequency	Load Frequency			
	50 km/hr	100 km/hr	150 km/hr	200 km/hr
0.520	0.785	1.569	2.354	3.139
1.044	0.535	1.070	1.606	2.141
	0.318	0.636	0.955	1.273
	0.268	0.535	0.803	1.070
	0.200	0.399	0.599	0.798
	0.178	0.357	0.535	0.714
	0.145	0.291	0.436	0.582
	0.134	0.268	0.401	0.535
	0.114	0.229	0.343	0.457
	0.107	0.214	0.321	0.428
	0.094	0.188	0.283	0.377
	0.089	0.178	0.268	0.357
	0.080	0.160	0.240	0.320

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4 Conclusions

Without TMD, Cisomang Railway Bridge still fulfils the Indonesian Government Criterion based on PM 60 – 2012 by its deformation but does not meet requirement of comfort criteria based on DIN-Fachbericht 101 by its acceleration. Furthermore, without TMD, only for the speed train 50km/h dynamic responses of structure fulfil safety criteria based on Eurocode EN 1990:2002, whereas the other speed variations do not meet that requirement.

TMD reduce the structure's acceleration. After the use of TMD 1% mass ratio, the structure fulfils the safety criteria for all speed train variations, which previously only for 50 km/hour for structure without TMD. It can be concluded that the use of 1% TMD mass ratio is enough to fulfil safety level but still not enough to fulfil comfort level. After the use of TMD 1.6% mass ratio, all the structure fulfils the safety and comfort criteria except 100 km/h speed only fulfils the safety criteria. Tuned mass damper which is tuned to first mode as the most dominant mode gives the most effective result.

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