TMD's Optimization for Dynamic Analysis of Walkways Excited by Pseudorandom Pedestrian's Load

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Abstract. In this work, optimization of vibration absorbers (TMD) will be presented for dynamic analysis of walkways in aerospace structures excited by pedestrians. The dynamic loading used to excite the walkway will be a pseudorandom model. Using this type of loading, it is possible to cover a band of frequencies and amplitudes of possible excitation to the structure, similar to a PSD. The deterministic dynamic loading used as a basis is the Schulze loading. First, a simply supported beam representing a walkway will be modeled via a commercial FEM software to obtain modal mass, modal stiffness and frequency. Next, a two-degree-of-freedom model of the critical vibration mode of the structure close to the excitation frequency is presented, with a vertical TMD and a horizontal TMD, the latter modeled as a pendulum. Using MATLAB tools, the TMD mass ratio is optimized using as objective function the minimization of the difference between the maximum acceleration of the system and limit accelerations recommended by standards of human comfort. These optimal parameters will be carried back to the FEM model for comparisons.

Keywords: Walkways, TMD, Optimization, Dynamic Load, Pseudorandom Pedestrian Load.

1 Introduction

Dynamic loads in structures, such as wind, people walking, vehicles motions and machinery, must always be considered. This type of loading may or may not interfere with the Ultimate Limit State (U.L.S.) verification, but it may present Serviceability Limit State (S.L.S.) problems. When structure present cyclic motions due to these loads, this can also affect the U.L.S. due to the fatigue phenomenon.

Here we study SLS problems related to people's comfort when using the structure. If the structure presents great amplitude motions, even if it supports the load, people may not feel safe and avoid using the place [1]. Some examples of research on walkway vibrations can be found in [2], [3]. [4]. [5] and [6]

This article proposes to develop reliable procedures for pseudorandom dynamic analyses. In addition, we study the optimization of passive vibration control devices.

2 Dynamic Equations

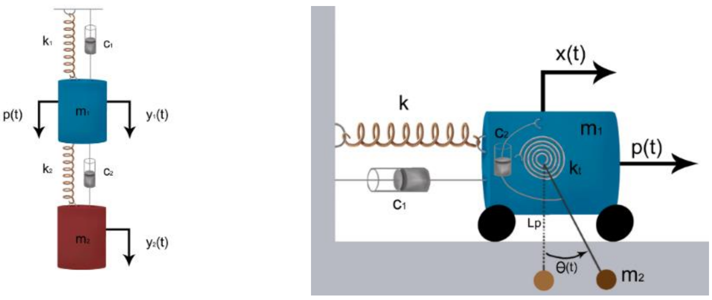

Figure 1 – 1.a – 2 DOF system for vertical vibrations. 1.b – 2 DOF system for horizontal vibrations.

Figure 1 presents 2 DOF models of walkways vibration with attached TMD devices. Their equations of motion are:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{Bmatrix} \ddot{y}_1 \\ \ddot{y}_2 \end{Bmatrix} + \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix}\begin{Bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{Bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}\begin{Bmatrix} y_1 \\ y_2 \end{Bmatrix} = \begin{Bmatrix} p(t) \\ 0 \end{Bmatrix} \tag{1}$$

$$\begin{bmatrix} m_1 + m_2 & m_2 Lp\cos(\theta) \\ m_2 Lp\cos(\theta) & m_2 Lp^2 \end{bmatrix}\begin{Bmatrix} \ddot{x} \\ \ddot{\theta} \end{Bmatrix} + \begin{bmatrix} c_1 & -m_2 Lp\dot{\theta}\,sen(\theta) \\ 0 & c_2 \end{bmatrix}\begin{Bmatrix} \dot{x} \\ \dot{\theta} \end{Bmatrix} + \begin{bmatrix} k & 0 \\ 0 & k_t + m_2 g Lp \dfrac{sen(\theta)}{\theta} \end{bmatrix}\begin{Bmatrix} x \\ \theta \end{Bmatrix} = \begin{Bmatrix} p(t) \\ 0 \end{Bmatrix} \tag{2}$$

where m1 is the modal mass, c1 its modal damping and k1 is the modal stiffness of the walkway, m2 is the mass of the TMD, k2 is the spring stiffness of the TMD, kt is the torsional stiffness of the pendulum, c2 is the damping of the TMD system, Lp is the length of the pendulum and p(t) is the dynamic loading. y are the vertical displacements of each vertical degree of freedom, x is the horizontal degree of freedom and "θ" the angle of the pendulum. Time derivatives are denoted by superposed dots.

3 Pseudorandom loading of a walkway excited by people walking

In walkways, there are two random variables, the mass and the walking frequency. According to Franco [7] the frequency of a person's step vary from 1.8 to 2.2 Hz and the mass from 0.52P to 1.35P, averaging P = 80 kg. According Hauksson [5] the step of a person vary from 1.4 to 2.4 Hz in the vertical and 0.7 to 1.2 Hz in the horizontal directions. According Matsumoto [8] and Schulze [9], the vertical frequency varies from 1.5 to 2.5 Hz. For Gaussian normal distribution, the mean frequency is 2 Hz, standard deviation 0.13 Hz [9] to 0.18 Hz [8].

For the horizontal frequency, a mean value 1 Hz and standard deviation 0.065 Hz is considered. According Lacerda [10], the average mass of a person between 18 and 67 years old is 78.82 kg, standard deviation 13.15 kg.

Starting from the deterministic formulation of Schulze [9], we create n pseudorandom loadings with parameters varying with a normal distribution at each time. In Figure 2, we consider a synchronization factor equal to 1, density of 1 person/m², a unit width of 1 m of the walkway and that the parameters vary every 2 seconds.

For pseudorandom loadings, based on the deterministic loading with horizontal frequency 2 Hz, the horizontal frequency value found randomly, from the normal distribution, will be multiplied by 2.

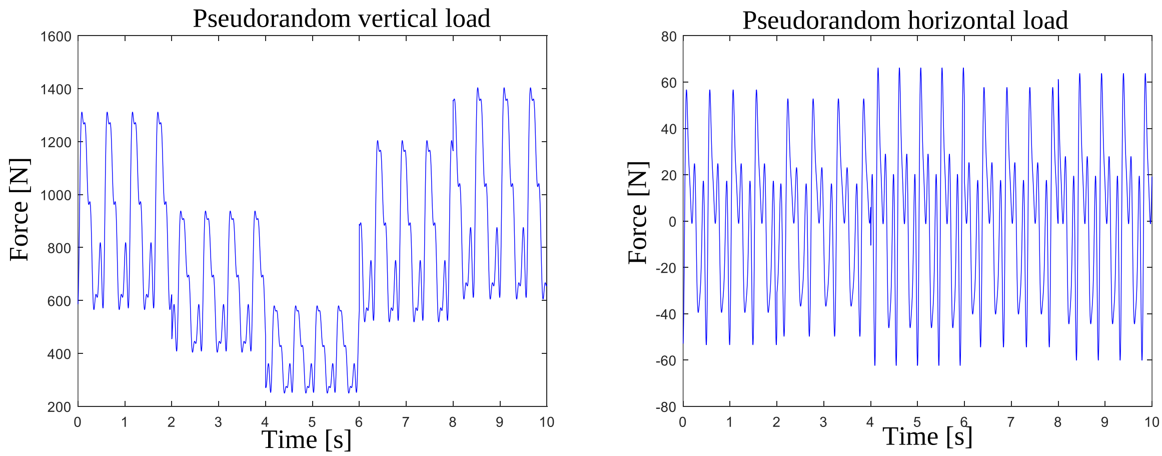

Figure 2 - Pseudorandom force as a function of time - Schulze's deterministic model [9].

4 FEM modeling of a simply supported beam with a T section

Using commercial FEM software, a T-section simply supported beam will be modeled, as shown in Fig. 3, considering material tangent modulus of elasticity 33.0 GPa, specific mass of 2.5 ton/m³ and gravity of 9 .81 m/s².

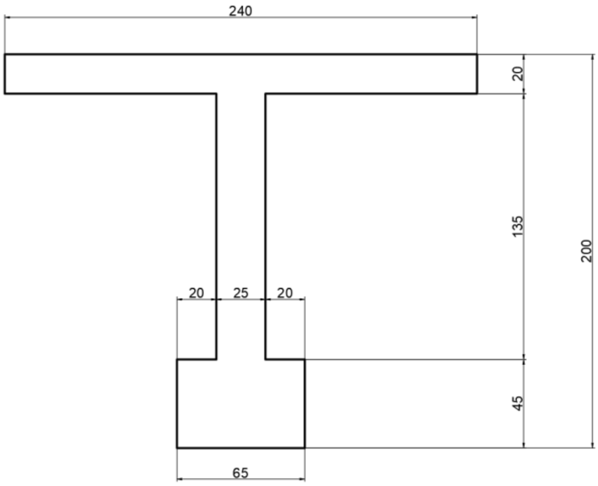

Figure 3 - Typical T section for walkways

We use the tangent modulus of elasticity since we compute accelerations in the Serviceability Limit State (S.L.S) As inertia is different in the vertical and horizontal directions, different spans will be considered for each model so that the walkways present resonance problems. For vertical motions, the span is 45.25m and for horizontal motions, the span is 36.50 m. A deck 2.4 m wide was considered (neglecting the pavement mass). The load will be applied over 1.8 m (30 cm on each side of the deck will be disregarded). The beams were modeled using 40 bar elements. Both walkways are designed so that the first natural frequency is 2 Hz.

5 Optimization for pseudo-random loading

5.1 Vertical TMD Optimization

Next, optimization considering pseudorandom loading will be presented. The objective function is the difference between the maximum acceleration of the system and the desired threshold acceleration. However, it is necessary to meet the upper and lower limits of the constraints. The limit mass ratio between the TMD and the walkway must be greater than 0% and less than 5%. According to SÉTRA [11], the maximum acceleration for people's comfort on walkways is 0.5 m/s² RMS for vertical vibration and 0.1 m/s² RMS for horizontal vibration.

The dynamic calculation was performed for each possible TMD for 0.01% mass ratio step until the desired limit acceleration is reached and the problem global minimum is found. With 1,000 randomly generated loads, we get values presented in Table 1 and Figure 4. The processing time was 18.64 hours.

Table 1 - Results for N = 1000 pseudorandom loads.

Statistics	RMS Acceleration (m/s²)	Mass ratio (%)
Average	0.4995	2.186
Standard deviation	0.0006	1.641
Variance	3.07E-07	2.695
Maximum	0.5000	18.32
Minimum	0.4964	0.00

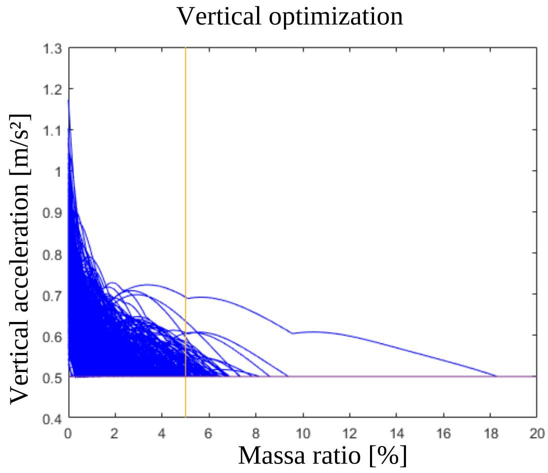

Figure 4 – Optimization for N=1000 pseudo-random loads.

Maximum and minimum RMS accelerations are less than or equal to limit acceleration 0.1 m/s^2, that is, all loads were mitigated to the desired acceleration. However, it was necessary for some TMD's to reach higher percentages than the 5% limit, but the average found for the TMD's is within the limit, 2.186% ± 1.641%.

There were loads for which it was not necessary to use TMD, for mass ratio equal to 0.

To reach an efficiency of 80%, a mass ratio 3.56% is required, that is, a TMD of 4.47 ton.

New 1,000 samples were generated with the previously calculated TMD. Results are shown in Table 2. Processing time was 6.2 minutes.

Table 2 - Results found for the dimensioned TMD.

Statistics	RMS Acceleration (m/s^2)	Mass ratio (%)
Average	0.4452	3.560
Standard deviation	0.0658	0.000
Variance	4.30E-03	0.000
Maximum	0.6911	3.560
Minimum	0.2385	3.560

According to eq. (3), 79.67% of the loads generated pseudo randomly are below the desired limit using the Z Score.

$$Z_{aRMS} = \frac{x - \mu}{\sigma} = \frac{0.50 - 0.4452}{0.0658} = 0.833 \rightarrow 79.67\% \tag{3}$$

Five new randomly generated loads were chosen for modeling in the FEM software to verify the acceleration and compatibility with the results found in the 2-DOF model, Figure 5. The adopted spring ratio is 6.97×10^5 N/m.

It is important to notice that the graphs are spread vertically due to the positive reference of the vertical axis. In MATLAB the vertical axis is positive oriented downwards and in MIDAS the positive is oriented upwards.

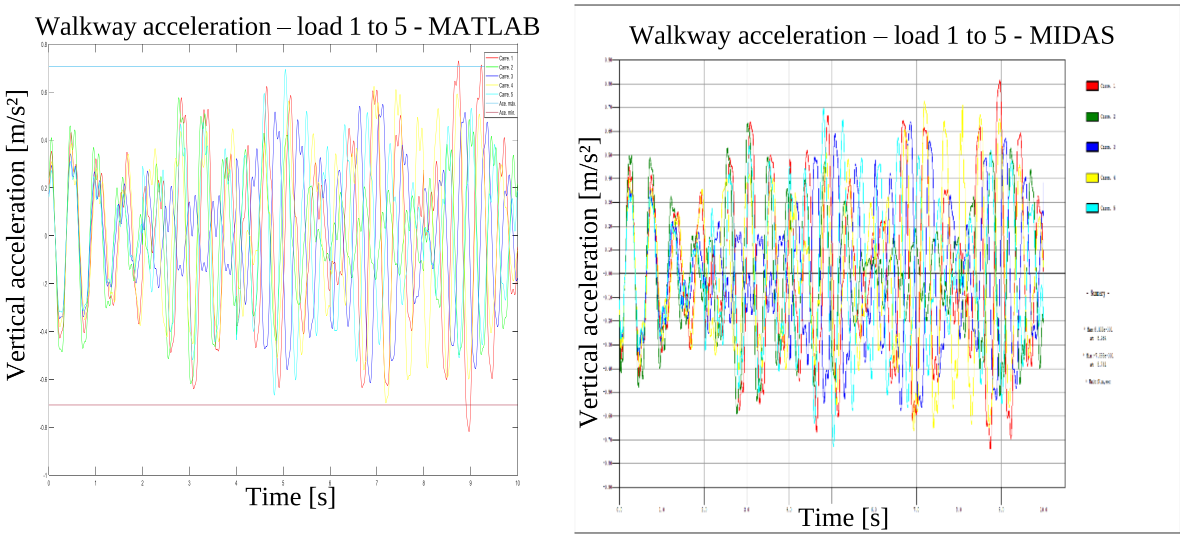

Figure 5 - Acceleration due to pseudorandom loading from 1 to 5 – MATLAB / MIDAS.

5.2 Horizontal TMD Optimization

Next, horizontal pendulum TMD optimization with pseudorandom loading will be presented. Here, the limit is the mass ratio between the TMD and the walkway greater than 0% and less than 5%. The step used was 0.10%. With a sample of 1,000 randomly generated loads, the values shown in Table 3 and Figure 6 were arrived at. The length of the pendulum is Lp = 2.00. The processing time for the optimization was 23.92 hours.

Table 3 - Results for N = 1,000 pseudorandom loads – 0.10% step.

Statistics	RMS Acceleration (m/s²)	Mass ratio (%)
Average	0.0995	8.406
Standard deviation	4.8726	4.297
Variance	2.37E-03	18.466
Maximum	0.1000	40.60
Minimum	0.0962	0.70

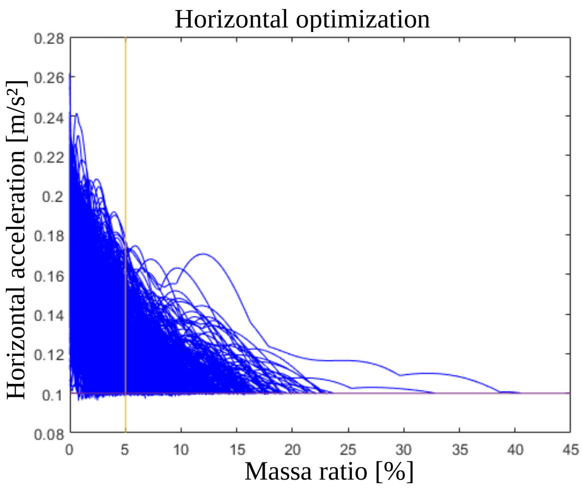

Figure 6 - Optimization for N=1,000 pseudorandom loads $\mu = 0.10\%$.

As the mean for both cases exceeded the upper limit 8.406% ± 4.297%, the percentage of cases that a mass ratio between TMD and walkways is 5.0% will be verified in eq. (4).

$$Z_{\mu,\,0.10\%} = \frac{5.0 - 8.406}{4.297} = -0.793 \rightarrow 21.48\% \tag{4}$$

A mass ratio 5.0% is required, that is, a TMD of 5.06 ton.

Running 1,000 cases again, we arrived at the following result in Table 4. Processing time of 17.15 minutes.

Table 4 - Results for N = 1,000 pseudorandom loads – μ = 5.0%.

Statistics	RMS Acceleration (m/s²)	Mass ratio (%)
Average	0.1207	5.0
Standard deviation	0.0209	0.0
Variance	4.38E-04	0.0
Maximum	0.1941	5.0
Minimum	0.0523	5.0

$$Z_{aRMS\,(\mu,\,5{,}0\%)} = \frac{0.1 - 0.1207}{0.0209} = -0.990 \rightarrow 16.67\% \tag{5}$$

As a result, the upper limit of 5.0% met 16.67% of cases, close to the expected value of 21.48%.

Five new randomly generated loads were chosen for modeling in the FEM software to verify the acceleration and compatibility with the results found with the 2-DOF, Figure 7, with spring ratio 3.12 x 106 N.m/rad.

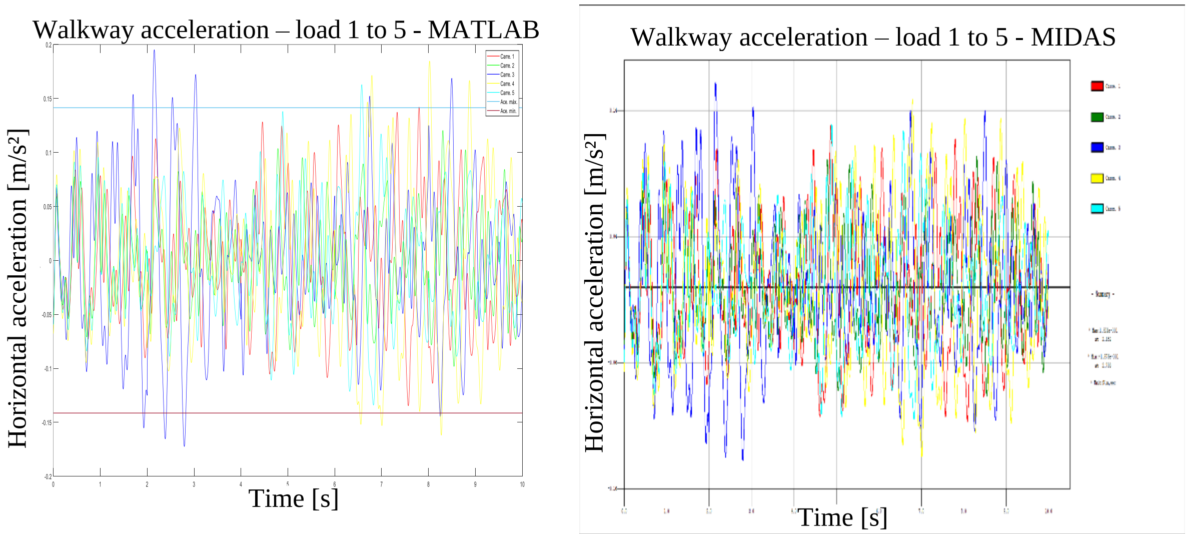

Figure 7 - Acceleration due to horizontal pseudorandom loading from 1 to 5 – MATLAB / MIDAS.

6 Conclusions

It was presented how it is possible to develop a pseudorandom load from a previously chosen deterministic load. From such loading, with the presented optimization method, it was possible to find the smallest ratio between TMD and walkways to reach a desired limit acceleration for vertical and horizontal vibrations, starting from a TMD mass-spring-damper system and with a pendular system with spring and torsion damper. Once the TMD system was dimensioned using a 2-DOF model, a FEM commercial software was used, with the vibration absorber system. As the responses found by both software were compatible, the same method can be applied in more complex structures to mitigate the vibration and optimize the passive vibration absorbers, applied in the TMD's, excited by a pseudorandom loading.

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