Semi-active tuned mass damper with MR damper for Volgograd Bridge, Russia

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Problem

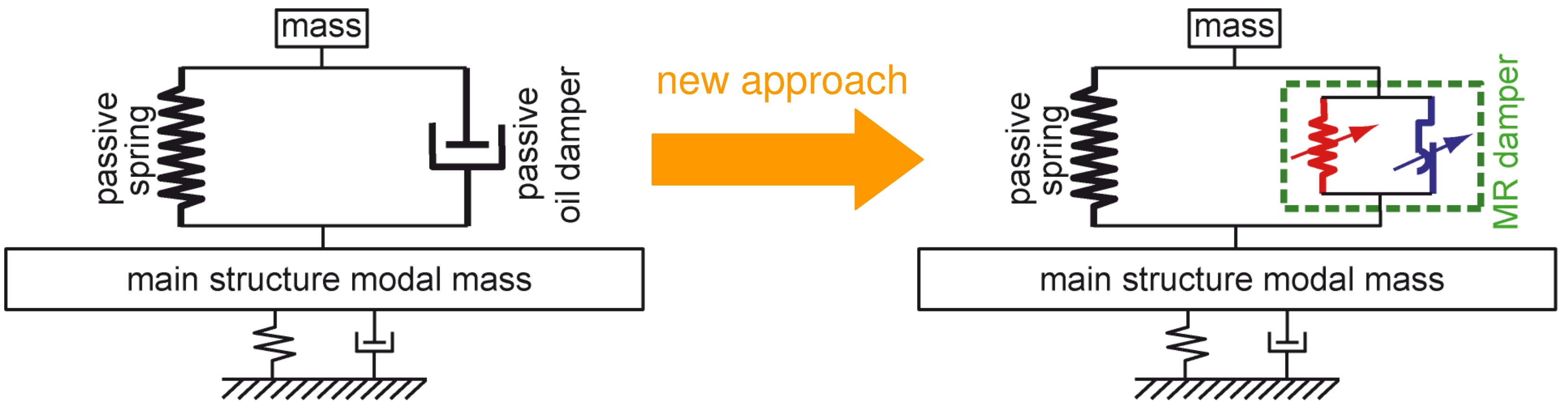
Volgograd Bridge:
- Google „Wolga Bridge“ ➔ several youtube movies
- Wind excitation of 3 bending modes at 0.45Hz, 0.57Hz and 0.68Hz

Movie of Volgograd Bridge

Approach

Semi-active tuned mass damper with MR damper (MR-STMD)

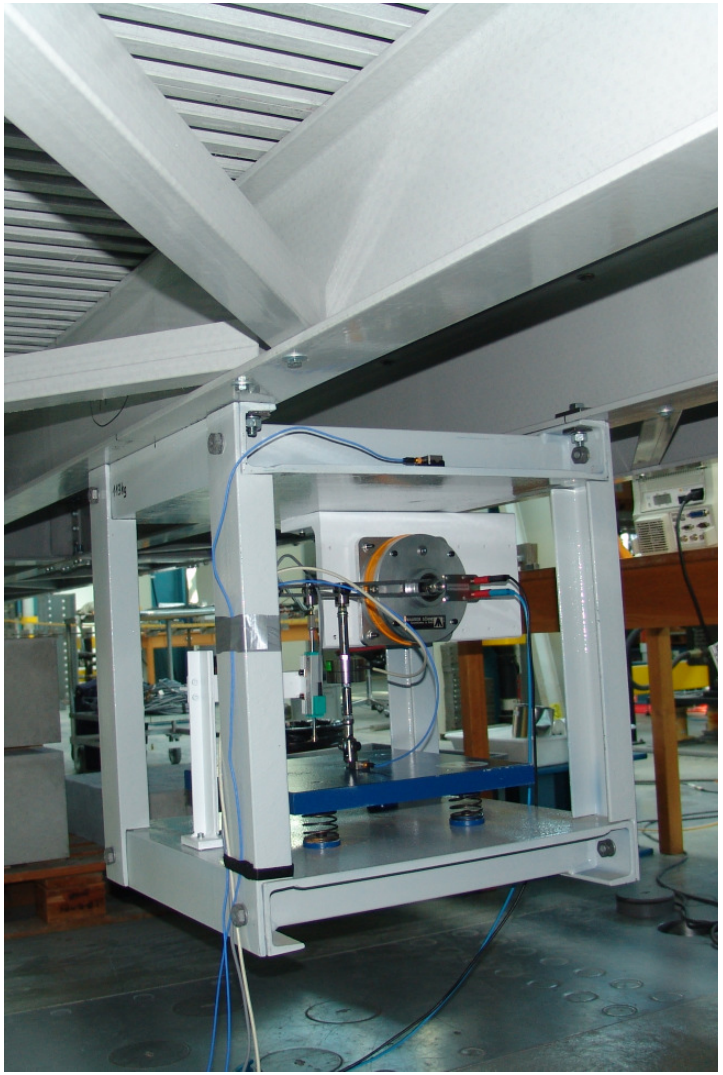
(Weber and Maślanka 2012)



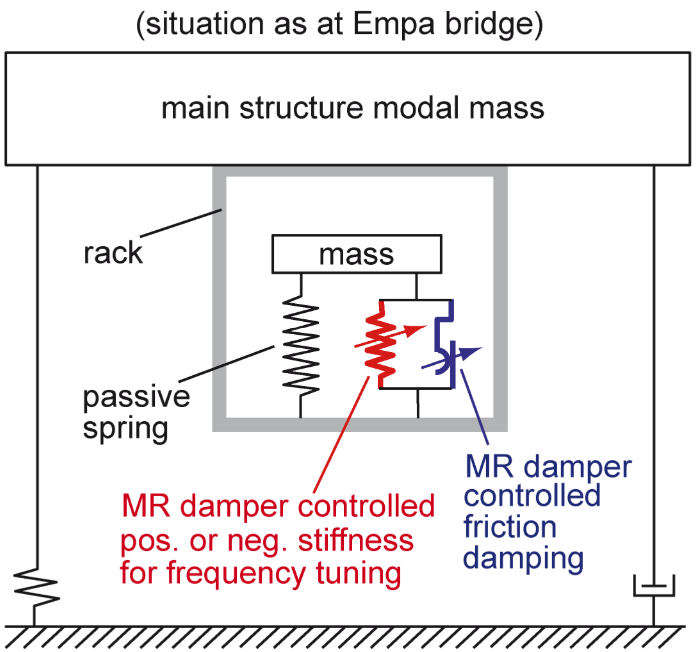
1. Design mass and spring of tuned mass damper according to Den Hartog (1934)
2. Replace viscous damper by MR damper
3. **Controlled stiffness force in MR damper adjusts natural frequency of mass-spring-system to actual frequency of main structure** according to Den Hartog (1934)
4. **Controlled damping in MR damper adjust energy dissipation in MR-STMD to actual frequency of main structure** according to Den Hartog (1934)

Den Hartog JP 1934 *Mechanical Vibrations* McGraw-Hill Book Company, The Maple Press Company, York, Pa.
Weber F and Maślanka M Frequency and damping adaptation of a TMD with controlled MR damper *Smart Mater. Struct.* **21** (2012) 055011.

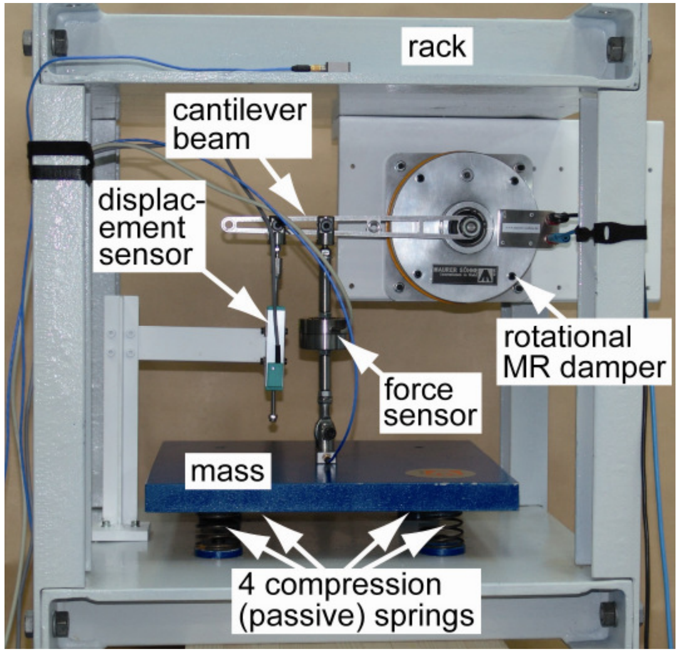
Prototyp MR-STMD at Empa bridge



Prototyp MR-STMD

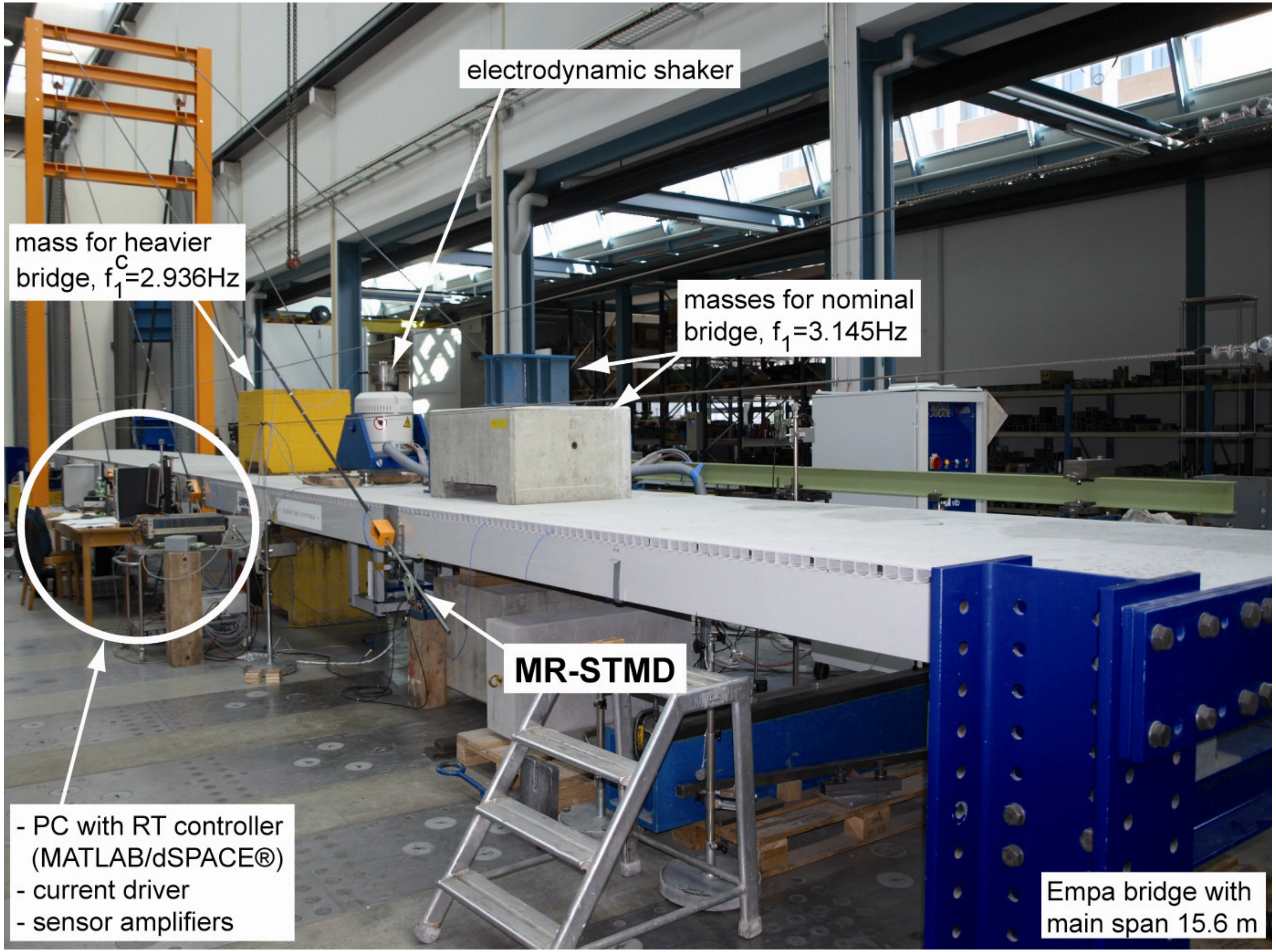


Mass spring system:
- Natural frequency 3.1Hz
- Mass 26.325kg
- Damping ratio 0.1%-0.2%
  (6mm-12mm damper motion)



MR damper:
- Rotational typ
- Max. torque 45Nm at max. current 2A
- Model-based designed by Empa
- Manufactured by Maurer Söhne

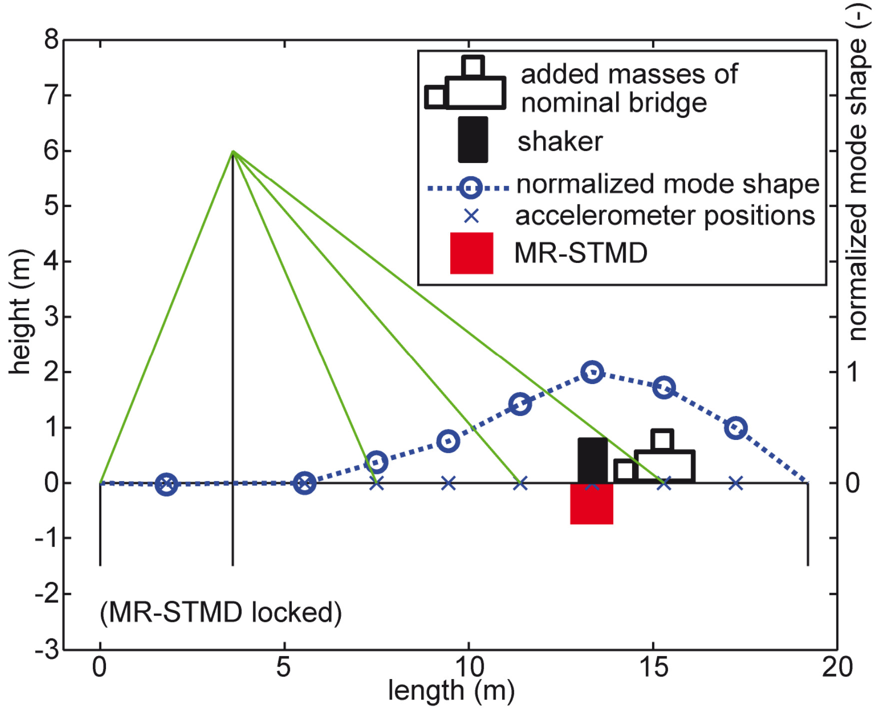
Empa bridge



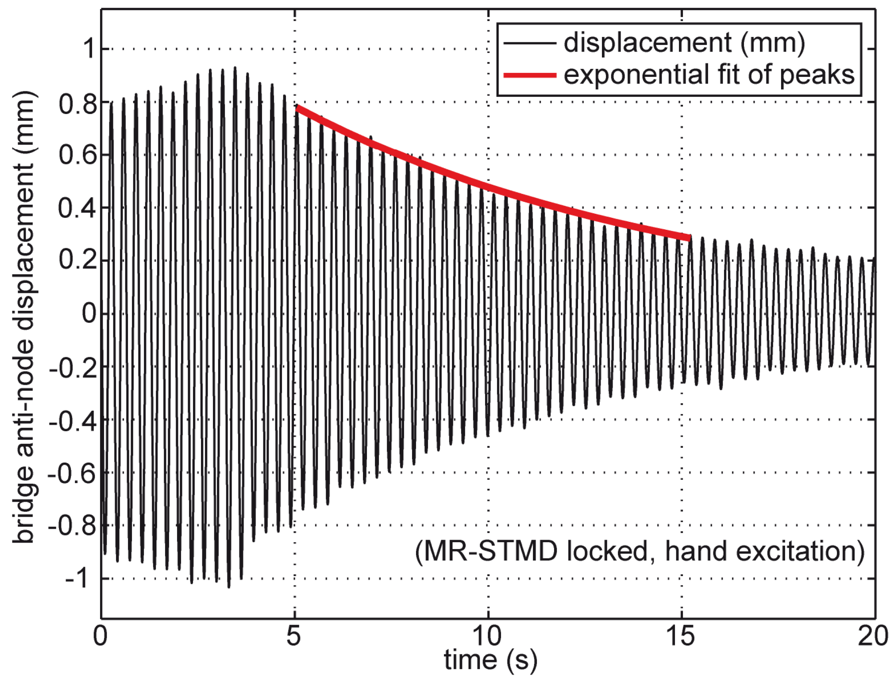
electrodynamic shaker
mass for heavier bridge, f_1^c=2.936Hz
masses for nominal bridge, f_1=3.145Hz
MR-STMD
- PC with RT controller (MATLAB/dSPACE®)
- current driver
- sensor amplifiers
Empa bridge with main span 15.6 m

Empa bridge: configuration “nominal”

MR-STMD at anti-node of 1st bending mode:



Exponential decay of 1st bending mode:



Bridge configuration “nominal”:

- f_1=3.145Hz (bending mode)
- Modal mass approx. 1680kg
- Damping ratio approx. 0.4% (0.5mm-1mm bridge amplitude)

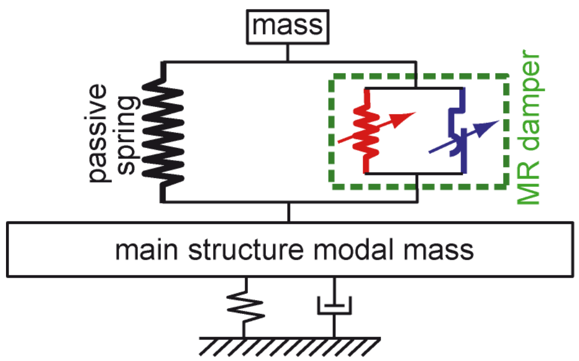
TMD / MR-STMD:

- Mass 26.325kg
  ➔ mass ratio approx. 1.57%

Real-time control algorithm

Frequency tuning:

$$f_2 = \frac{f_w^{est}}{1+\tilde{\mu}} \quad \text{where: } \tilde{\mu} = \mu\left(\frac{f_w^{est}}{f_1}\right)^2 = \frac{m_2}{m_1}\left(\frac{f_w^{est}}{f_1}\right)^2$$

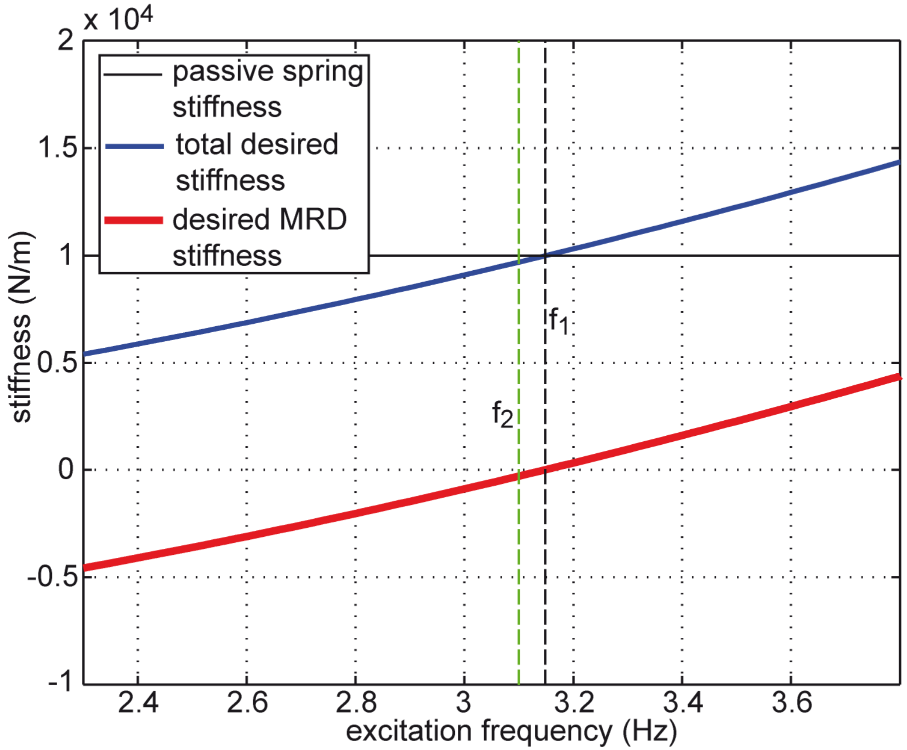


Desired MR-STMD stiffness:

$$\tilde{k}_2^{des} = k_1 \frac{\tilde{\mu}}{(\tilde{\mu}+1)^2}$$

Desired MR damper stiffness:

$$\boxed{k_{mr}^{des} = \tilde{k}_2^{des} - k_2}$$

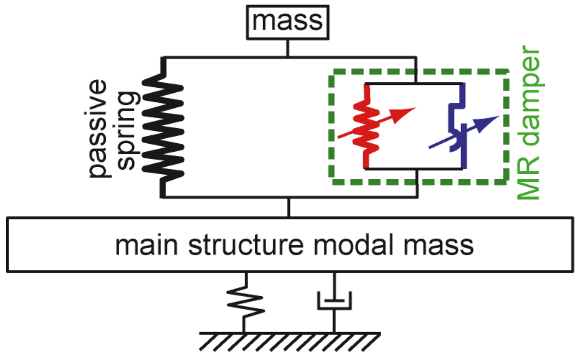


Real-time control algorithm

Damping tuning:

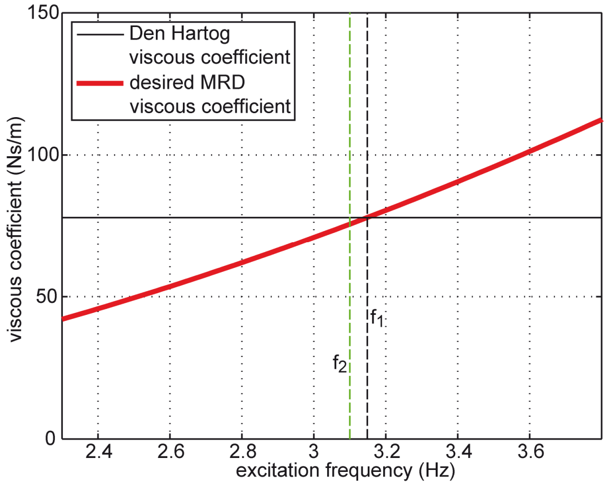
$$\tilde{\zeta}_2^{des} = \sqrt{\frac{3\,\tilde{\mu}}{8\,(\tilde{\mu}+1)^3}}$$

where: $\tilde{\mu} = \mu \left(\frac{f_w^{est}}{f_1} \right)^2$



Desired MR damper viscous coefficient:

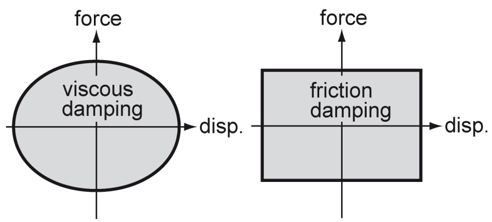
$$\tilde{c}_2^{des} = 2\,\tilde{\zeta}_2^{des}\,m_2 \left(2\pi f_w^{est} \right)$$



Desired, energy equivalent MR damper friction damping force:

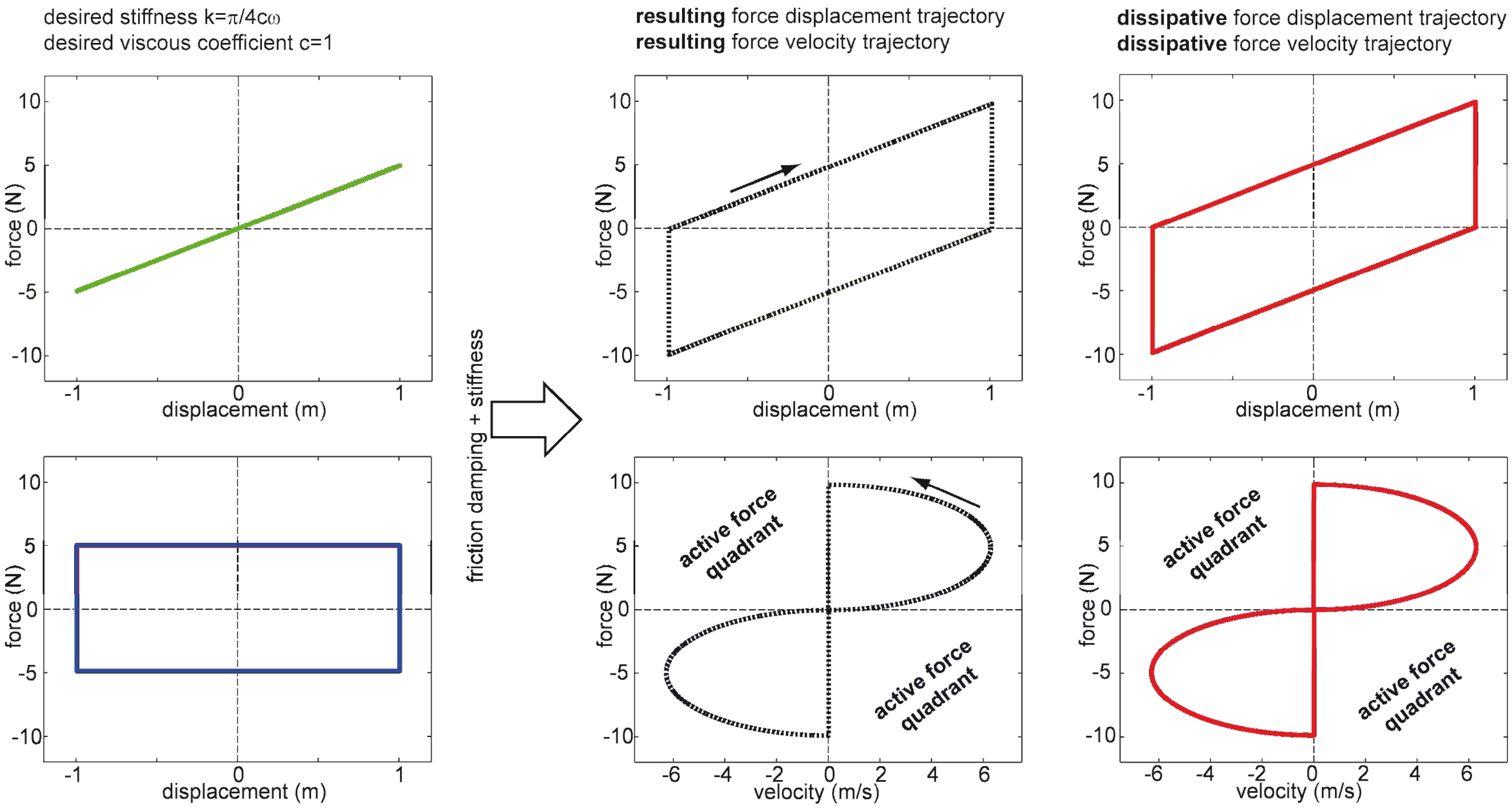
$$\boxed{F_{mr}^{des} = \frac{\pi}{4}\,\tilde{c}_2^{des} \left(2\pi f_w^{est} \right) X_d}$$

displacement amplitude of m_2



Why stiffness combined with friction damping?

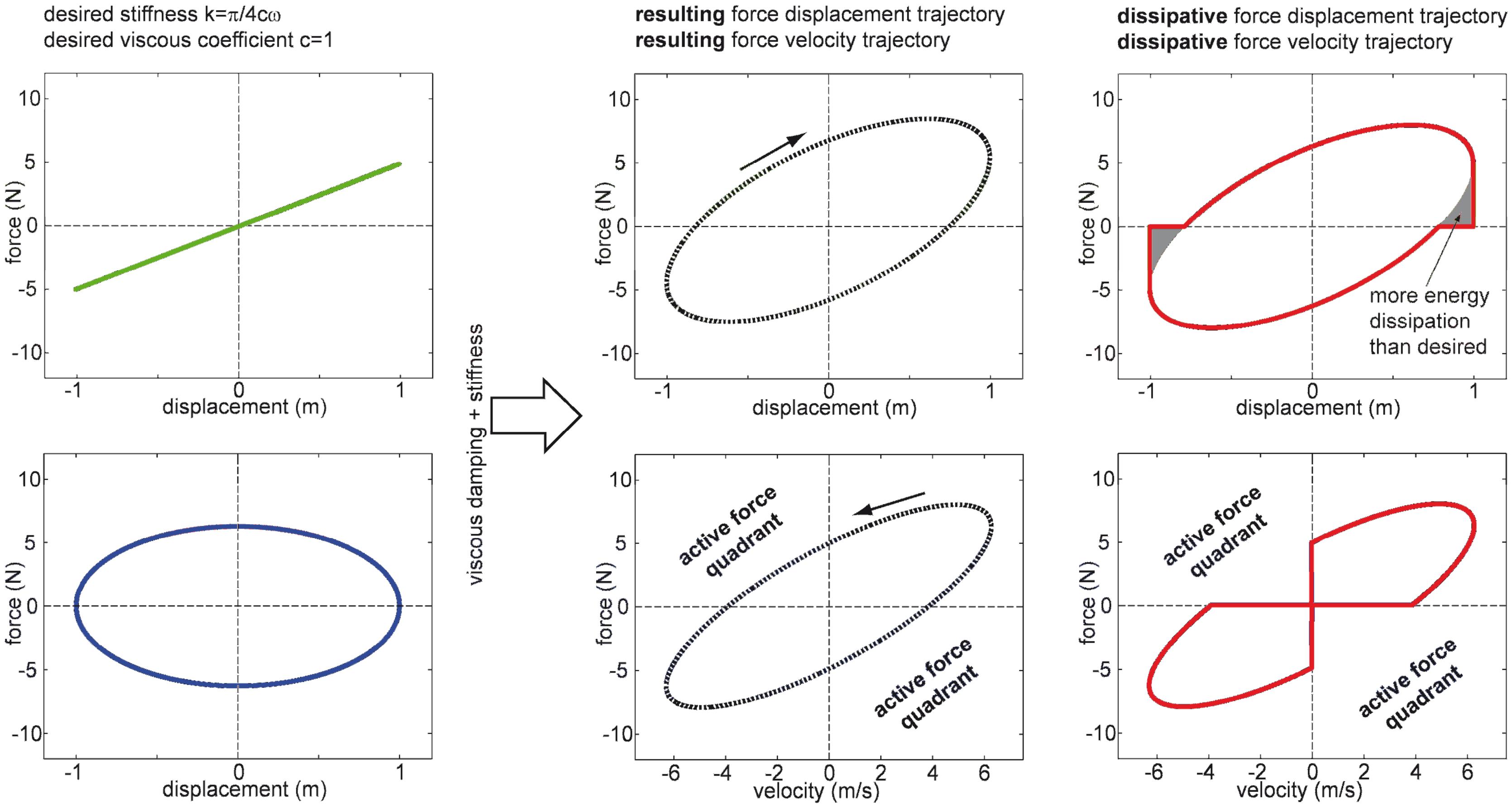
Case a): maximum stiffness force = friction force: $F_{mr}^{des} = \frac{\pi}{4}\tilde{c}_2^{des}\left(2\pi f_w^{est}\right)X_d = k\,X_d \Rightarrow \boxed{k = \frac{\pi}{4}\tilde{c}_2^{des}\,\omega_w}$



Precise emulation of stiffness and energy dissipation

Why stiffness combined with friction damping?

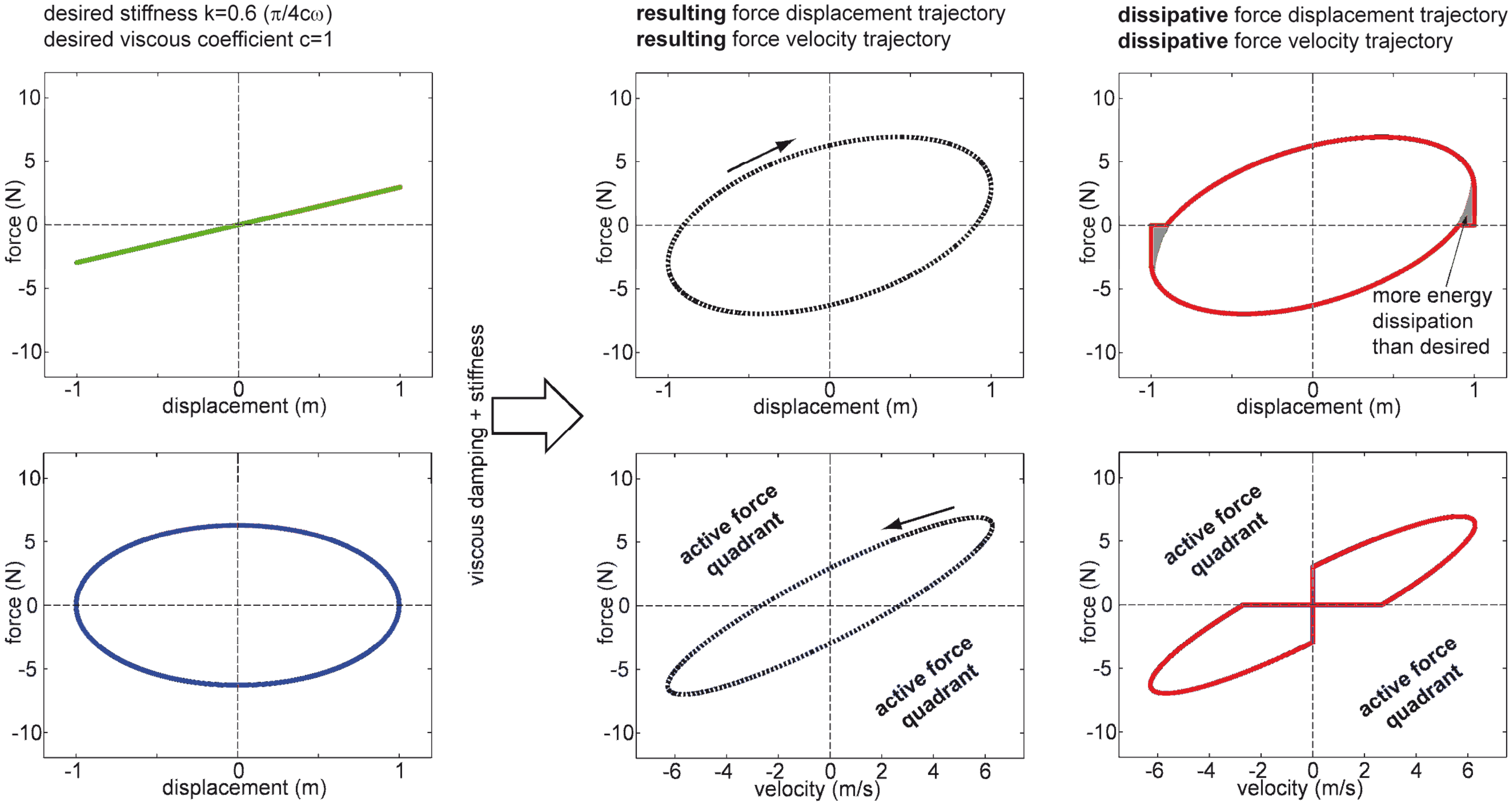
Stiffness combined with viscous damping for: $k = \frac{\pi}{4}\tilde{c}_2^{des}\omega_w$



Stiffness smaller and energy dissipation larger than desired

Why stiffness combined with friction damping?

Stiffness combined with viscous damping for: $k = 0.6\left(\frac{\pi}{4}\tilde{c}_2^{des}\omega_w\right)$



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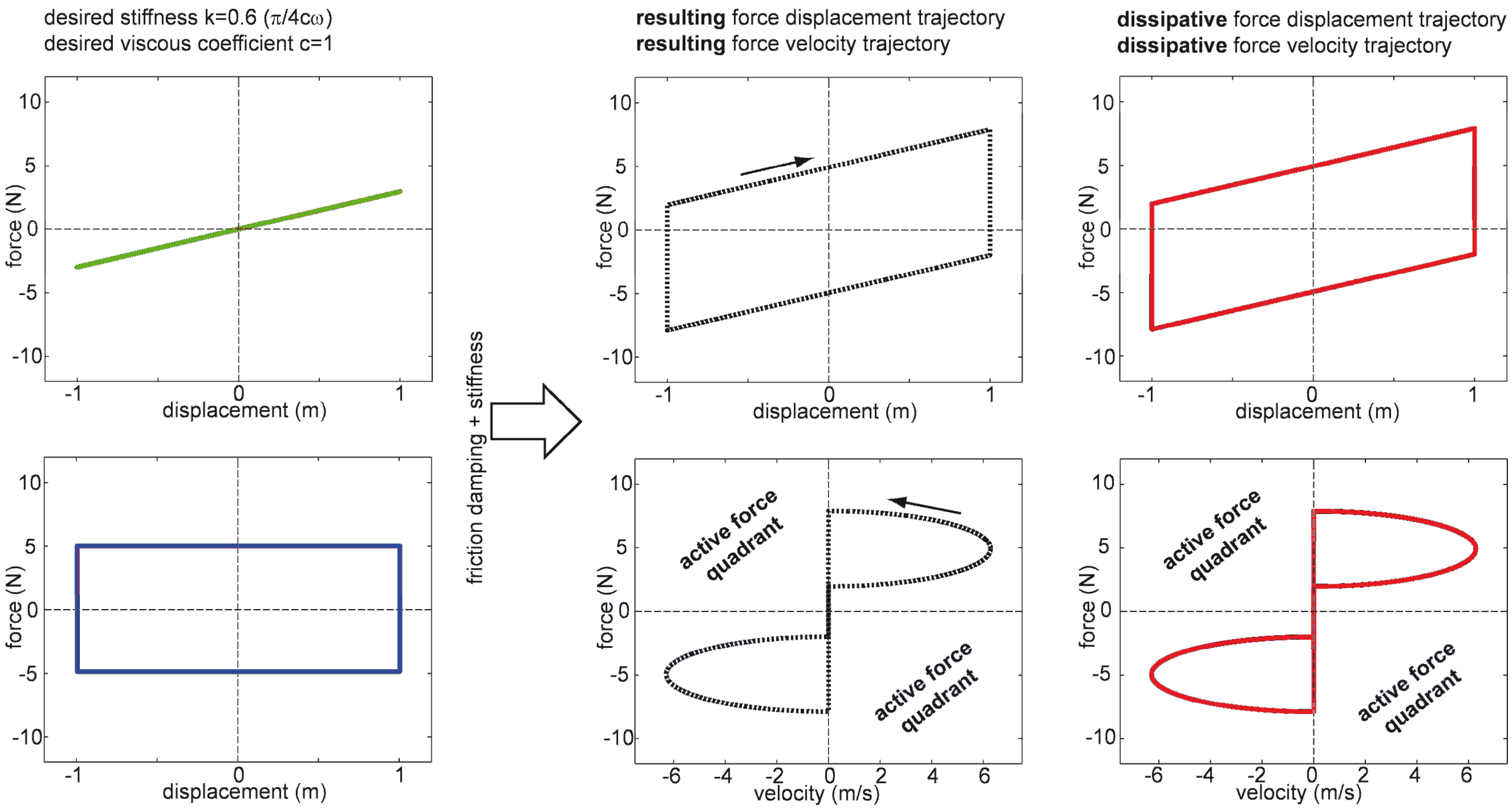
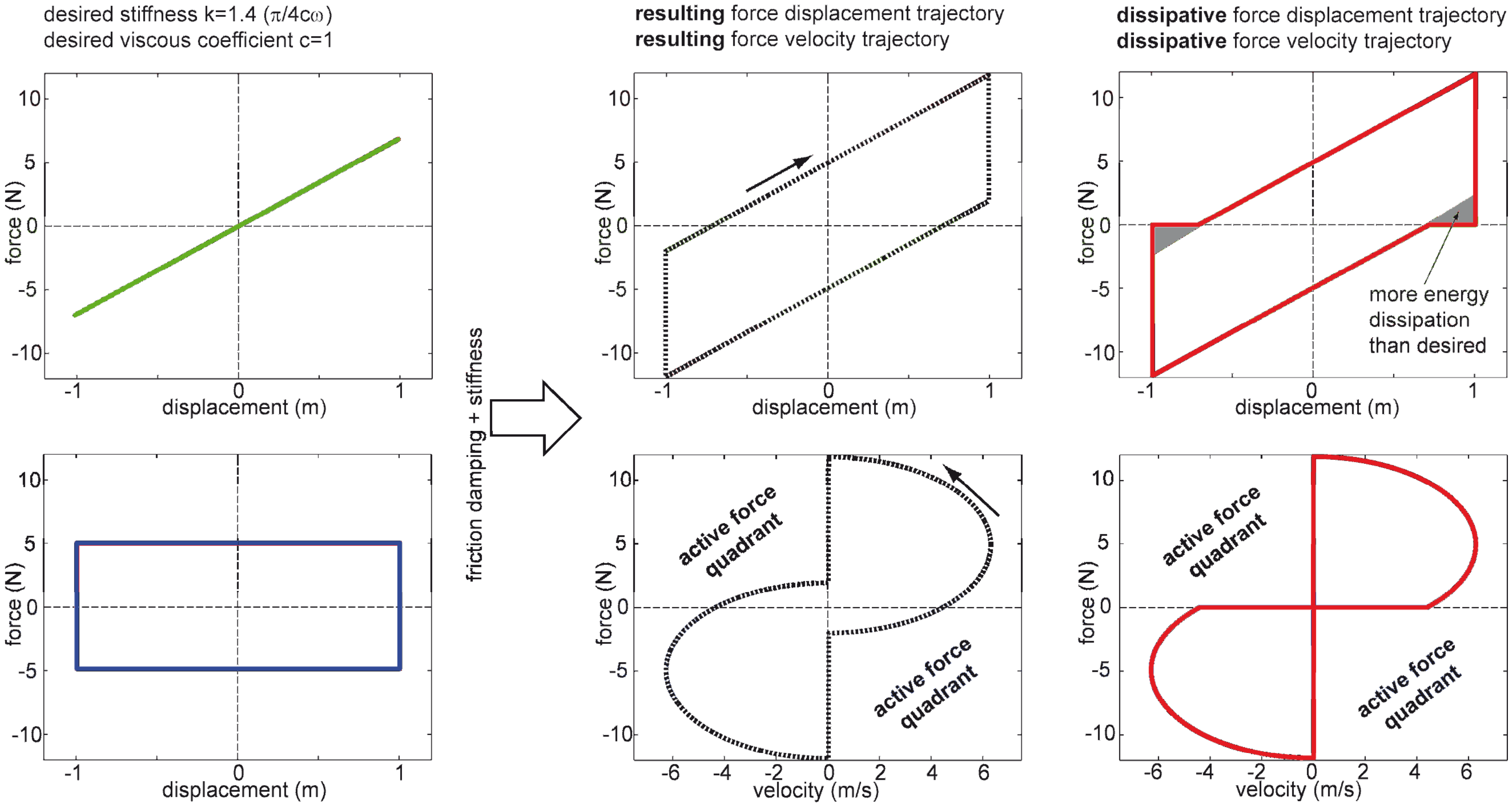


Precise emulation of stiffness and energy dissipation

Why stiffness combined with friction damping?

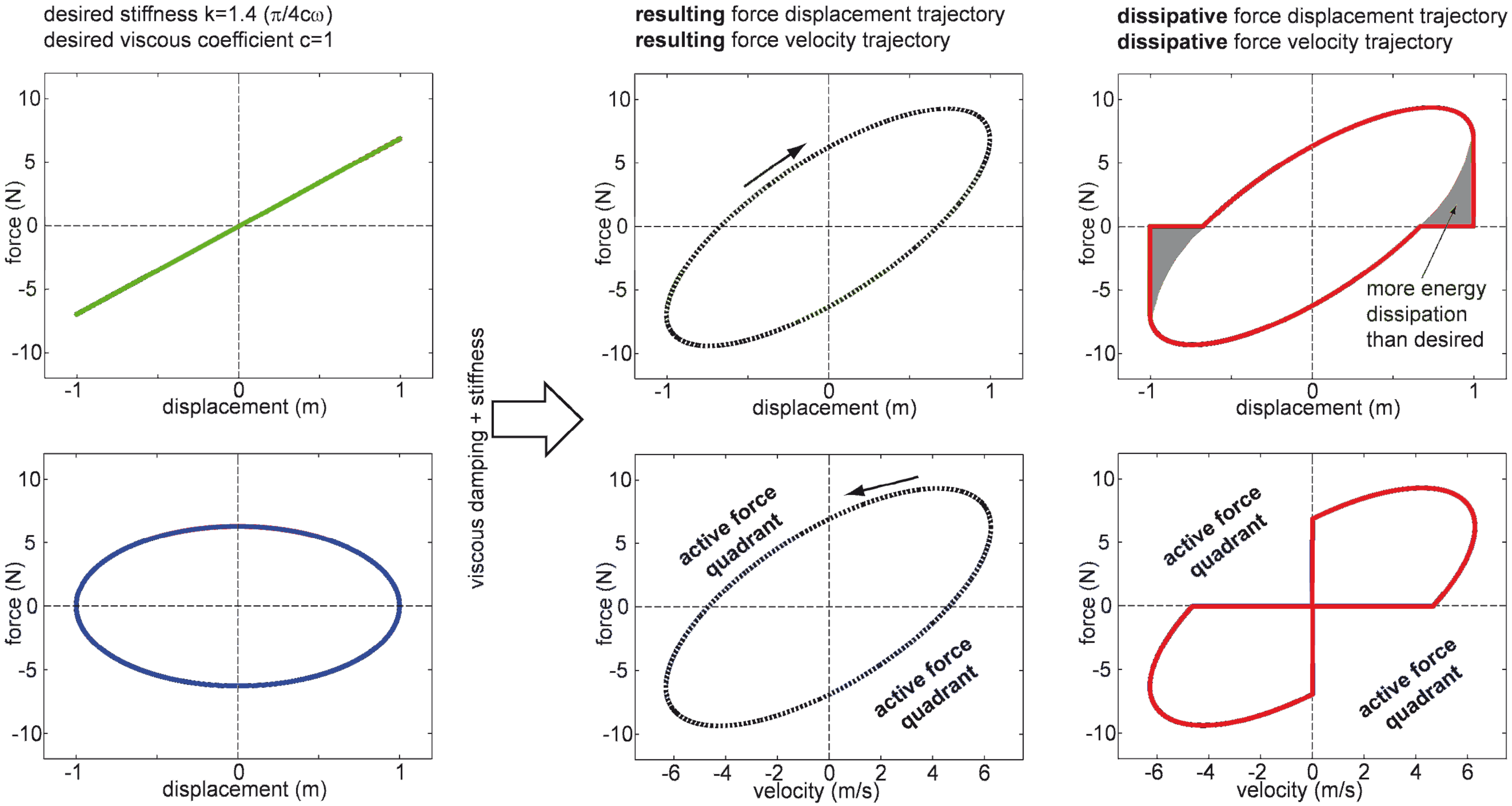
Stiffness combined with friction damping for: $k = 1.4\left(\frac{\pi}{4}\tilde{c}_2^{des}\omega_w\right)$



Only for $k > \frac{\pi}{4}\tilde{c}_2^{des}\omega_w$ stiffness smaller and energy dissipation larger

Why stiffness combined with friction damping?

Stiffness combined with viscous damping for: $k = 1.4\left(\frac{\pi}{4}\tilde{c}_2^{des}\omega_w\right)$



Stiffness smaller and energy dissipation larger than desired

MR-STMD stiffness and damping controlled in real-time: movie

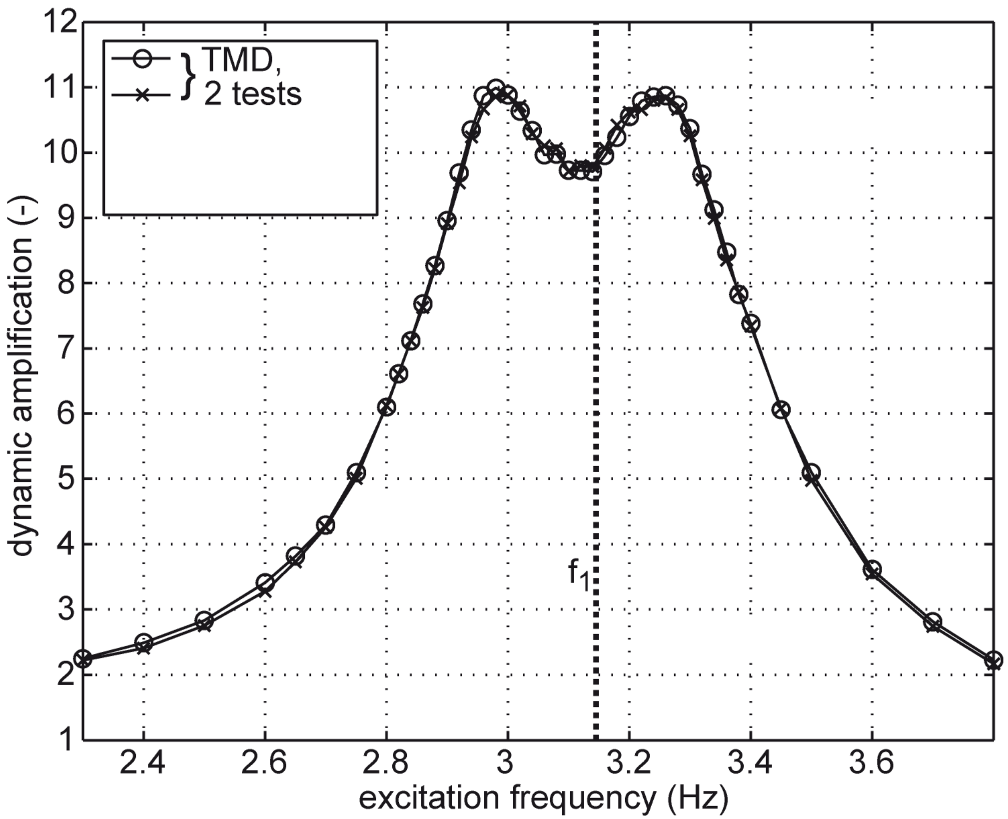
- Nominal bridge configuration
- Excitation frequency nominal ➔ up ➔ down ➔ nominal

Movie of MR-STMD running
at Empa bridge

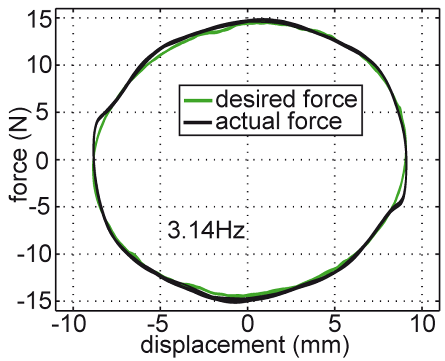
MR-STMD at Empa bridge: configuration “nominal”

Benchmark damper:
- TMD according to Den Hartog (1934) emulated by MR-STMD
- Magnitude of peaks not equal due to damping ratio of main structure

“Nominal” bridge with TMD:



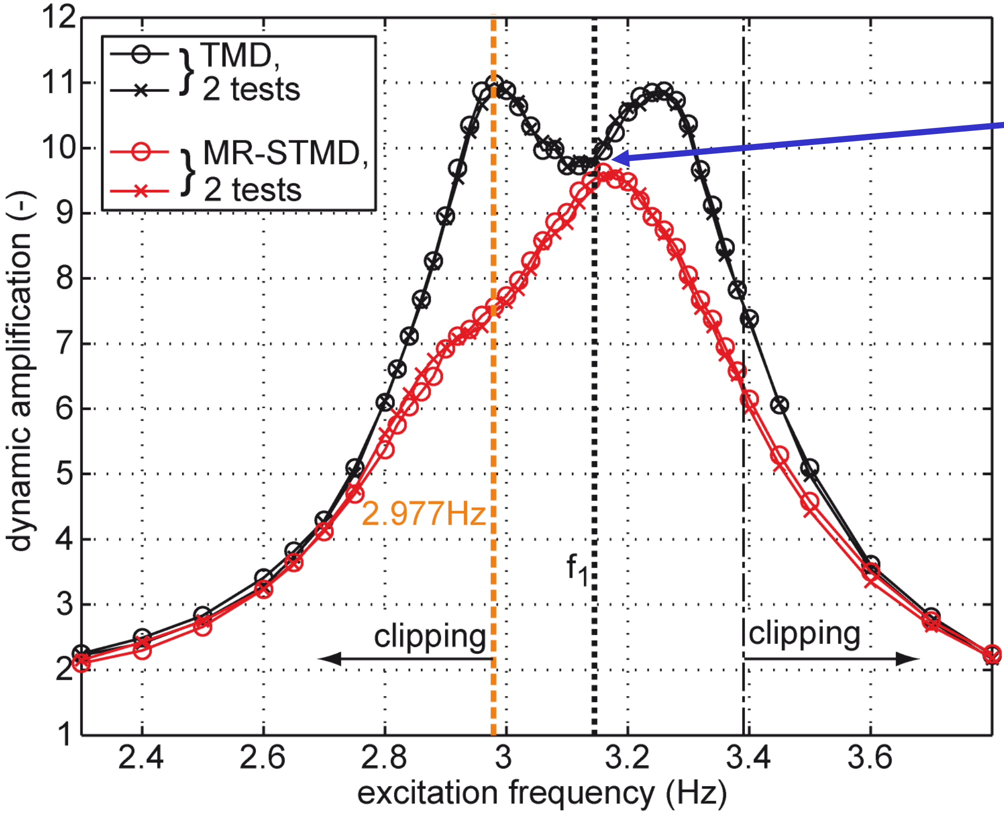
Force tracking for emulated TMD:



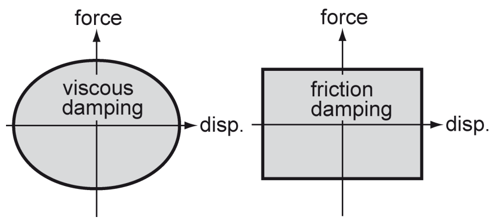
MR-STMD at Empa bridge: configuration "nominal"

Comparison :
- 3.145Hz: energy equivalent damping ➔ same response as with TMD
- **max. improvement of 48% at 2.977Hz**

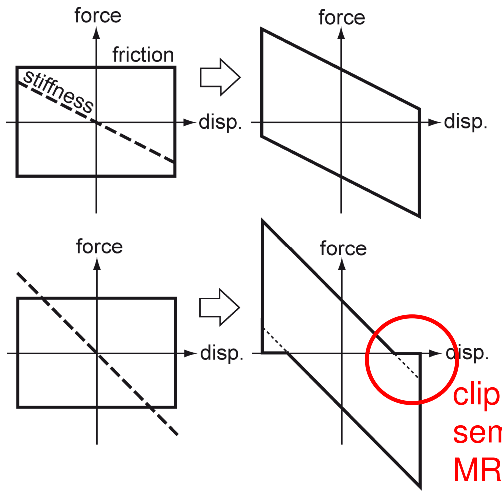
"Nominal" bridge with TMD and MR-STMD:



Energy equivalent damping:



Stiffness with friction:

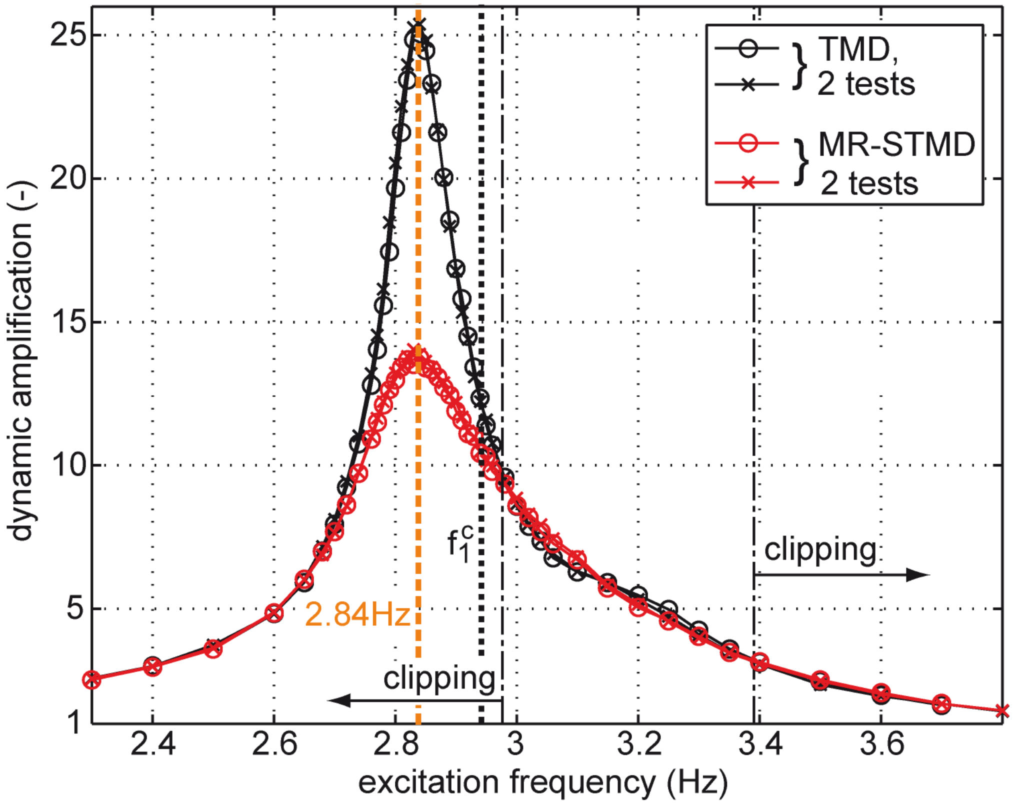


MR-STMD at Empa bridge: configuration “c”

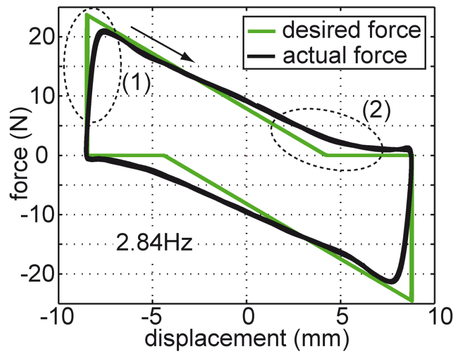
Bridge configuration “c”:
- Plus 880kg at cable support 2
- Resonance frequency f_1^c =2.936Hz
- Damping ratio approx. 0.39%

Comparison:
- **Max. improvement of 56% at 2.84Hz**

Bridge configuration “c” with TMD and MR-STMD:

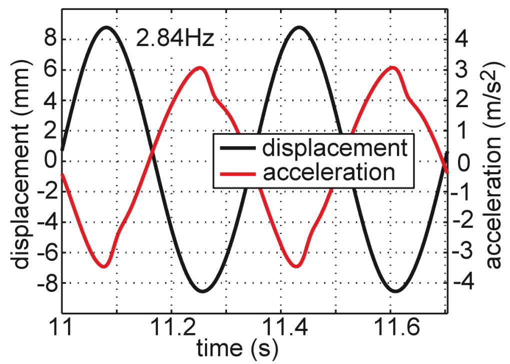


Force tracking errors:



(1) current driver dynamics, max. current limit.
(2) remanent magnetization

Nonlinear motion in MR-STMD?

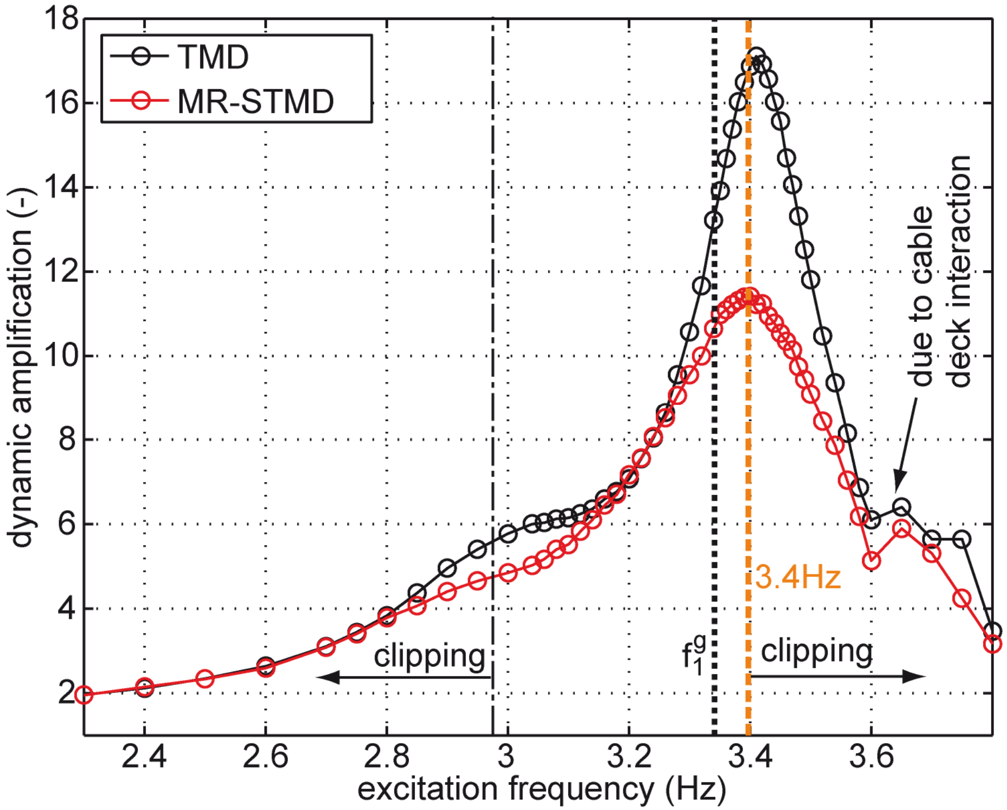


MR-STMD at Empa bridge: configuration “g”

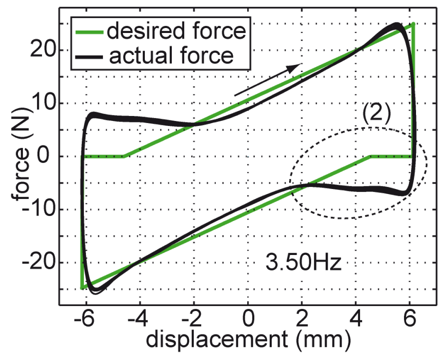
Bridge configuration “g”:
- Minus 268kg at cable support 3
- Resonance frequency f_1^c =3.341Hz
- Damping ratio approx. 0.48%

Comparison:
- **Max. improvement of 39% at 3.4Hz**

Bridge configuration “g” with TMD and MR-STMD:

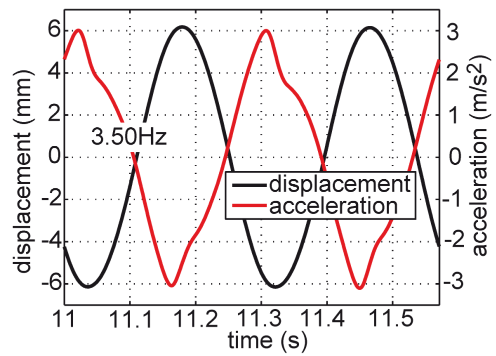


Force tracking errors:



(2) remanent magnetization

Nonlinear motion in MR-STMD?

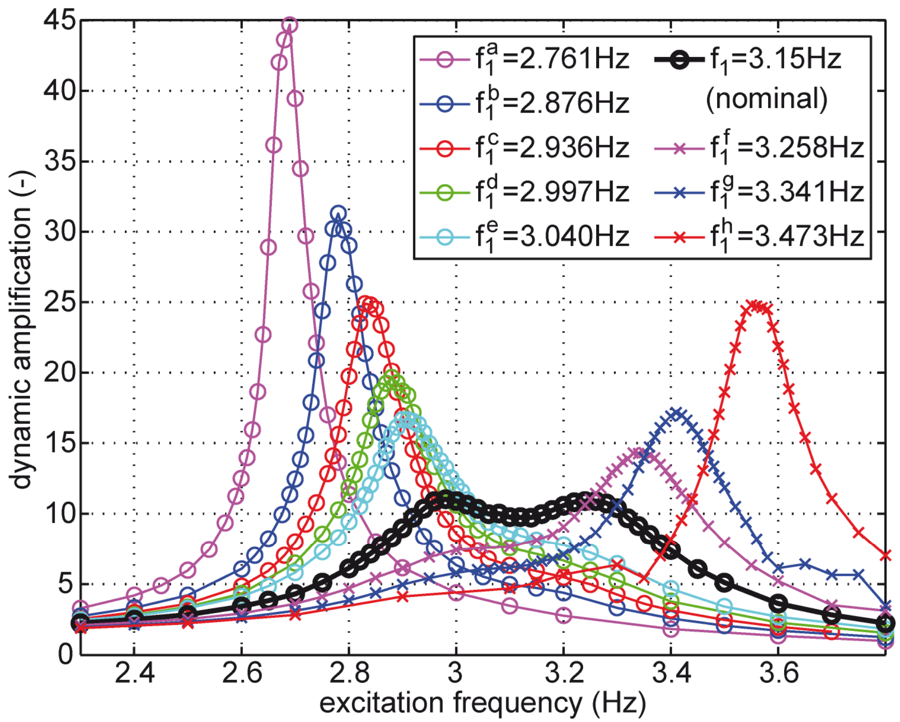


MR-STMD at Empa bridge: all tested configurations

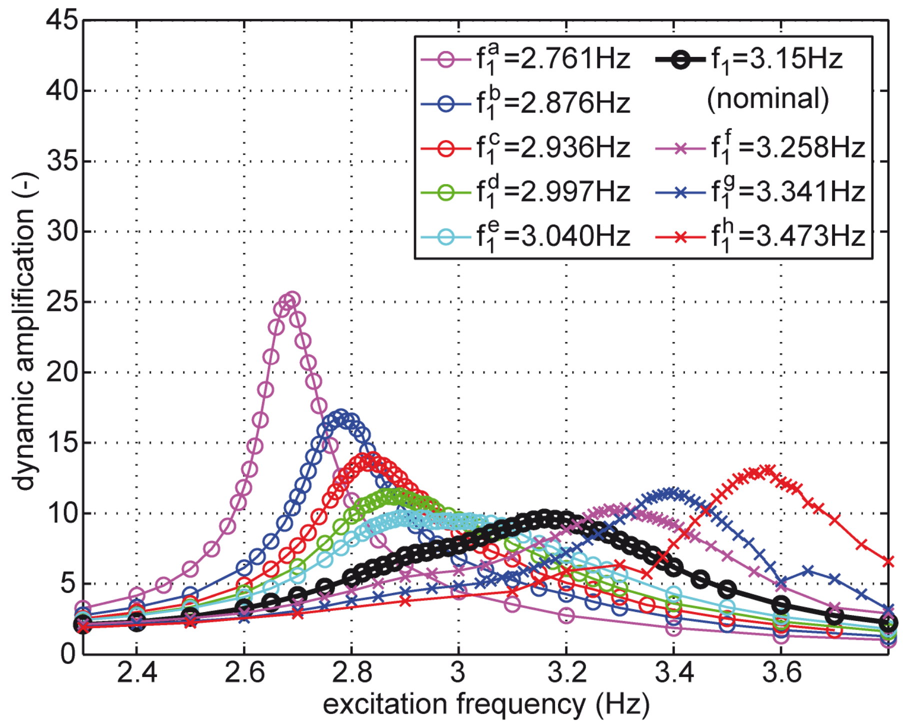
Maximum tested frequency shifts:

- +10.4%, limited by multi-mode vibrations due to cable deck interaction
- -12.2%, limited by amount of added masses
- **Max. improvement up to 63%**

Tested bridge configurations with TMD:



Tested bridge configurations with MR-STMD:



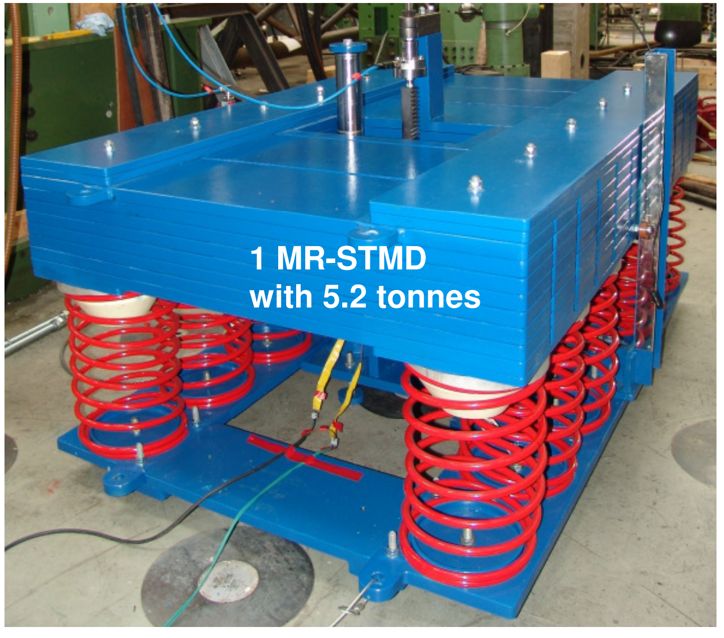
12 MR-STMDs for Volgograd Bridge

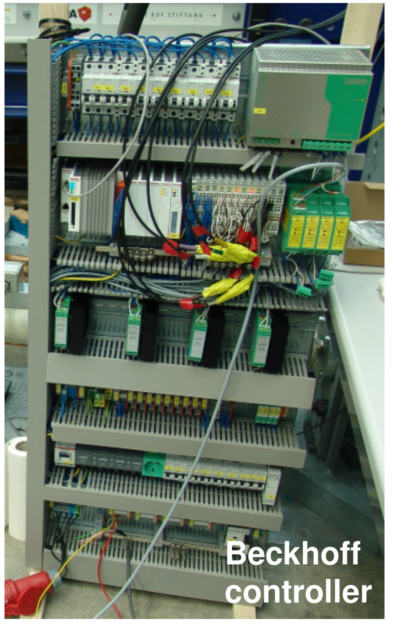
Mass ratios:
- 4 MR-STMDs for mode 1 with 0.45Hz; 20.8t correspond to 0.84% of target modal mass
- 4 MR-STMDs for mode 2 with 0.57Hz; 20.8t correspond to 0.97% of target modal mass
- 4 MR-STMDs for mode 3 with 0.68Hz; 20.8t correspond to 1.14% of target modal mass

Concept:

mode 2 at 0.57Hz +/-Δf vibrating

↙	↓	↘
4 MR-STMDs with f_{res}≈0.45Hz tuned to mode 2	4 MR-STMDs with f_{res}≈0.57Hz tuned to mode 2	4 MR-STMDs with f_{res}≈0.68Hz tuned to mode 2



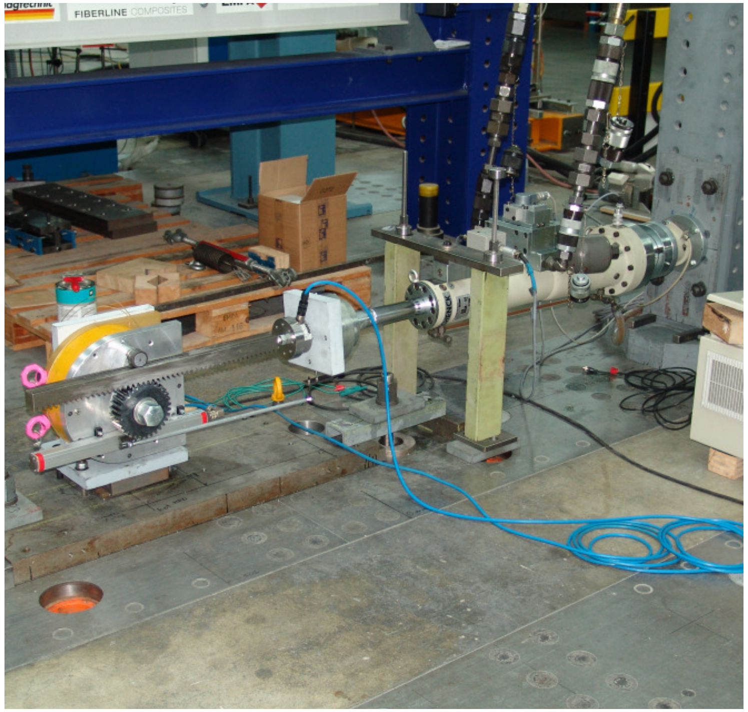


12 MR-STMDs for Volgograd Bridge

Programming and testing code @ Empa:

- Tested for all 3 modes with frequency shifts +/-20%
- Hardware (sensors, amplifiers,…) and codes (force tracking parameters) **of all 12 single control loops tested**

Hydraulic cylinder for sinusoidal motion:



Frequency sweep from -20% to 20% of nominal value:

Movie force tracking with MR damper

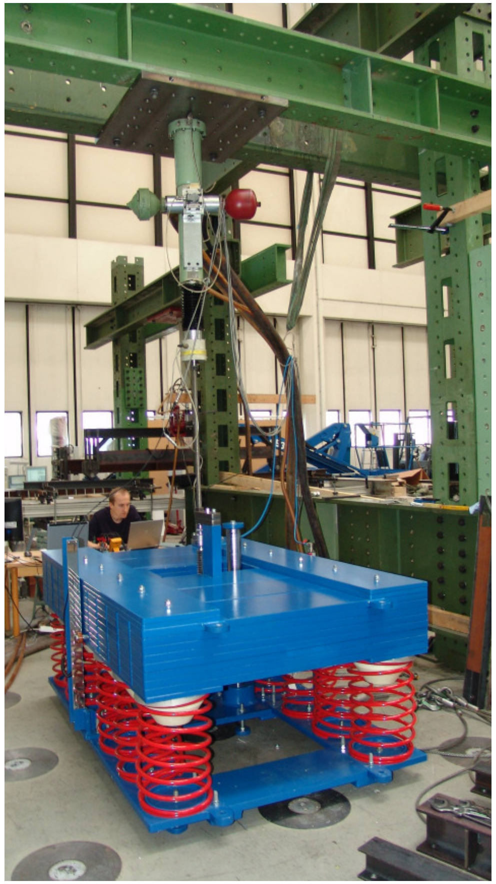
red: actual force
blue: desired force

left: force displacement trajectory
right: force velocity trajectory
below: current & detected frequency

12 MR-STMDs for Volgograd Bridge

Tests at University of the German Armed Forces, Munich, Germany (Bundeswehrhochschule München):

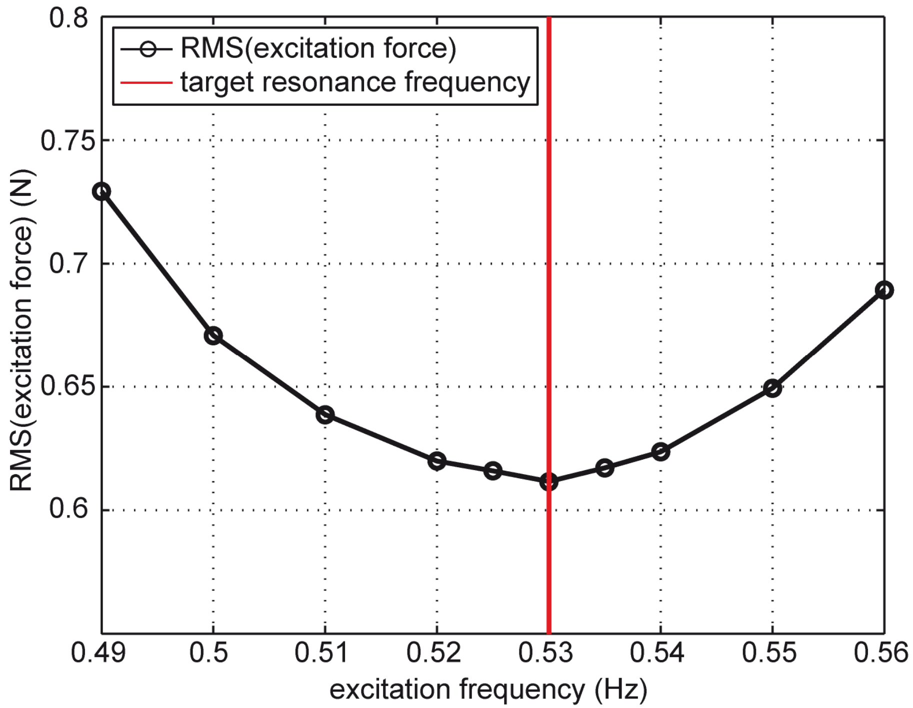
- MR-STMD tested for 2nd mode with 0.57Hz
- Frequency shift -20% ➔ 0.45Hz
- Frequency shift +20% ➔ 0.68Hz



Movie full scale tests at Uni. German Armed Forces

12 MR-STMDs for Volgograd Bridge

Example: target resonance frequency 0.53Hz:



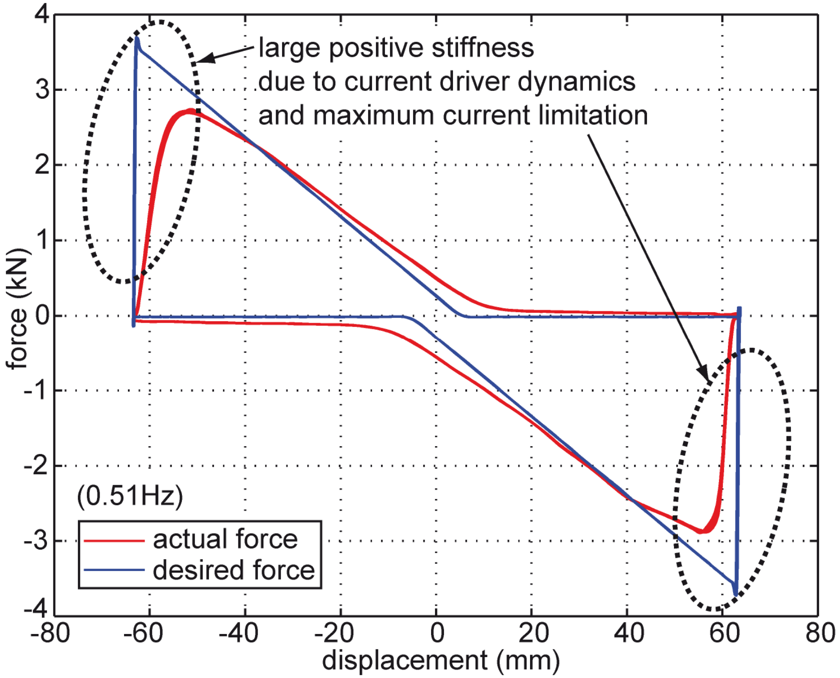
All test results:

Target resonance frequency (Hz)	Achieved?
0.45 (0.8*nominal)	No
0.47	Yes
0.51	Yes
0.53	Yes
0.55	Yes
0.57 (nominal)	Yes
0.59	Yes
0.61	Yes
0.63	Yes
0.65	Yes
0.68 (1.2*nominal)	Yes

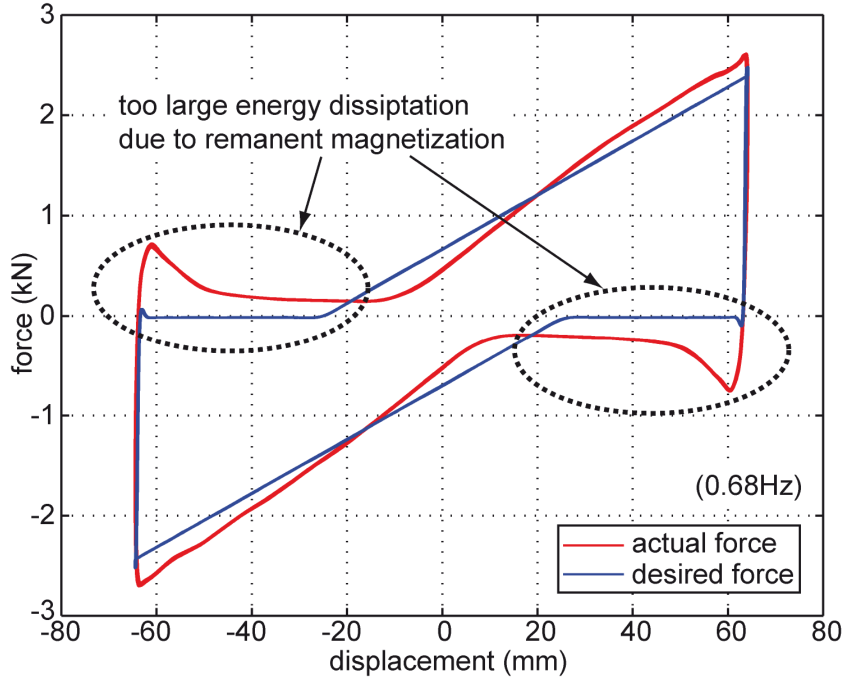
Limitations of MR-STMD

- Maximum negative stiffness limited by current driver dynamics and maximum current limitation
- Too large energy dissipation due to remanent magnetization in case of positive stiffness

Clipped negative stiffness with friction:



Clipped positive stiffness with friction:



Thank you for your kind attention.

Questions?