Wolfhard Zahlten

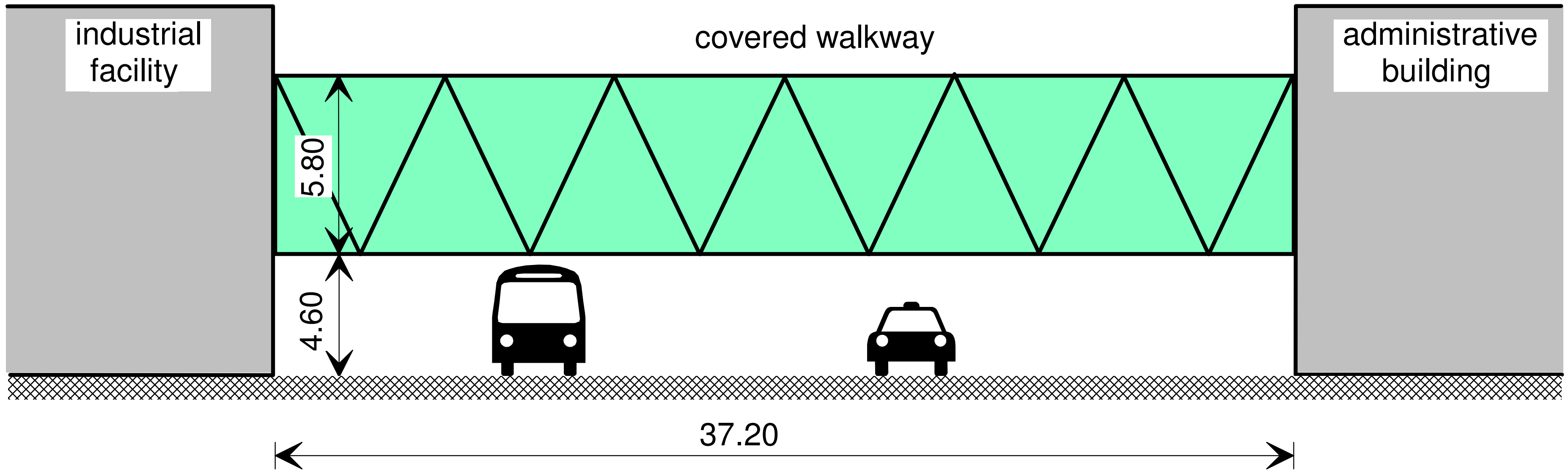
Tuned Mass Dampers in the Design of Light-Weight Structures

Theory, Numerical Simulation, Application

Lecture 05
Practical Applications

Eusani & Zahlten Engineering Consult
Solingen

Project 1: Industrial Walkway



Two buildings of a logistics company are to be connected by a covered walkway. Within the walkway there shall be located a cafeteria which shall also be used for parties, so that human excitation by party guests is to be considered.

Scope of the Study - Problems

The structure was problematical since it was originally designed exclusively with respect to maximum stresses and displacements under *static loads*. The *dynamic nature* of the party loads was only later, after the design was finished, recognized by the check by an independent external engineer.

Then EZI was asked to check the dynamics of the walkway by numerical simulations of the human excitation and, if necessary, develop remedies to reduce the amplitudes.

One general problem in structural dynamics is the strong dependency of the response on the eigenfrequencies in case of resonance and the dependency of the eigenfrequencies on parameters which are only known with a certain fuzziness.

Specifically in the present case there was also the problem that the party loads are not regulated in codes and can also only be defined with a certain fuzziness according to literature.

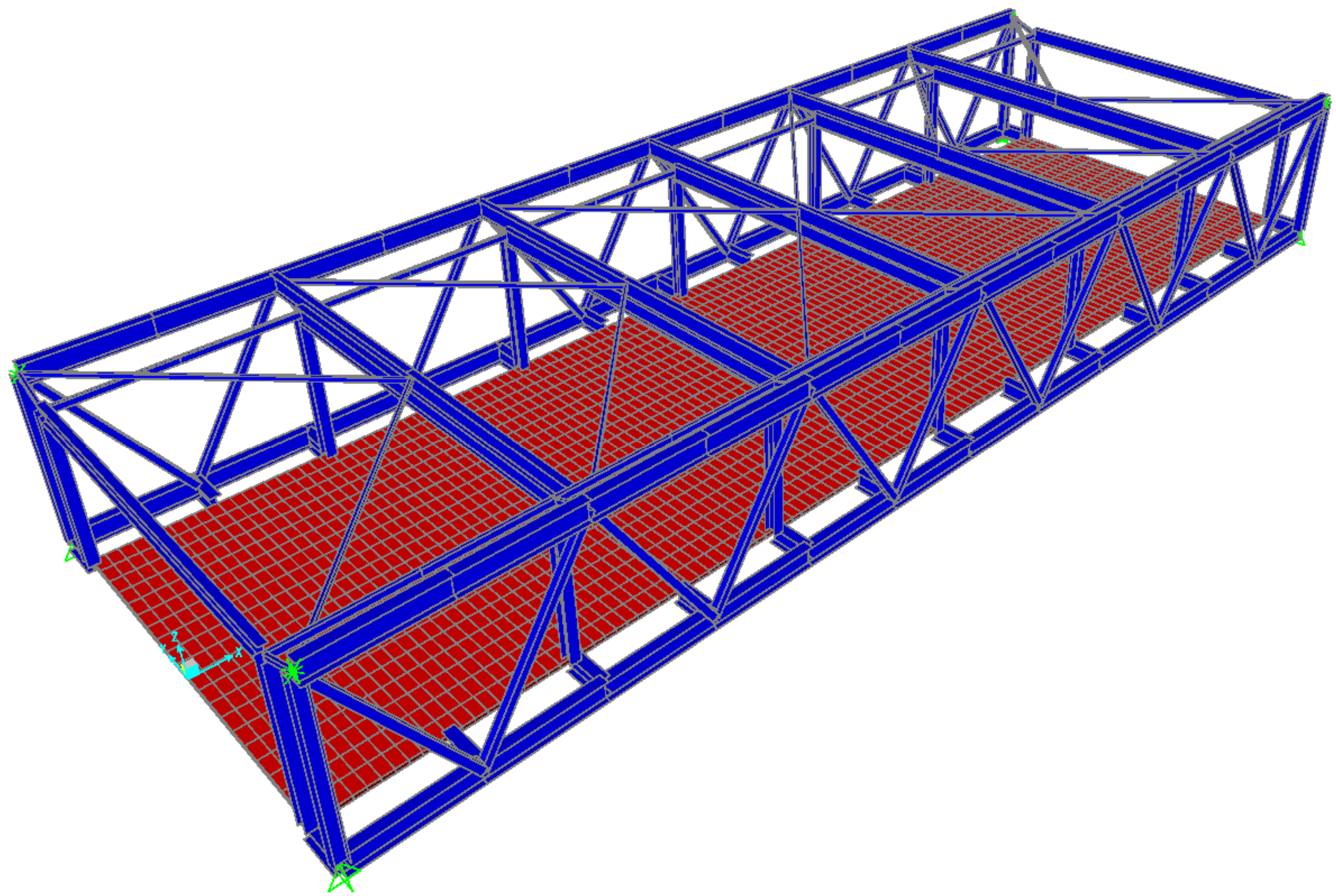
Simulation Strategy

In order to come to a thorough understanding of the structural behaviour and specifically of the sensitivities connected to the fuzziness of certain parameters, several *scenarios* were studied:

- Parameters influencing the eigenfrequencies:
  - rigidly supported walkway,
  - elastically supported walkway (elasticity of the soil),
  - influence of human masses.
- Different party scenarios which each produce a worst case for the different excited modes:
  - Varying the frequencies with which people dance and jump
  - Varying the area where the dancing and jumping takes place

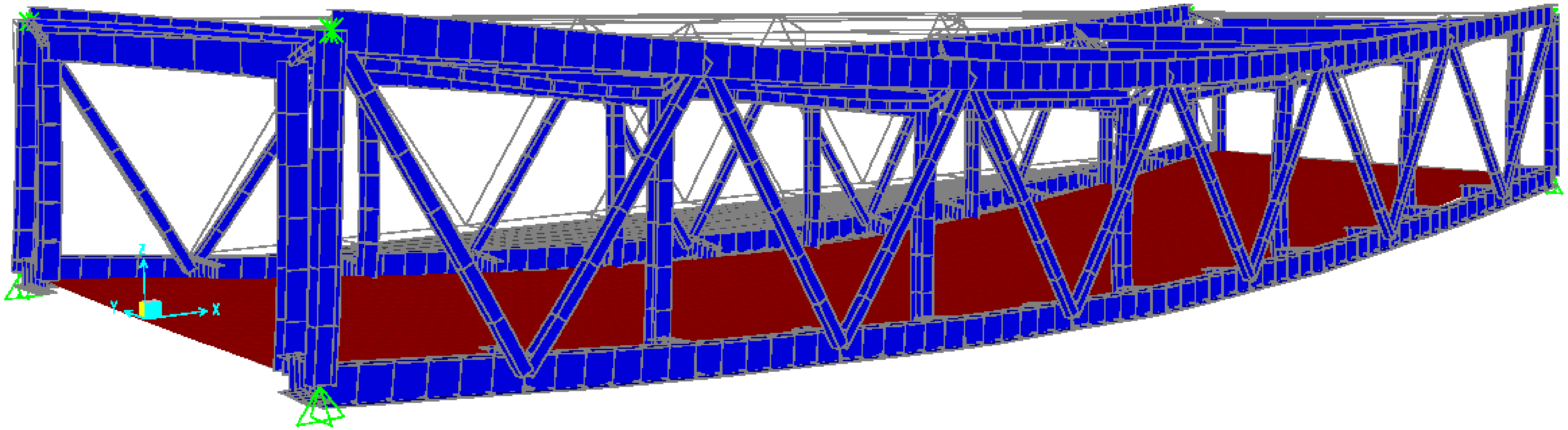
Based on these scenarios, an optimized design for a TMD was developed which allows a fine-tuning after erection.

Numerical Model



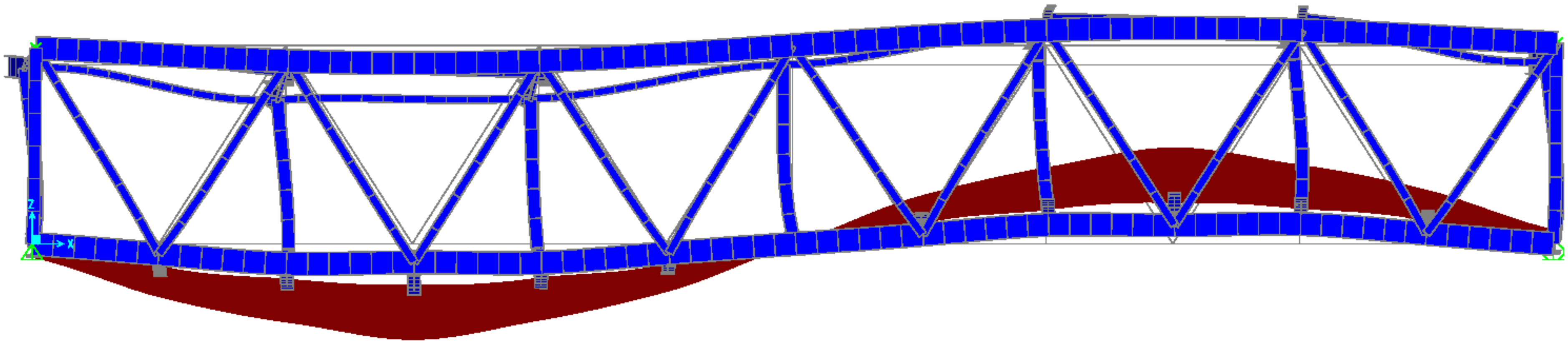
Analyses were performed with SAP2000

First Global Bending Mode



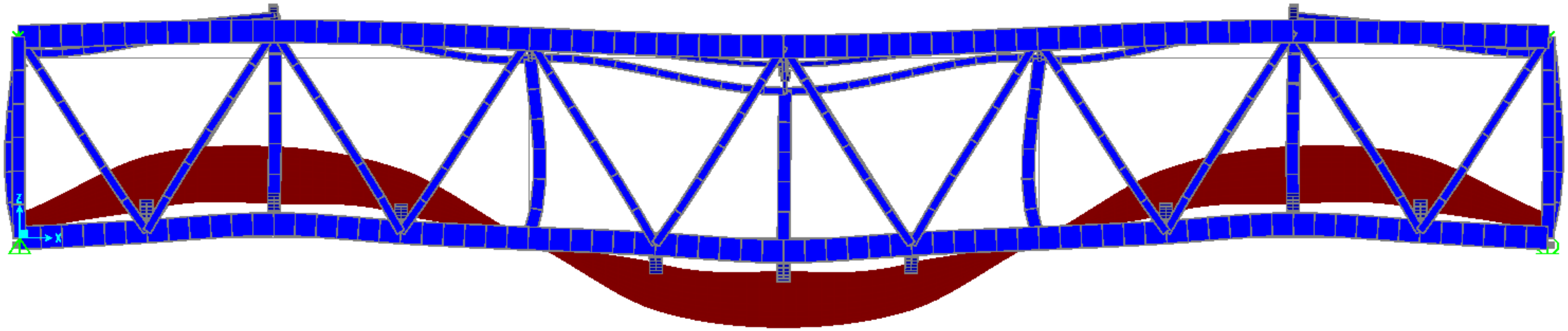
frequencies: 3.08 Hz – 3.43 Hz

Second Bending of the Slab



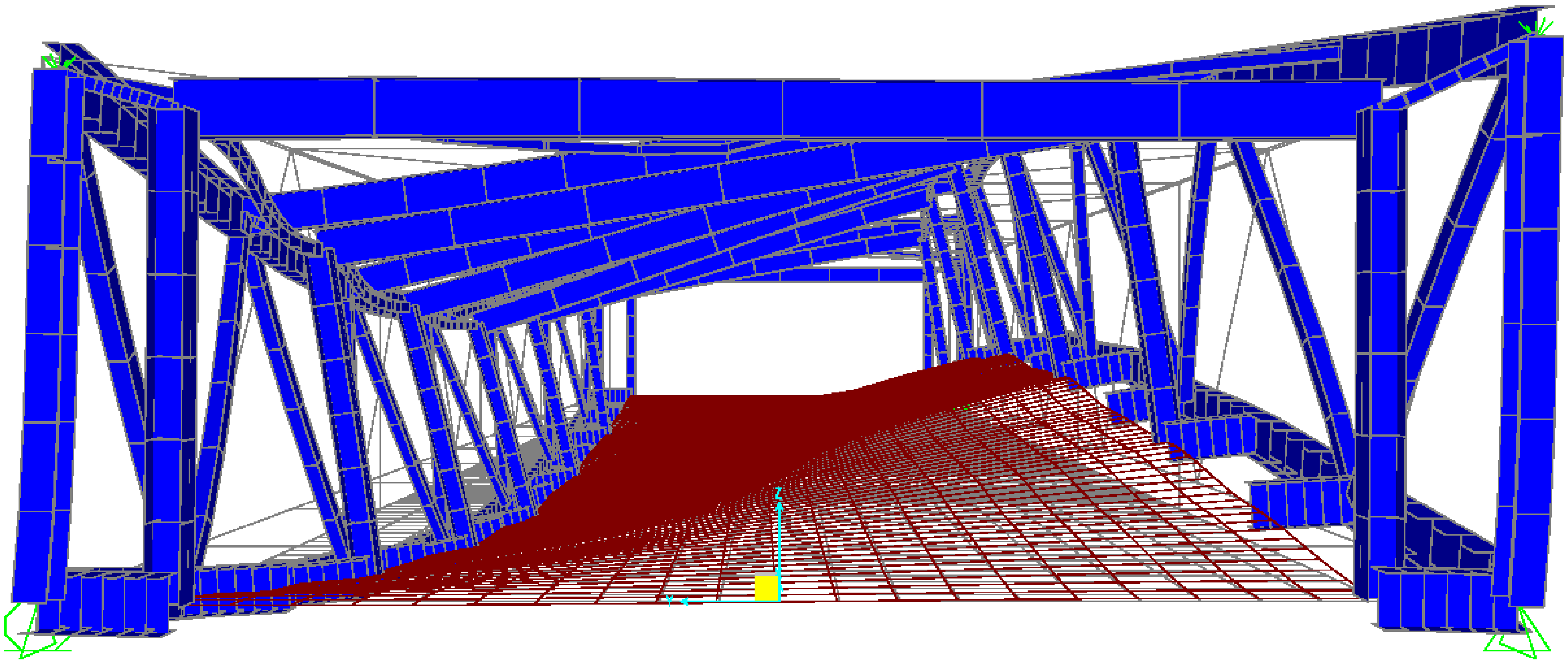
frequencies: 5.02 Hz – 5.54 Hz

Third Bending of the Slab



frequencies: 6.12 Hz – 6.42 Hz

First Global Torsion



frequencies: 5.84 Hz – 6.68 Hz

Excitation by Dancing and Jumping

Dancing and jumping are nearly periodic loads which can be approximated by a Fourier series with 3 terms. The frequencies of the individual harmonics are empirically given by:

harmonics	dancing	jumping
f_1 [Hz]	1.5 - 3.0	1.6 - 3.4
f_2 [Hz]	3.0 - 6.0	3.2 - 6.8
f_3 [Hz]	4.5 - 9.0	4.8 - 10.2

The eigenfrequencies of the first 4 modes are such that these modes can come into resonance with one of the load harmonics. Therefore large amplitudes can be expected which have to be computed by time domain simulations.

Excitation by Dancing and Jumping

Deterministic load model for an equivalent surface load

$$p(t) = \frac{n \cdot G}{A} Co(n,i,K) \cdot \sum_{i=1}^{3} \{1 + \alpha_i \sin(\omega_i - \varphi_1\}, \quad \omega_i = i \cdot 2\pi f_1$$

Agu & Kasperski: A random load model for loads induced by coordinated movements of crowds, Eurodyn 2005, Proceedings, pp 479-484.

n:	number of persons
G:	average weight of the standard person
A:	load area
Co:	coordination parameter
K:	number of how many times the event is repeated
α_i, φ_i:	Fourier coefficients and phases

Assumptions for the Walkway

The true loading in the future can only be guessed at and cannot be regulated in a code. It must be fixed in discussion with the owner who knows (or should know, or least can define his expectations) the use his walkway will get during its lifetime.

It has been assumed:

- up to 300 persons take part in a party
- dancing: 75 persons are assumed to dance in rhythm with the music
- jumping: 25 persons are assumed to jump in rhythm with the music
- these events occur 50 times during the lifetime of the walkway
- the Fourier coefficients are to be taken from Kasperski

Evaluation According to ISO10137

Problem:

- maximum accelerations might occur only during a short time
- the human perception of maximum accelerations depends on their frequencies

Therefore the necessity arises to define **effective values** which take into account the relative duration and the dependency on frequency.

effective acceleration according to ISO10137

$$\ddot{v}_{eff} = \sqrt{\frac{1}{T_{tot}} \int_{o}^{T_{tot}} \ddot{v}^2(t)dt}$$

threshold values for 4 Hz < f < 8 Hz:

comfort threshold: $1.0 \ m/s^2$

panic threshold: $2.0 \ m/s^2$

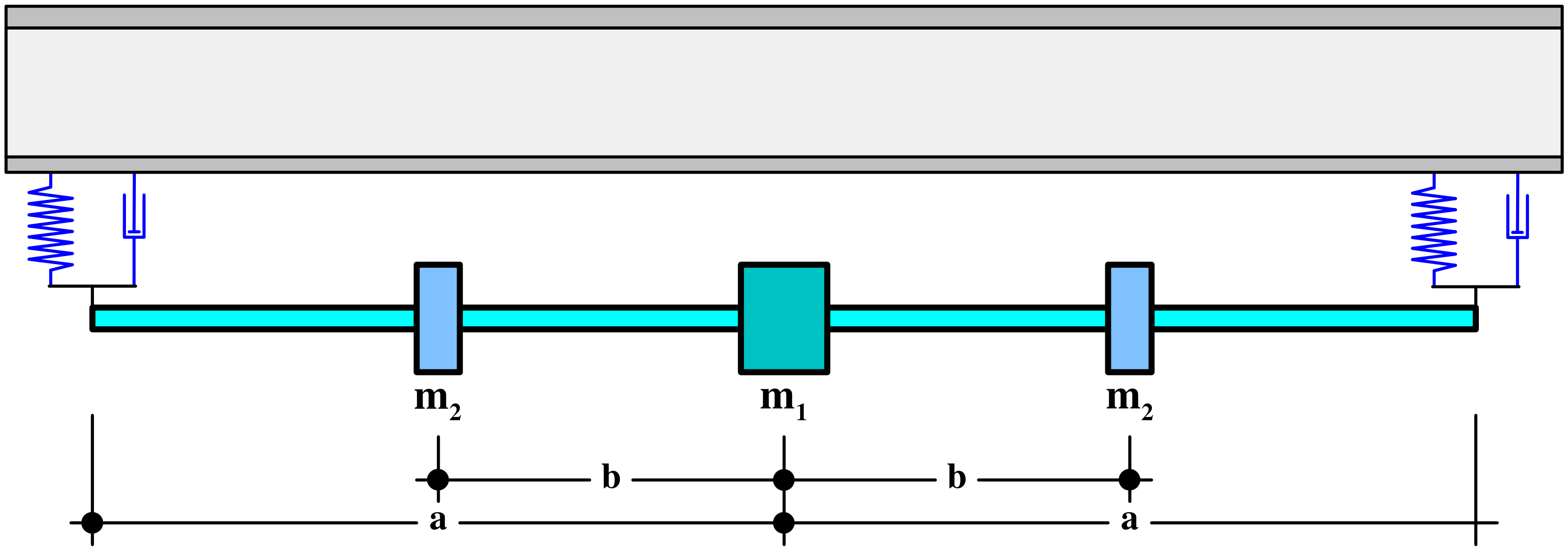
ISO 10137, cited from: Agu & Kasperski: A random load model for loads induced by coordinated movements of crowds, Eurodyn 2005, Proceedings, pp 479-484.

Original Structure without TMD

accelerations in [m/s^2] for dancing			
excited mode	node	effective	maximum
bending 1	857	3.84	5.95
bending 2	854	2.68	4.29
bending 3	853	1.39	2.20
torsion 1	2056	2.12	3.53

accelerations in [m/s^2] for jumping			
excited mode	node	effective	maximum
bending 1	857	8.08	14.07
bending 2	854	6.73	15.17
bending 3	853	4.54	7.36
torsion 1	2056	7.29	12.72

TMD for Mode B1 and T1



The TMD consists of two seesaws which work both for the vertical displacement and the torsional rotation of the walkway. They are located almost in midspan. The 3 masses must add up to the desired percentage of the modal mass for mode 1 and the combination of m_2/b can be chosen such that the resulting moment of inertia gives the desired frequency. The effectiveness must be checked by time-domain simulations.

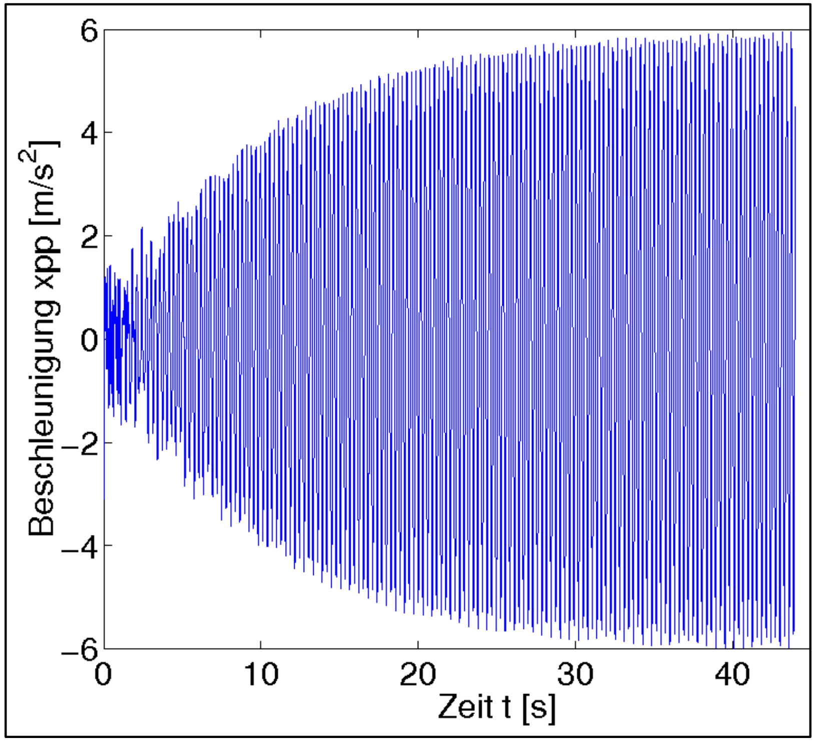
Example for a Seesaw

The footbridge Kehl-Strasbourg over the river Rhine had to be stabilized by TMDs against bridge flutter and pedestrian excitation. The TMD design was done by a collaboration between EZI and PSP Technologien Aachen

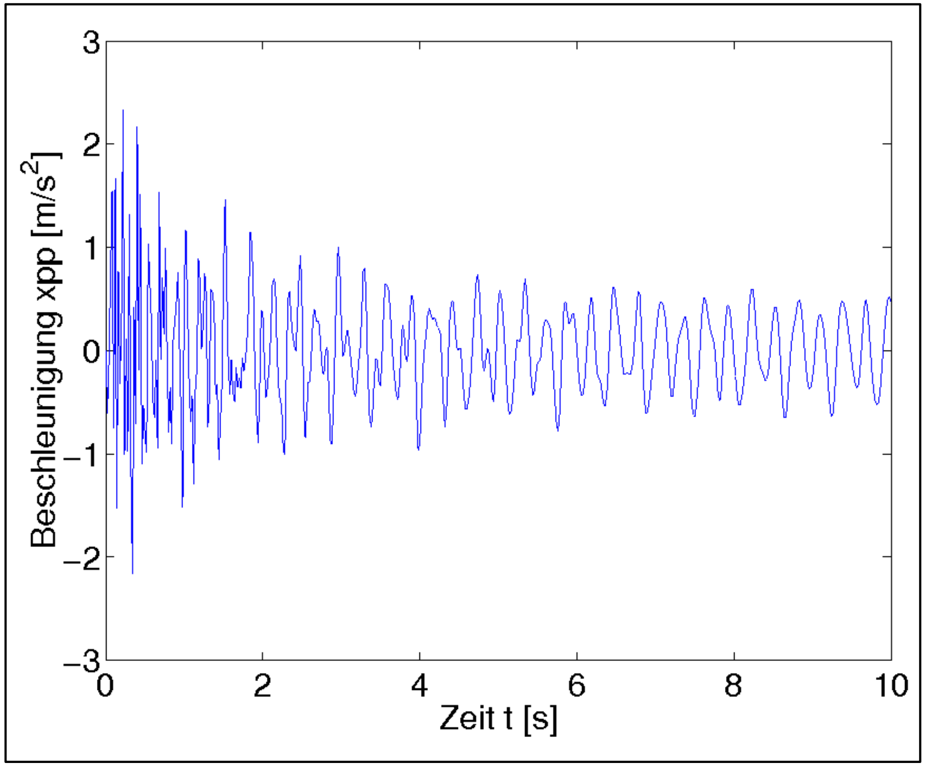
Effect of TMD-1

excitation: dancing

without TMD-1



with TMD-1



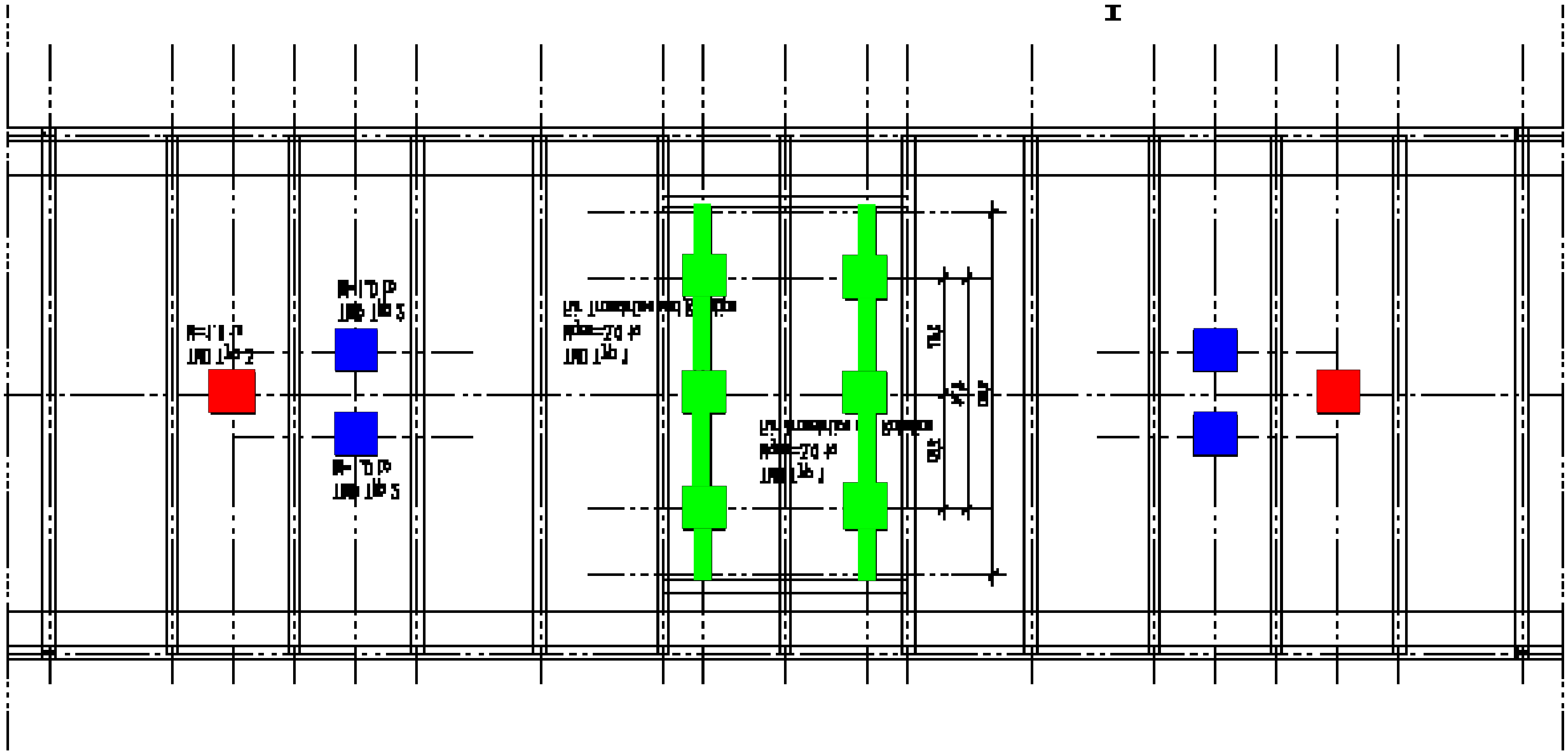
Effect of TMD-1

accelerations in [m/s²] for dancing					
		without TMD		with TMD-1	
excited mode	node	effective	maximum	effective	maximum
bending 1	857	3.84	5.95	0.39	1.01
bending 2	854	2.68	4.29	1.70	2.78
bending 3	853	1.39	2.20	0.69	1.36
torsion 1	2056	2.12	3.53	0.19	0.60

accelerations in [m/s²] for jumping					
		without TMD		with TMD-1	
excited mode	node	effective	maximum	effective	maximum
bending 1	857	8.08	14.07	1.40	2.78
bending 2	854	6.73	15.17	3.33	5.31
bending 3	853	4.54	7.36	2.31	3.95
torsion 1	2056	7.29	12.72	0.97	1.32

TMDs for modes B2 and B3

The TMDs for B2 and B3 are simple mass-damper-spring systems



blue: TMD for bending mode 2
red: TMD for bending mode 3

Effects of TMD-2 and TMD-3

accelerations in [m/s²] for dancing						
excited mode	without TMD		with TMD-1+2		with TMD-1+2+3	
	effective	maximum	effective	maximum	effective	maximum
B1	3.84	5.95	0.33	0.56	0.32	0.55
B2	2.68	4.29	0.77	1.49	0.59	1.14
B3	1.39	2.20	0.55	0.95	0.27	0.49
T1	2.12	3.53	0.17	0.49	0.21	0.50

accelerations in [m/s²] for jumping						
excited mode	without TMD		with TMD-1+2		with TMD-1+2+3	
	effective	maximum	effective	maximum	effective	maximum
B1	8.08	14.07	1.35	2.45	1.35	2.00
B2	6.73	15.17	1.04	2.36	0.78	1.80
B3	4.54	7.36	1.79	3.37	0.87	1.91
T1	7.29	12.72	0.94	1.32	1.02	1.43

Results and Recommandations

- Without TMDs the amplitudes would be too large. The original design would have been unsafe.
- The response depends on the damping. Depending on this unknown quantity, one or more modes must be restrained by TMDs.
- There is hope that – the damping being large enough – not all TMDs are required.
- This can only be decided by experiments after erection. To preserve the option of installing the TMDs, the load bearing construction should be designed for the static and dynamic loads the TMDs transmit into it.
- The TMDs can be fine-tuned at installation for the true, experimentally measured eigenfrequencies.

Project 2: Modern Bell Tower

Modern bell tower (campanile) in steel with welded connections (extremely low damping).

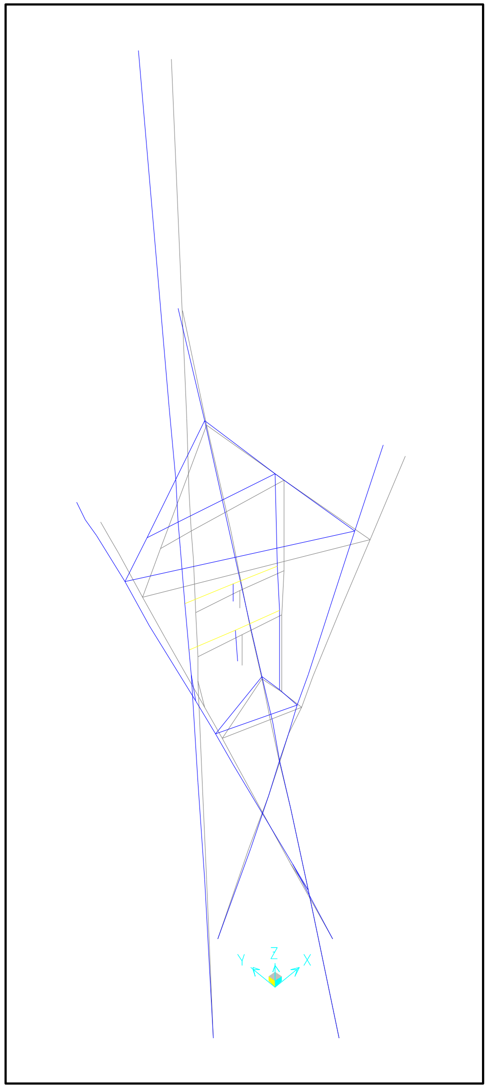
Large deformations have been observed by church goers who became afraid to go near the campanile.

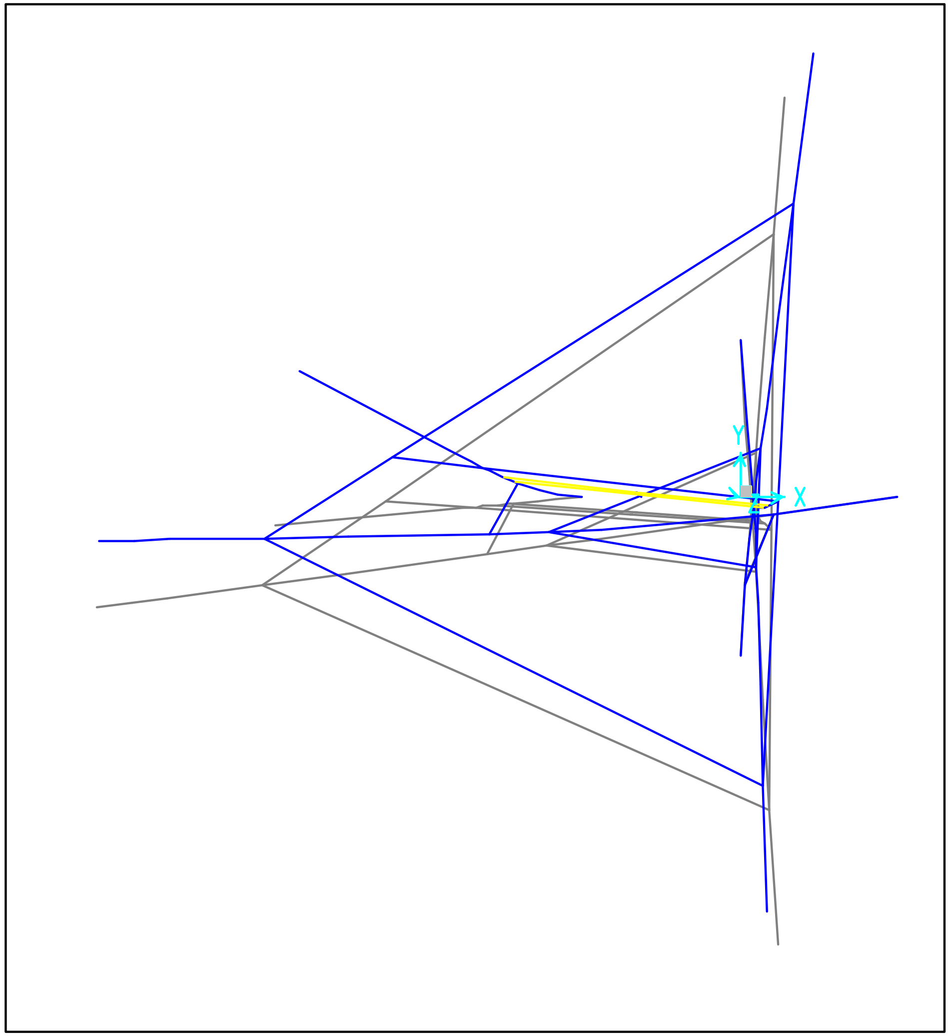
The original design was exclusively for static loads; no dynamic analysis has been performed.

The architect refused to change the appearance of the tower, e.g. by cable stays.

Eigenmode 1

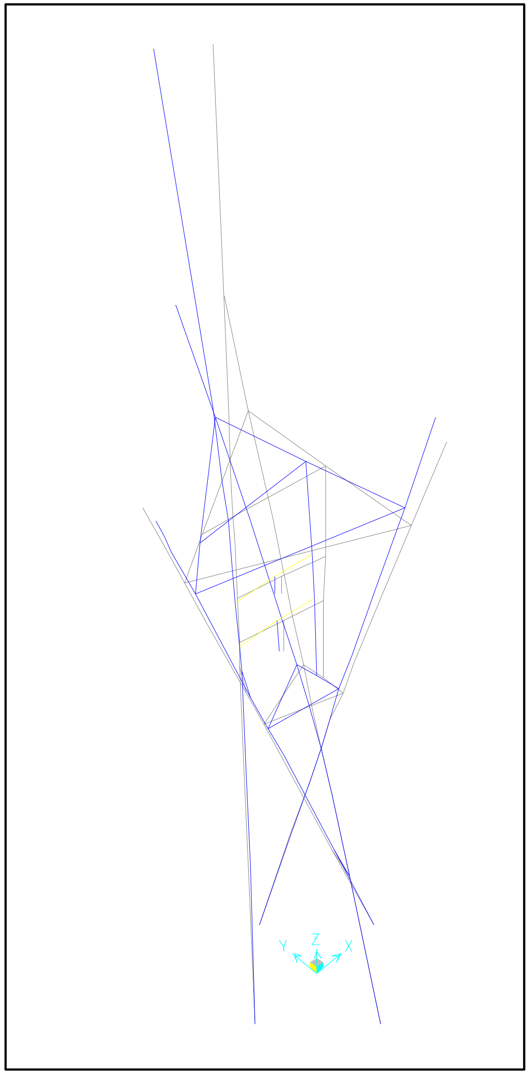
mode 1: f = 1.90 Hz

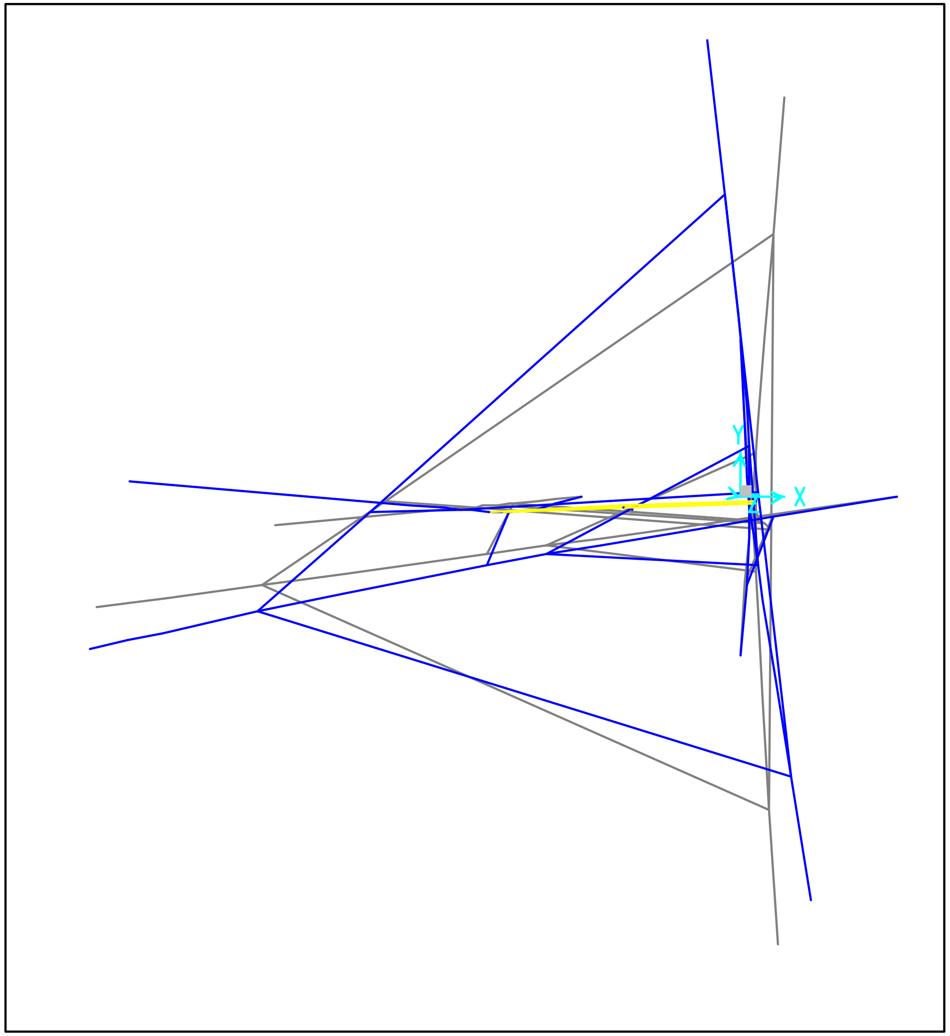




Eigenmode 2

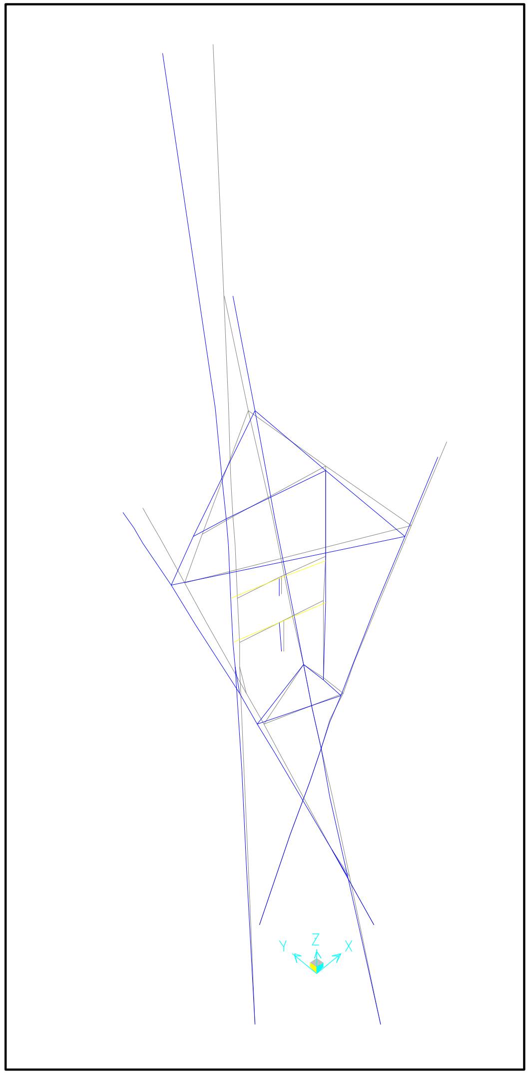
mode 2: f = 3.42 Hz

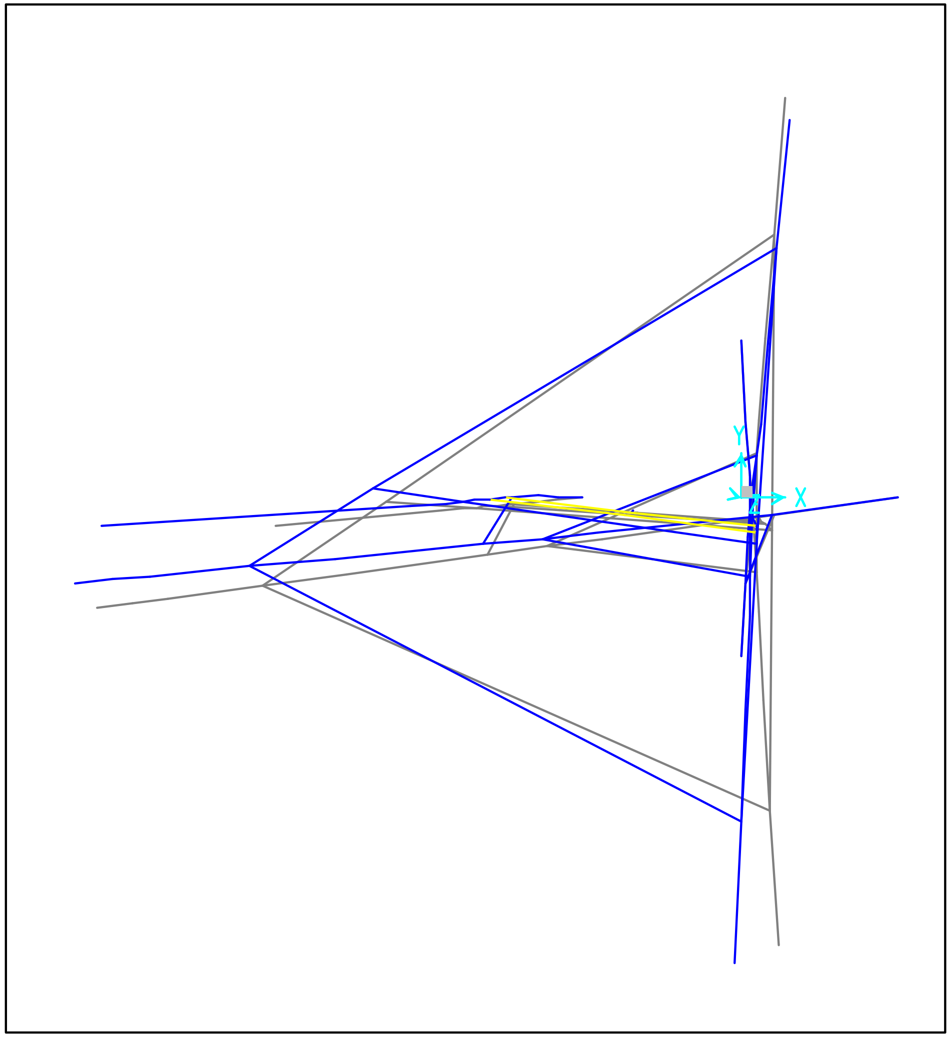




Eigenmode 3

mode 3: f = 3.77 Hz





Excitation by Ringing Bells

The ringing bells produce periodic loads which can be approximated by a Fourier series with 3 terms. The frequencies of the individual harmonics are recording in the so-called „bell book" and are in the present case:

bell no.	harmonic 1	harmonic 3	harmonic 5
1	0.567 Hz	1.701 Hz	2.835 Hz
2	0.665 Hz	*1.995 Hz*	3.325 Hz

The German code suggests that a frequency gap of about 20% (numerical analysis) or 10 % (measurements) should exist between the relevant eigenfrequencies and the bell harmonics. Here we have hit the 2nd bell harmonic of bell 2 bullseye with the eigenfrequency. This explains the large observable amplitudes.

Scope of the Study

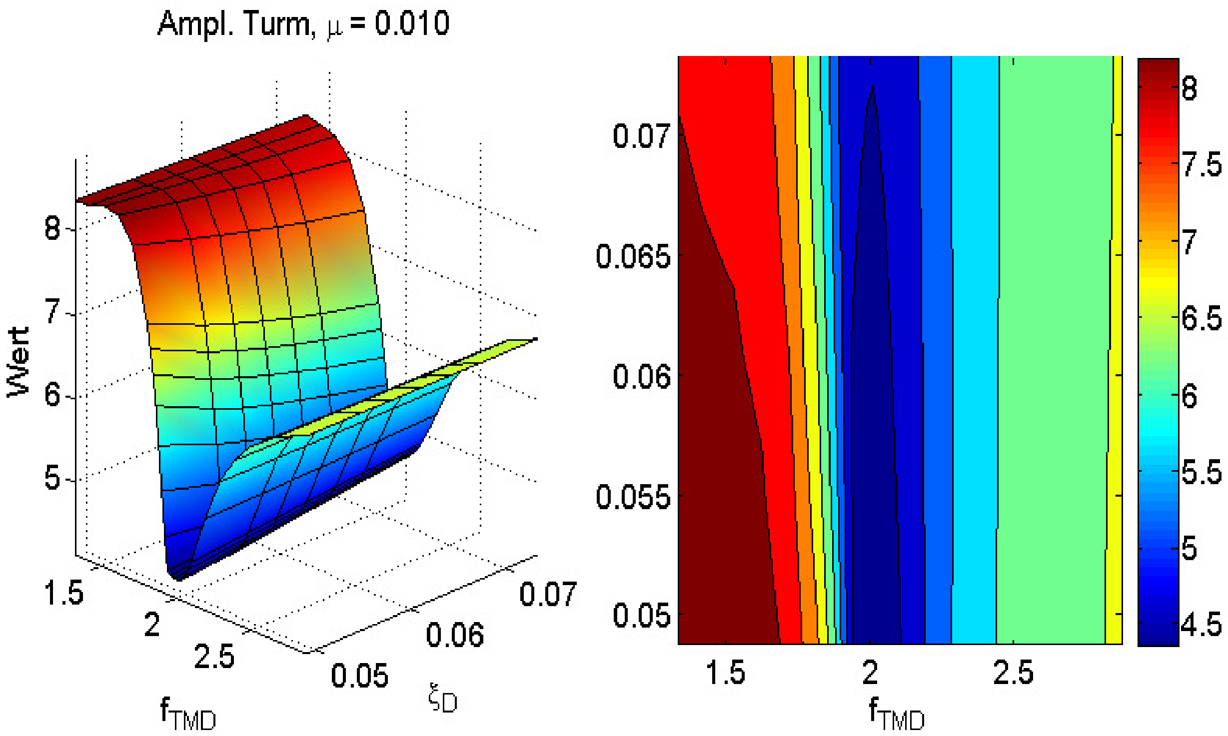
The violation of the recommended frequency difference does not mean that the design is not permissible. It only needs be proven by suitably accurate analyses that the resulting displacements and stresses remain within acceptable bounds, especially that the durability is not compromised by the alternating stress cycles. This has been done by us with the result that the tower satisfies all stress criteria, yet just barely (this has been plain luck!).

For the displacements there do not exist, for such types of structures, any threshold values in the German codes. Such values limiting the displacements exist for buildings to ensure their serviceability, but a bell tower is no building in the classical sense, so it is not covered by those codes.

So additionally it was studied in how far TMDs were able to reduce the vibrations.

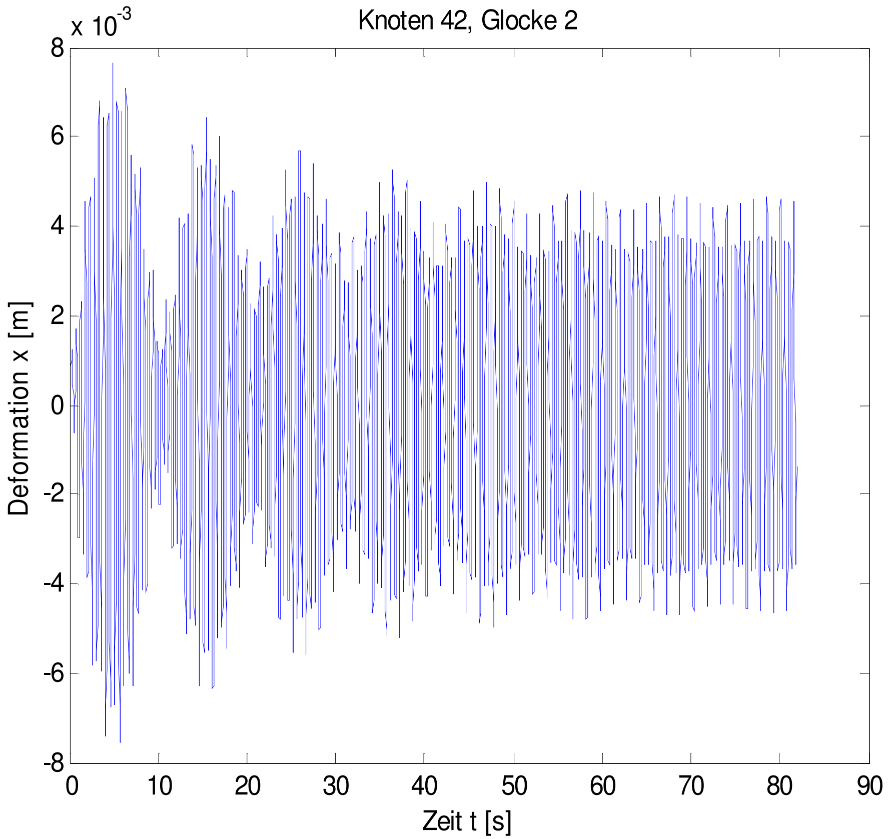
TMD1 Against Bell 2 (3rd Harmonic)

It was attempted to design a TMD for the first eigenmode to damp out the effect of the second harmonic of the second bell. First it was optimized as 2-dof system.

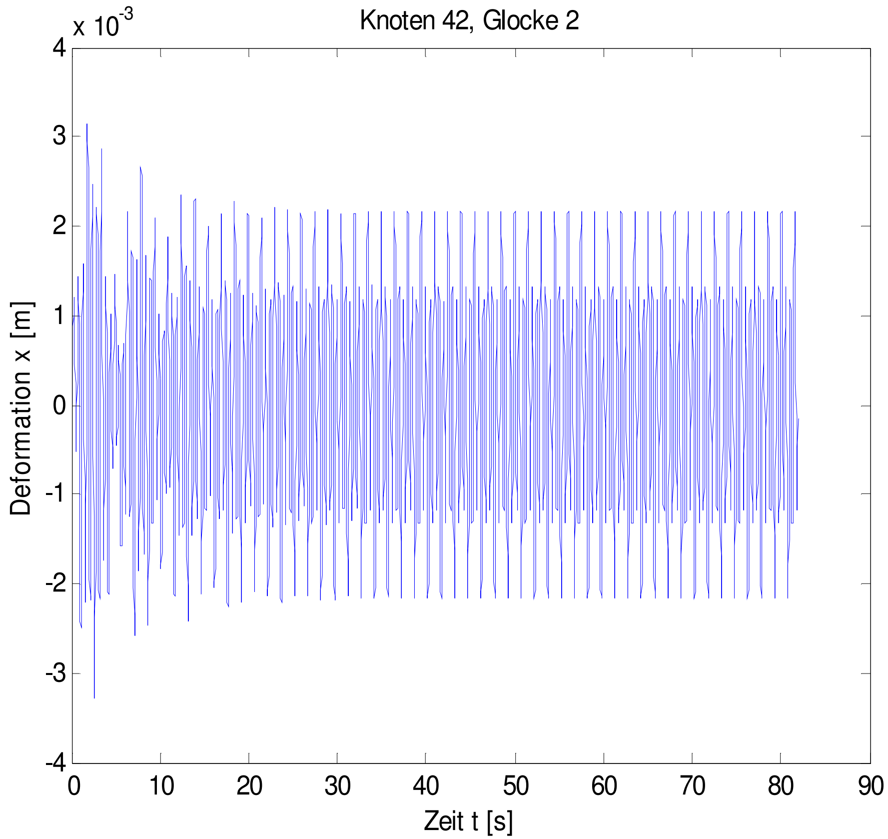


Effect of the TMD: Bell 2

without TMD



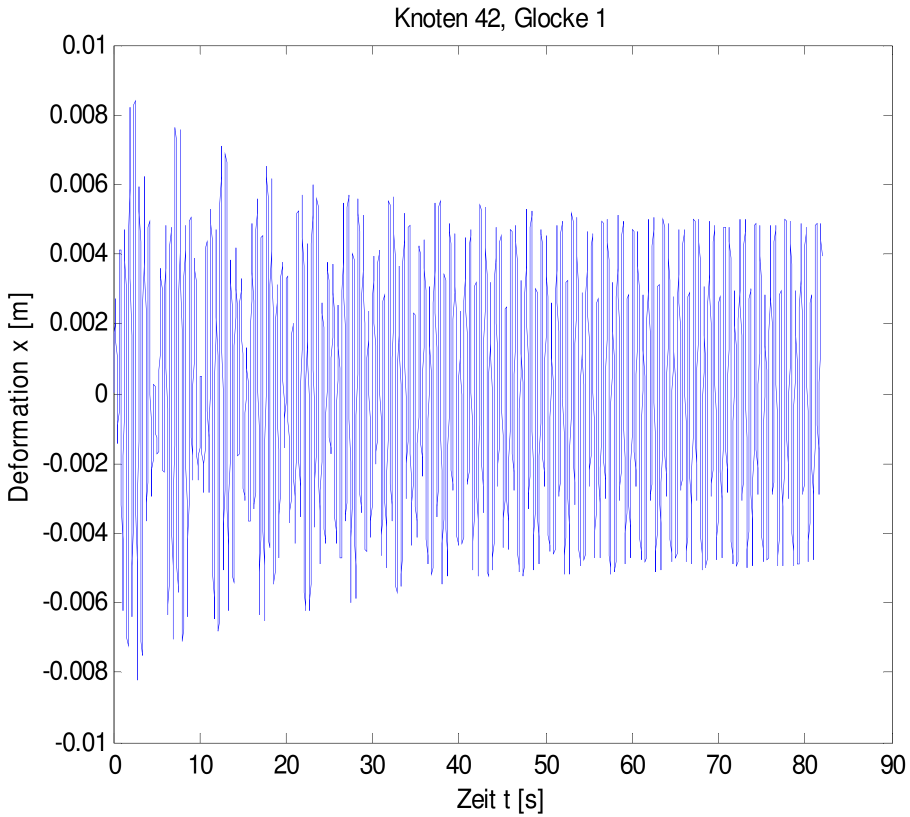
with TMD1

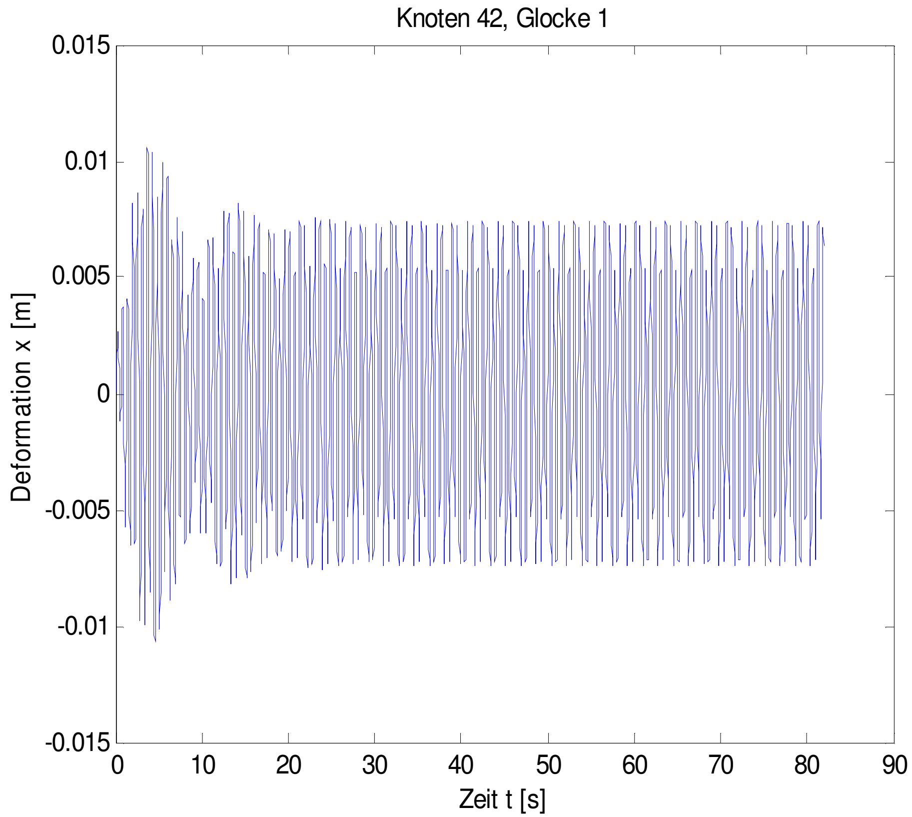


The total response is the result of all harmonics acting on all eigenmodes. So the overall effectiveness is smaller than in the purely harmonic case: the reduction is only by a factor of 2.

Effect of the TMD: Bell 1

without TMD	with TMD1

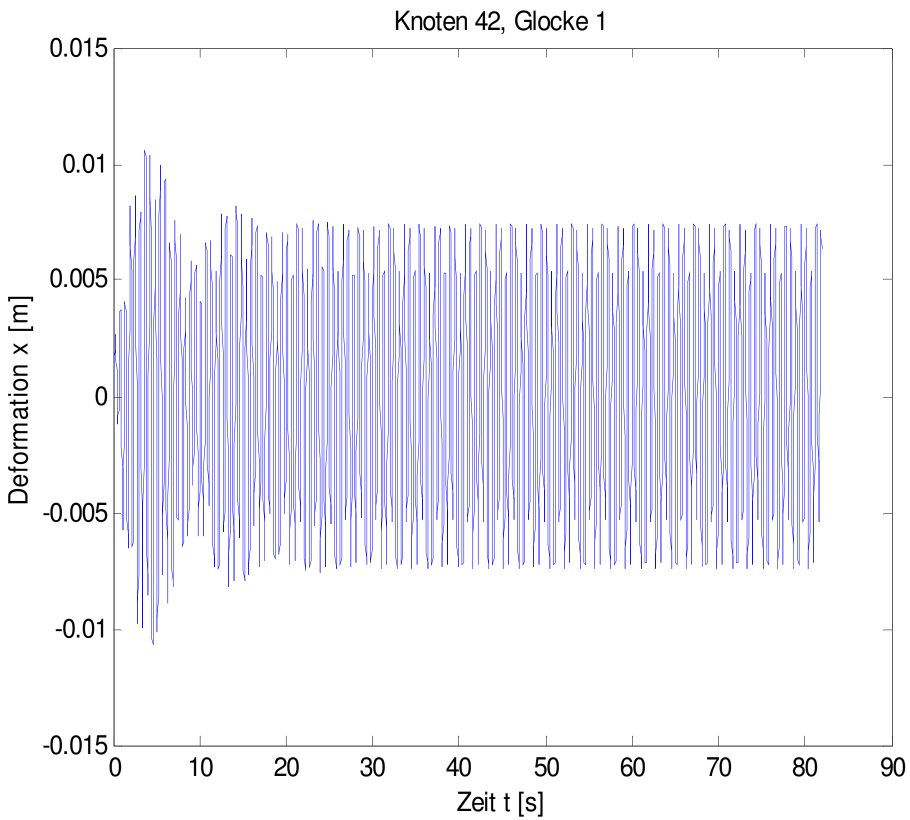




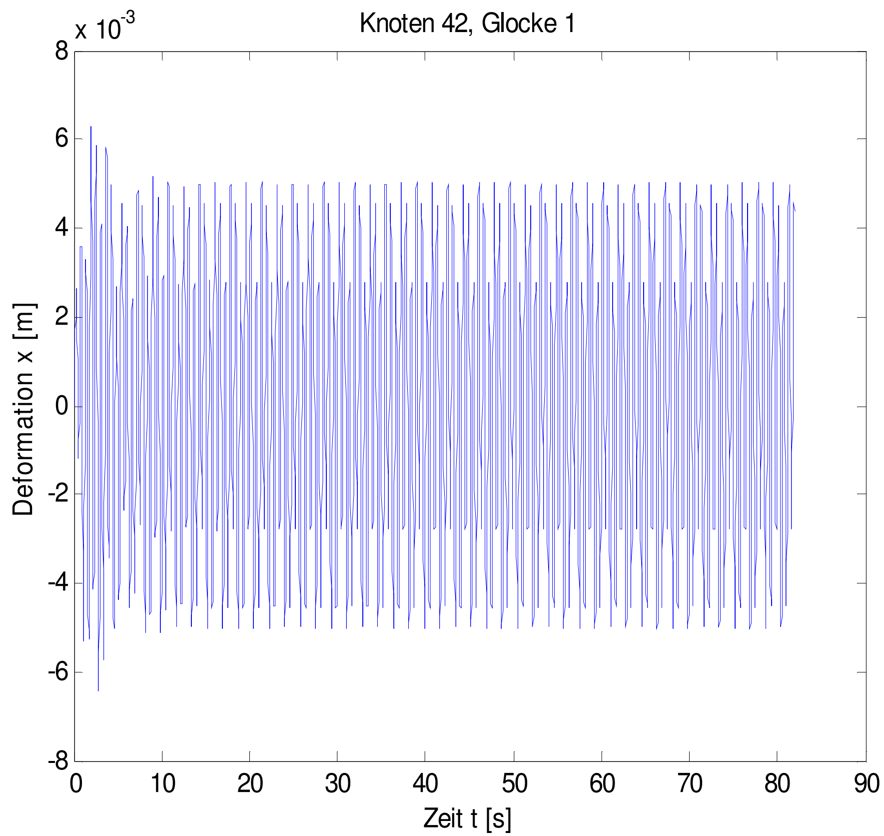
The effect on bell 2 is negative! That is due to the fact that the TMD lowers the eigenfrequency of the structure so that now the 3rd harmonic of bell 1 comes closer to resonance.

TMD2 Against Bell 1 (3rd Harmonic)

with TMD1: bell 1



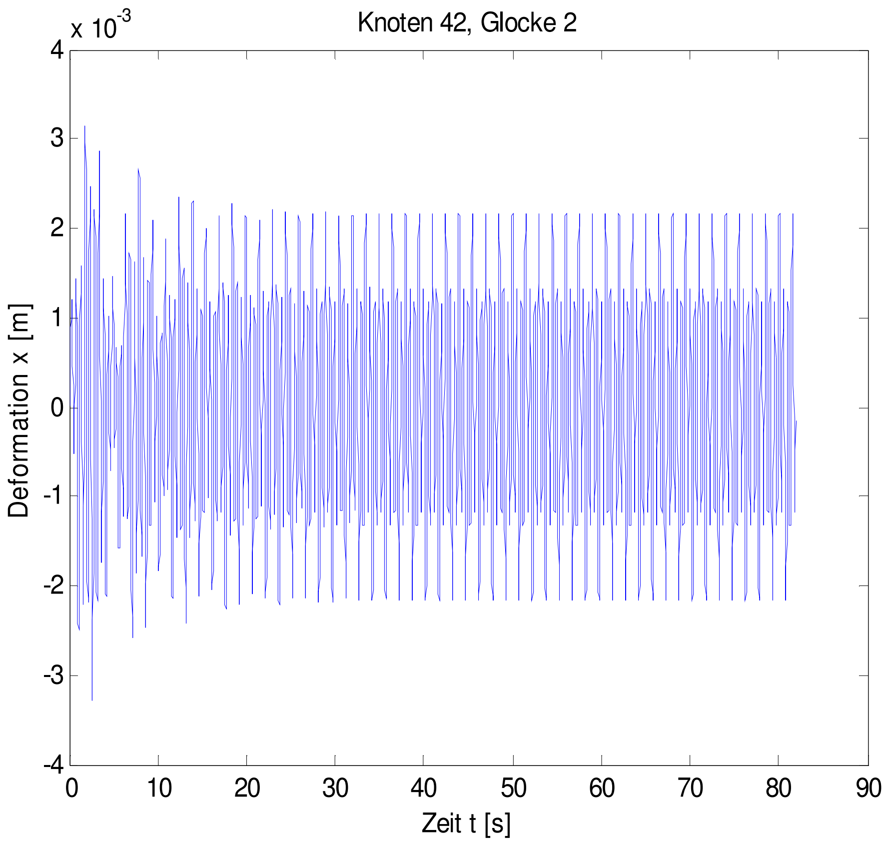
with TMD1+2: bell 1



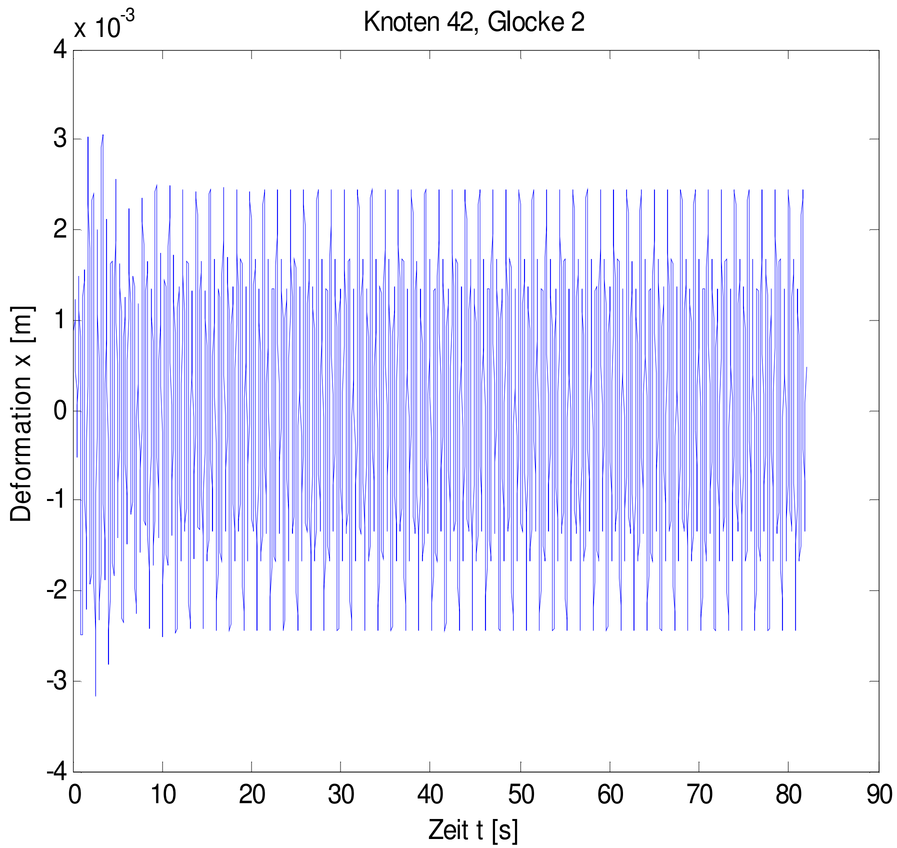
TMD2 reduces the amplitudes by a factor of about 1.6, so it is not terribly effective.

TMD2 Against Bell 1 (3^{rd} Harmonic)

with TMD1: bell 2



with TMD1+2: bell 2



TMD2 changes once again the eigenfrequencies. This does not, however, have any negative effects on the response to bell 2.

Results and Recommandations

General perception: The effectiveness of TMDs with multi-harmonic excitation can be noticeably smaller that in the purely single-harmonic case.

Recommendations for the bell tower: Even though the two TMDs can reduce the amplitudes by half, they are not deemed cost-effective, since such a TMD would cost about €10000 - €15000. Also it would be difficult to hide the TMDs within the structure, which would require some additional construction. So the use of TMDs is not recommended here.

Last words: TMDs are a powerful means to reduce vibrations. They are not, however, a heal-all medication for sick structures. Today's powerful computational methods allow simulations even for complex structures and loadings. These analyses, however, are not trivial and require well-educated engineers.