MAURER
Tuned Mass Dampers

Technical Information and Products
MAURER – Tuned Mass Dampers

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1. Introduction

1.1 Why are TMDs necessary?

Many tall and overhanging structures are susceptible to vibrations. Mostly these are structures with low natural damping in combination with mostly rather low natural frequency. In case such vibrations are not going to be damped:
- A normal service or walking on these structures is not possible,
- Fatigue phenomena with crack in the structure can occur, which can lead finally to the structural collapse.

For best possible reduction of structural vibrations Maurer TMDs are individually adapted to the structural requirements and characteristics. From there almost any kind of shape and size (up to 30,000 kg or even more) can be realised, as every TMD will be individually calculated and designed according to:
- critical structural natural frequency,
- kinetic equivalent structural mass, and
- appearing vibrations with regards to direction, admissible vibration amplitude and acceleration.

Fig. 1: Samples for vibration sensitive structures
1.2 Functions of a TMD

A TMD is connected to the structure (bridge, chimney, etc.) at the location where a significant or the biggest vibration is occurring. The device is consisting of a moving mass, springs and a damping element. The below sketches describe the principle of horizontal and vertical vibrations. The TMD should be placed at the location of the greatest vibration, as then the efficiency is granted to be highest possible with lowest effort.

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**Fig. 2: Principle of system and location for TMDs**

For instance in case the main system (Index H) with certain characteristics (mass = $m_H$, stiffness = $k_H$, natural damping = $d_H$) will vibrate under certain circumstances, a TMD with certain characteristics (mass = $m_D$, stiffness = $k_D$, natural damping = $d_D$) will be firmly set onto this main system. Between main system and the TMD mass a spring element and a damping element is arranged to adapt the TMD in a way, that it is mitigating and partially accommodating the vibrations of the main system.

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**Fig. 3: Working principle of TMD**

**Without external input**

- Kinetic equivalent structural mass ($m_H$)
- With eigenelasticity ($k_H$) and eigendamping ($d_H$)

**With external force input (F)**

- TMD with mass ($m_D$)
- Springs ($k_D$)
- Damping element ($d_D$)
- Implications due to external input force ($F$)
- Kinetic equivalent structural mass ($m_H$) with eigenelasticity ($k_H$) and eigendamping ($d_H$)
Introduction of the above physical values:

- **Main system:**
  - \( m_H \) = kinetic equivalent mass of structure [kg]
  - \( k_H \) = stiffness coefficient [N/m]
  - \( d_H \) = damping coefficient [N/m/s=Ns/m]
  - \( y_H(t) \) = displacement of \( m_H \) [m]
  - \( F = F(t) \) = external influence force acting onto \( m_H \)

- **TMD:**
  - \( m_D \) = moving/swinging mass of TMD [kg]
  - \( K_D \) = stiffness coefficient [N/m]
  - \( d_D \) = damping coefficient [N/m/s=Ns/m]
  - \( y_D(t) \) = displacement of \( m_D \) [m]

The absolute displacement \( y_D \) of the TMD mass is of less practical interest compared to the relative displacement of \( m_D \) to \( m_H \): \( z_D = y_D - y_H \)

The main system will react with a harmonic vibration – after a short transient phase - if an external harmonic force \( F = F(t) = F \cdot \sin \omega t \) is acting and the main system is vibrating stationary with the natural frequency \( \omega \). In case the main system is not fitted with a TMD, it is reacting with severe vibrations if the exiting frequency of the external force is correlating with the structural natural frequency, which is called resonance.

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**Fig. 4: Dynamic response of the main system with and without TMD**

The coupling of a TMD to a main system with mass \( m_D \), while considering certain rules for the optimal TMD dimensioning – spring stiffness \( (k_D) \) and damping \( (d_D) \) – results in much less reactions of the main system (see Fig. 4). The mitigation of the vibration of the main system results of counteracting displacements of the damper mass \( (m_D) \), the frequency adaptation of the springs and the simultaneous damping supplied by the special damping element.
2. Adaptation of the TMD onto the main system (structure)

2.1 Adaptation criteria

For a optimal efficiency of the TMD a accurate adaptation with respect to following issues is necessary:

- **Mass**: The mass ratio (\(\mu\)) of the TMD mass to the kinetic equivalent structural mass has to be chosen sufficiently. For small ratios (\(\mu \leq 0.025\)) big vibration amplitudes of the TMD mass relatively to the structure are resulting. In addition a small mass ratio is decreasing the effective range of the TMD (Fig. 5). The TMD mass movements are significantly smaller for bigger ratios (\(\mu > 0.025\)) and the effective range around the resonance frequency is greater too.

![Fig. 5: Frequency range with respect to \(\mu\)](image)

- **Frequency**: To achieve the best possible mitigation of the main system vibration the natural frequency of the TMD has to be calculated in a certain ratio to the natural frequency of the main system, means both frequencies must not be identical. The ration between them is called deviation \(k\) or to be out of tune respectively (Fig. 6).

\[
\kappa_{\text{opt}} = \frac{f_D}{f_H}
\]

with \(\kappa_{\text{opt}}\) = optimal deviation
\(f_D\) = natural frequency of TMD
\(f_H\) = natural frequency of main system

and according to DEN HARTOG it is valid for harmonic excitation:

\[
\kappa_{\text{opt}} = \frac{1}{1 + \mu} < 1
\]

![Fig. 6: Behaviour of main system if deviation varies](image)

- **Damping**: The necessary optimal damping \(\zeta_{D,\text{opt}}\) of the TMD has to be adapted to the chosen mass ratio \(\mu\), while following equation is valid:

\[
\zeta_{D,\text{opt}} = \sqrt{\frac{3\mu}{8 \times (1 + \mu)^3}}
\]
2.2. Consequences of a wrong or bad adaptation of the TMD

- **Too less mass ratio $\mu$:**
  For small mass ratios (ca. $\mu < 0.04$) the effective range of the TMD is limited. This means, that in case of environmental temperature changes, structural fatigue, etc., the natural frequency of the structures is changing, the efficiency of the TMD with a $\mu$ less than 4% is influenced more than for bigger mass ratio values (see Fig. 5).

  In addition small $\mu$-values result in bigger mass amplitudes (Fig. 4), which can not be realised due to a lack of available space within the structure.

  Example: The maximum relative displacement of the tuned mass for $\mu = 0.2$ is by the factor 5.36 bigger than the maximum displacement of the structure itself. For $\mu = 0.1$ this factor is 2.53 only.

- **Deviation of the optimal „out of tune“ value:**
  The optimal natural frequency of the TMD is not identical with the natural frequency of the structure! The TMD frequency is out of tune to the structural frequency by a well defined value, which is the deviation with a big influence on the final efficiency of the TMD. Therefore the structural natural frequency and the kinetic equivalent structural mass has to be known. Due to the complexity of structures and lack of knowledge of stiffness values (soil, bearings, etc.), it is usually difficult to determine exactly the natural frequency of the structure to be damped. This is valid also for the kinetic equivalent mass. In the upper part a) of Fig. 8 the value max $\frac{y}{y_{st}}$ for the three different mass ratios 0.04, 0.06 und 0.08 is shown along the relation $\frac{\kappa}{\kappa_{opt}}$ (on horizontal axis).

  Example: In case of a value of 0.8 for the relation $\frac{\kappa}{\kappa_{opt}}$ – the deviation $\kappa$ is 20% less than the optimal value – the maximum related amplitude for $\mu = 0.04$ with 29 is by factor 4 ($= 29/7.2$) bigger compared to the optimal deviation.
Deviation to optimal damping: The correctly adapted damping for the TMD mass is helping to provide best possible efficiency of the unit also. The deviation to the optimal damping has got less influence than the deviation to the optimal TMD frequency.

Example: In case the deviation of damping is within the range of ±30% to the optimal values, there is minor influence on the overall efficiency of the TMD! In Fig. 9 consequences of damping deviation (see factor on horizontal axis) on the vibration amplitudes of the structure (index y; lower curve) and on the TMD (index z; upper curve) are shown. In general significant changes in amplitudes will result due to deviations greater than ±50%. Therefore damping is important but the structure will react not such sensitive to deviations to the optimal values.

Fig. 9: Deviation of damping with resulting changes of structure and TMD amplitudes for \( \mu = 0.04 \)

2.3. Assessment of the three main adaptation criteria for a TMD

1) The most important criteria is the optimal deviation from the structural natural frequency. In case the TMD frequency including the defined value for the deviation is not optimally fitting to the structure, already small frequency deviations can result in major efficiency loss of the TMD (Fig. 8).

2) A important criteria is an effective mass ratio value granting a wide-banded range of operation (Fig. 7).

3) The damping is less important than the above two criteria, as here the biggest deviations are acceptable without creating a big loss in efficiency (Fig. 9).
3. Necessary technical data for the design of the TMD

For the dimensioning and the design of TMDs following input data are required:

a) Kinetic equivalent bridge mass, which is the vibrating mass of the structure or alternatively the mass ratio is already supplied.

b) Natural frequency of the structure.

c) Optional: Space requirements for the TMD.

d) Optional: Degree of damping for the damping element of the TMD.

The data of a) and b) have to be known, as otherwise a TMD cannot be designed. The two last data are not essentially necessary. In these data are not fixed, the design is done according to economical considerations.

4. Optimal procedure for TMD dimensioning

- Determination of critical natural values or –frequencies respectively and the kinetic equivalent structural mass.
- Evaluation of TMD type and TMD-design (number, mass, location, etc.) and design of necessary structural fixation brackets.
- Vibration test by MAURER or an University or other specialists after erection of the structure and recording of the real frequencies.
- Final TMD design based on vibration tests and manufacture of TMD.
- Installation of TMD.
- Possibly a second vibration test to verify the efficiency of the TMD.

5. Different types of MAURER-TMDs

MAURER-TMDs are always individually adapted to the structure with regard to mass, frequency, damping and available space.

The below listed types are showing up the design principles only, which are finally adapted individually to the structure.

Different TMD types:

5.1 Vertically acting tuned mass dampers: TMD-V
5.2 Horizontally acting tuned mass damper: TMD-H
5.1. Vertically acting tuned mass damper TMD-V

5.1.1 Technical description of TMD-V

**Principle of function:**
The TMD is placed at the structure’s location with the corresponding maximum of the vibration amplitude of the vertical natural frequency.
The fixation to the structure is provided normally by bolt connections to girders or structural brackets.
The TMD-V consists of a vertically swinging mass, which is placed onto steel springs. In parallel to the springs a damping element is arranged.

![Fig. 10: Principle of function of TMD-V](image)

![Fig. 11: Description of TMD-V](image)

1. Adjustable damping element => providing required damping ($\zeta$)
2. Vertical TMD - mass guide system => exact guidance of the mass in vertical direction
3. Adjustable steel mass => mass according to required mass ration ($\mu$)
4. Vertically acting steel springs with frequency ($f_D$) => adapted to eigenfrequency of the structure ($f_H$) including deviation ($K$)
5. Adjustable base plate => provides proper fixation of all components and is connecting the TMD to the structure itself

The TMD-V is individually adapted to the structure in co-operation with the contractor and the designer. Is available in all sizes (30,000 kg or even more), shapes (flat, tall, etc.) and adjustment versions (frequency, damping, etc.).
5.1.2 Practical application of TMD-V-1000/1660: Bridge Forchheim - Germany

TMD-Data:

a) TMD-mass: 1000 / 1660kg
b) frequency: 1.255 / 2.7 Hz
c) damping: 3280 / 4585 Ns/m

Fig. 12: Bridge Forchheim

Fig. 13: Side view

Fig. 14: Installed TMD-V

Fig. 15: Cross section through TMD-V
5.1.3 Practical application of TMD-V-550/725/1200: Abandoibarra Bridge
Bilbao - Spain

TMD-Data:
   a) TMD-mass:  550 / 725 / 1200kg
   b) frequency:  1,85 / 2,32 /2,78 Hz
   c) damping:   681 / 815 / 1241 Ns/m

Fig. 16: Abandoibarra Bridge

Fig. 17: Side and top view

Fig. 18: Cross section through TMD-V

Fig. 19: Installed TMD-V in bridge rail
5.2. Horizontally acting tuned mass damper TMD-H

5.2.1. Technical description of TMD-H

**Principle of function:**
The TMD is placed at the structure’s location with the corresponding maximum of the vibration amplitude of the horizontal natural frequency. The fixation to the structure is provided normally by bolt connections to girders or structural brackets. The TMD-H is consisting of a horizontally swinging mass, which is placed between steel springs. In parallel to the springs a damping element is arranged.

![Fig. 20: Principle of function of TMD-H](image)

1 = Adjustable damping element => providing required damping ($\ddot{z}$)
2 = Adjustable steel mass => mass according to required mass ratio ($\mu$)
3 = Horizontal TMD-mass guide system => exact guidance of the mass in horizontal direction
4 = Horizontally acting steel springs with frequency ($f_\text{D}$) => adapted to eigenfrequency of the structure ($f_\text{H}$) including deviation ($K_f$)
5 = Adjustable base plate => provides proper fixation of all components and is connecting the TMD to the structure

![Fig. 21: Description of TMD-H](image)

The TMD-H is individually adapted to the structure in co-operation with the contractor and the designer. Is available in all sizes (30,000 kg or even more), shapes (flat, tall, etc.) and adjustment versions (frequency, damping, etc.).
5.2.2 Practical application for TMD-H-1900: Port Tawe footbridge in Swansea – United Kingdom

TMD-Data:
- a) TMD-mass: 1900kg
- b) Frequency: 1,159 Hz
- c) Damping: 3876 Ns/m

Fig. 22: Port Tawe Footbridge

Fig. 23: Side and top view of bridge

Fig. 24: Installed TMD-H

Fig. 25: Port Tawe bridge deck
6. Testing and recording of functions

Each MAURER TMD is tested before leaving the workshop, means the proper function is checked and documented:

- The moving capability of the TMD is checked, means the TMD mass has to move without significant internal friction within the guide system (Fig. 26).
- The specific spring frequency is recorded with a special sensoric and electronic system (Fig. 27).
- Das Dämpfungselement wird mit entsprechenden Prüfmaschinen getestet.

With special testing rigs the damping element is tested (Fig. 28+29).

- After total assembly of TMD a function test is carried out.