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Theoretical Calculation of Wind Response of Tall Structure with TMD and Comparison with Eurocode EN 1991-1-4 Procedure 2

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***Abstract* – This paper explores the possibilities of the Eurocode EN 1991-1-4 to be used to predict the response of structures with installed dynamic vibration absorber or TMD.The analysis is performed in a way that Davenport model is used to conduct theoretical calculation, and then is made calculation according to Eurocode procedure 2. Finally, results from both methods are compared. Floor displacements, accelerations, aerodynamical damping of structure and compliance to serviceability criteria ISO 10137:2007 is being calculated. In the end, remarks concerning the usability of the EN standard for predicting wind response of wind susceptible structures are given on the basis of calculated results from both methods.**

***Keywords* – wind response, tall structure, TMD, eurocode, serviceability criteria.**

1. Introduction

TMD has been used for mitigation of vibration of structures for many years, especially for reducing wind response [1]. TMD usually are installed on top floor of the structure, and have been tuned for the fundamental mode of vibration of the structure.

The structures which are susceptible to wind load random nature must fulfill the criteria for slenderness [2] and flexibility [3]. For the purpose of this research a 20 storey steel structure is used that meets the above mentioned criteria [4].On this structure wind forces are applied calculated theoretically and according to EN code.

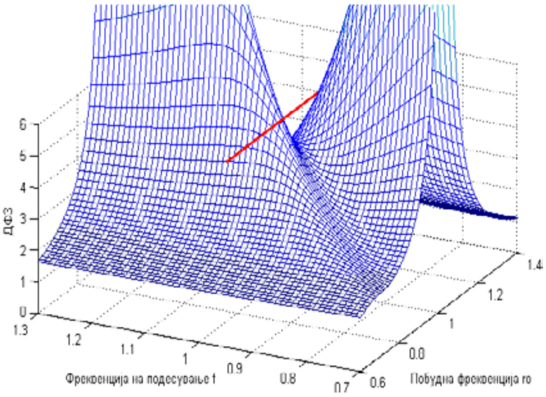

Fig. 1 Graphic interpretation of the optimization

Optimal values f_{opt} and $\xi_d|_{opt}$ for TMD installed on system with multiple degrees of freedom such as tall structure previously mentioned, are calculated with proposed formulas [5] based on minmax algorithm. Optimization depends on the dynamic force, and for the purposes of this paper they are assumed to be harmonic. Figure 1.shows optimization graphically. Optimal parameters are selected at the tangent points of dynamic factor surface.

TMD optimal values are given in table 1.

Tab. 1 Optimal values for TMD

Mass	Frequency		Eq. stiffness	$\xi_d|_{opt}$
[kg]	[rad/s]	[Hz]	[N/m]	%
127230	1.58	0.25	318109	0.1375

The prototype of 20 story structure is modeled as shear type of building (figure 2) using the formula defined by Muto [6] for shear stiffness of floor.

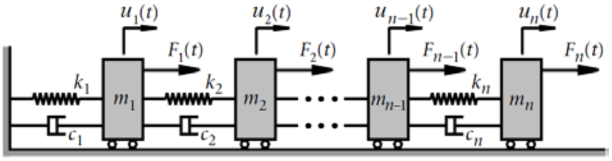

Fig. 2 Shear type of m.d.o.f. structure

Calculated parameters of the 20 story structure model are given in table 2.

Tab. 2 Optimal values for TMD

Floor	Mass [kg]	Stiffness [N/m]
20	292200	3.866E+07
19	276200	6.274E+07
18	276200	8.235E+07
17	276200	9.256E+07
16	276200	1.077E+08
15	276200	1.077E+08
14	276200	1.114E+08
13	276200	1.218E+08
12	276200	1.218E+08
11	276200	1.272E+08

10	276200	1.386E+08
9	276200	1.386E+08
8	276200	1.386E+08
7	276200	1.386E+08
6	276200	1.386E+08
5	276200	1.354E+08
4	276200	1.365E+08
3	276200	1.365E+08
2	276200	1.369E+08
1	283200	1.317E+08

Damping of primary structure is defined as classical Rayleigh damping, proportional to the mass and stiffness. Coefficients of the damping are given in table 3.

Tab. 3 Damping coefficients

Mass coefficient	Stiffness coefficient
0.0001	0.0240

Table 1, 2 and 3 fully define the structure with TMD for response analysis.

The influence of the wind is expressed through statistical properties. It is assumed that wind is random, stationary process with a Gaussian distribution. This means that the mean value of the fluctuation wind component is equal to zero and a standard deviationσ_u [7].

The Eurocode 1991-1-4 [8] provides two different procedures to calculate the structural factor and the comfort level. The structural factor $c_s c_d$ is important for the response analysis while the acceleration is important for the cofmort level.

There is broad agreement [9] that procedure 2 of EN 1991-1-4 is preferable for dynamic stochastic analysis of buildings. Therefore, it is used in this paper to calculate response of the structure with TMD.

The Eurocode only offers a procedure to evaluate the along wind response, while permitted accelerations of the structure are not covered.

ISO 10137 [10] provides different criteria for serviceability of buildings for offices and residential facilities i.e. the latter should be 1/3 more stable than the first. Human comfort criteria presented in ISO 10137:2007 is given on figure 3.

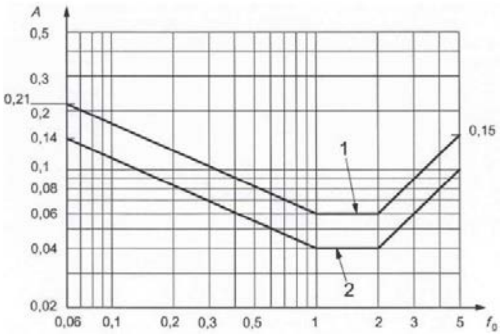

Fig. 3 ISO 10137:2007 comfort criteria

The first three natural frequencies of the primary structure are given in table 4. They are important for defining permitted acceleration.

Tab. 4 Natural frequencies of primary structure

1 тон [Hz]	2 тон [Hz]	3 тон [Hz]
0.2652	0.7378	1.1984

According to the ISO 10137 comfort criteria, the peak acceleration response with a one year return period should not be greater than 7 cm/s2 for wind velocities of 21 m/s or less.

2. Calculation of response of primary structure

Theoretical calculation of the response of the 20 storey structure is conducted under same environmental conditions according to wind spectral density. The same conditions are applied in calculation of the structural factor $c_s c_d$ that takes into account background and resonant response factor.

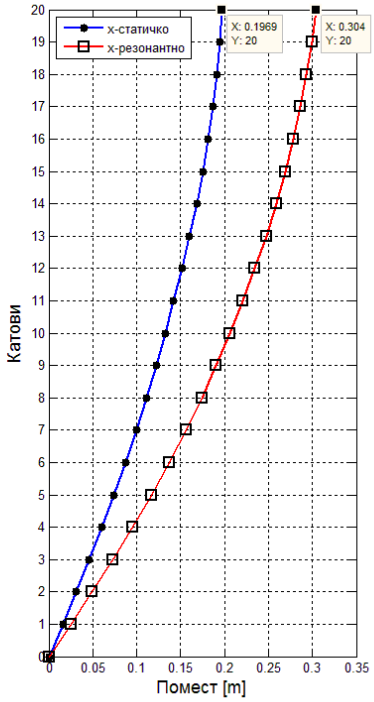

Fig. 4 Peak r.m.s. value of displacement

Figure 4.shows maximal displacement of the structure without TMD by Davenport theoretical model. The maximum response is calculated as the sum of the static response of the mean wind component and the dynamic response of the fluctuating component of the wind velocity.

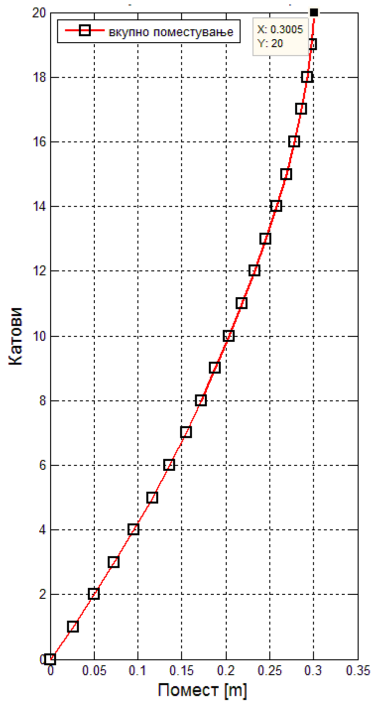

Fig. 5 Maximal displacement according to EN

In Eurocode 1991-1-4 maximum response is calculated by structural factor $c_s c_d$ and equivalent static forces. Prototype structure is loaded with them and gets static response which in essence is the maximum value of the peak root mean square value of displacement.

Figure 5. shows maximal displacement of the structure without TMD calculated according to Eurocode 1991-1-4.

For comparison, values of displacement for each floor are given in table 5.

Tab. 5 Maximum response of displacement

Floor	Davenport [m]	EN [m]	Diff.%
1	0.0253	0.0262	3.50
2	0.0491	0.0503	2.40
3	0.0724	0.0733	1.20
4	0.0950	0.0954	0.40
5	0.1167	0.1166	0.09
6	0.1370	0.1362	0.58
7	0.1561	0.1548	0.80
8	0.1740	0.1722	1.00
9	0.1905	0.1885	1.00
10	0.2057	0.2036	1.00
11	0.2207	0.2187	0.90
12	0.2348	0.2330	0.77
13	0.2473	0.2458	0.60
14	0.2592	0.2581	0.40
15	0.2697	0.2690	0.26
16	0.2785	0.2780	0.18
17	0.2866	0.2861	0.17
18	0.2935	0.2926	0.30
19	0.2995	0.2977	0.60
20	0.3040	0.3005	1.15

3. Calculation of response of primary structure with TMD

Following a similar order as in section 2, results of the response of structure with TMD are presented according to both methods.

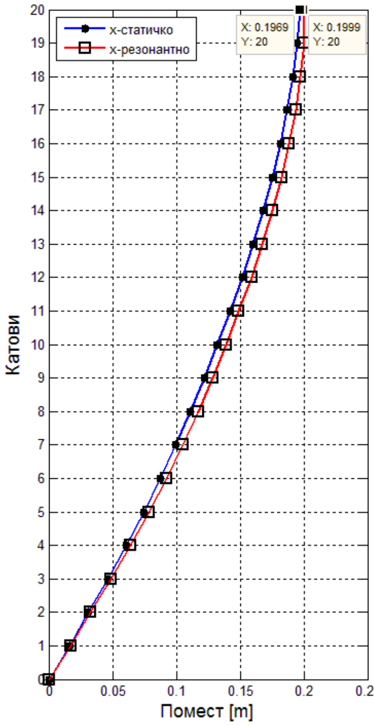

Fig. 6 Peak r.m.s. value of displacement

Figure 6. shows Davenport calculation.

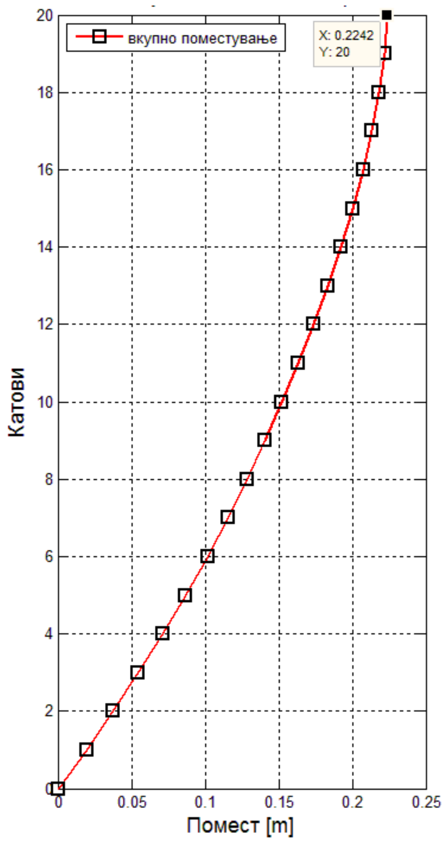

Fig. 7 Maximal displacement according to EN

Figure 7 shows results according to EN procedure.

Tab. 6 Maximum response of displacement

Floor	Davenport [m]	EN [m]	Diff.%
1	0.0170	0.0196	16
2	0.0330	0.0375	14
3	0.0486	0.0547	13
4	0.0637	0.0712	12
5	0.0784	0.0870	11
6	0.0920	0.1016	10
7	0.1049	0.1155	10
8	0.1170	0.1285	10
9	0.1283	0.1406	10
10	0.1388	0.1519	9
11	0.1492	0.1631	9
12	0.1589	0.1738	9
13	0.1676	0.1834	9
14	0.1758	0.1925	9
15	0.1829	0.2007	10
16	0.1887	0.2074	10
17	0.1937	0.2134	10
18	0.1976	0.2183	10
19	0.2000	0.2221	11
20	0.1999	0.2242	12

Table 6. summarizes the calculated values of maximum displacement with TMD.

4. Calculation of acceleration of primary structure

Acceleration values for each floor according to Davenport calculations are shown on figure 8.

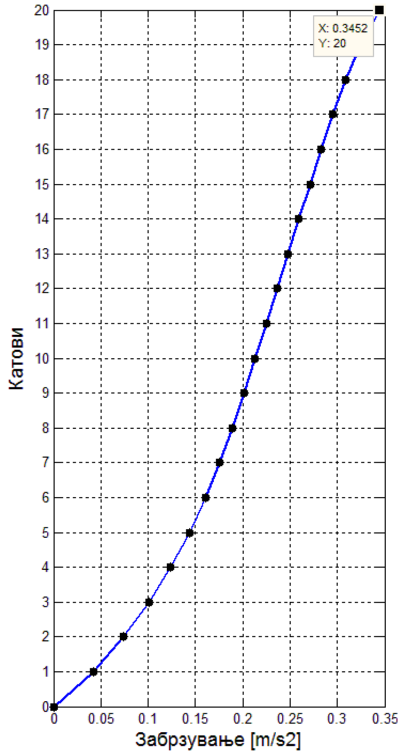

Fig. 8 Peak r.m.s. of acceleration

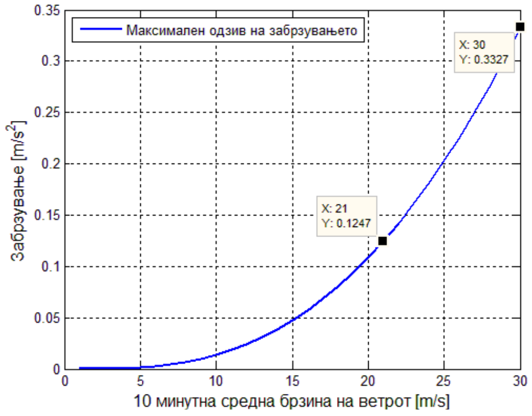

Fig. 9 Maximal displacement according to EN

In the initial conditions is taken that the average speed at 10 meters height is equal to 30 m/s, therefore the value of acceleration on the top floor of the structure according to EN is a given at figure 9 (X=30).

Tab. 7 Maximal acceleration response at top floor

Floor	Davenport [m/s^2]	EN [m/s^2]	Diff.%
20	0.3452	0.3327	3.6

Table 7. shows calculated values of maximal acceleration response at top floor of structure.

5. Calculation acceleration of primary structure with TMD

Following a similar order as in section 4, results of acceleration response of structure with TMD are presented according to both methods.

The value of acceleration on the top floor of the structure according to EN is a given at figure 11 (X=30).

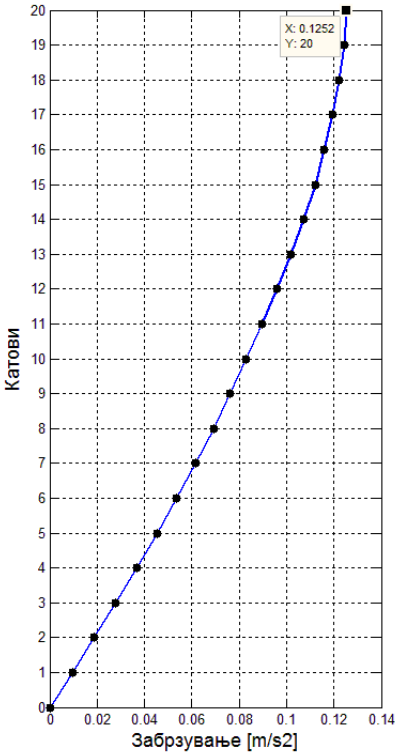

Fig. 10 Peak r.m.s. of acceleration

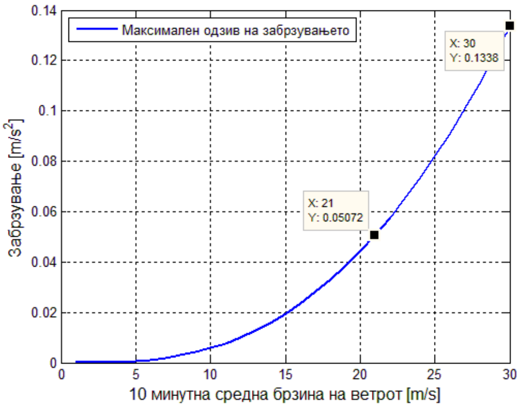

Fig. 11 Maximal displacement according to EN

Tab. 8 Maximal acceleration response at top floor

Floor	Davenport [m/s^2]	EN [m/s^2]	Diff.%
20	0.1252	0.1338	7

Table 8.shows calculated values of maximal acceleration response at top floor of structure.

6. Serviceability criteria

As defined in section 1, the criteria for serviceability of residential facilities gives the maximal value of allowed acceleration at top floor of 7 cm/s2 for basic wind velocities of 21 m/s or less.

Tab. 9 Review of accelerations at top floor

	without TMD		with TMD	
Method	Davenport	EN	Davenport	EN
[cm/s^2]	15.68	12.47	5.57	5.072
Diff.%	20		9	

Table 9.summarizes calculated maximum accelerations on the top floor without and with TMD. It is evident that the structure with TMD meets the criteria for human comfort according to both calculation methods.

7. Total structural damping

Table 10.provides an overview of the calculated structural damping coefficient in case of an additional source of damping on the primary structure.

Tab. 10 Total structural damping

Struct. damping		Theoretical	EN
without TMD	ξ_n	0.0200	0.0200
with TMD		0.0792	0.0200+0.1375

$*\xi_d|_{opt}$ =0.1375

It is evident that the EN is introducing large difference in comparison with theoretical calculated value.

8. Total structural damping

Aerodynamical damping is calculated by both methods for structure without and with TMD.

Tab. 11 Aerodynamical damping ξ_a

without TMD		with TMD	
0.2652 Hz		0.229 Hz	
Davenport	EN	Davenport	EN
0.0058	0.0011	0.0021	0.0014

Table 10 gives aerodynamical damping coefficients ξ_a calculated according to both methods. It is evident that there is significant difference between both methods.

9. Conclusion

From the analysis performed according to the Eurocode 1991-1-4, and taking into account the results obtained via theoretical calculation for the response of a prototype structure with parameters given in section 1, following shortcomings of the Eurocode procedure can be listed:

1. EN takes only fundamental mode of vibration and is giving greater response in the results especially in case of structure with TMD (table 5, 6),
2. EN imprecisely defines portion of the total structural modal damping resulting from installed TMD (sums modal coefficient of the primary structure with the damping of the device); total modal damping obtained theoretically differs from that calculated by the standard (table 10),
3. EN doesn't have defined procedure for calculating the maximal response of the TMD;
4. Theoretical analysis makes difference between oscillations having the same frequency but different amplitudes that affects aerodynamic coefficient; when there is structure without and with TMD, their frequencies are close, while the amplitude of oscillation of the first structure is significantly higher compared to the structure which has installed TMD (table 11).

Therefore, it can be concluded that EN doesn't have correct procedure for calculating the response of structure with TMD.

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