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Optimal damping of multi-story buildings under wind excitation

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ABSTRACT: Wind excited vibrations of high-rise buildings can be reduced by installing additional damping devices like tuned mass dampers. The design of tuned mass dampers on different levels of the building is performed via a computer–aided modeling and design approach. A multibody system model is used for describing the dynamic behavior of the structure, and the problem of optimizing the parameters of the damping devices is formulated as a nonlinear programming problem. An application to a building of the University of Stuttgart shows that optimal designs with minimal accelerations of the building can easily be obtained.

1 INTRODUCTION

Wind excited vibrations of high-rise buildings impair the structural safety as well as the well–being of the residents. For reducing the vibrations to a tolerable size additional damping devices can be installed, see e.g. Hirsch (1983). As a matter of fact, tuned mass dampers are widely used to suppress vibrations of civil engineering structures. In most cases, the design of such tuned mass dampers is based on a single degree–of–freedom model of the structure on the basis of the first natural frequency, e.g. Fujino and Abe (1992).

For designing tuned mass dampers on different levels and taking into account the multi–frequency response of the building, the multibody system approach can be used. The dynamic behavior of the structure is then described by a parametrized model where the stiffness and damping coefficients of the tuned mass dampers can be chosen as design variables for optimizing the dynamic behavior of the building with respect to wind excitation.

2 MODELING AND IDENTIFICATION

The method of designing multiple tuned mass dampers is demonstrated for a building of the University of Stuttgart with fourteen stories. The eigenfrequencies of the first two bending modes have been measured as $f_1 = 0.76\ Hz$ and $f_1 = 2.56\ Hz$ (Luz and Wallaschek 1992).

A model being closely related to the structure of the building consists of fourteen rigid floors connected by elastic columns which result in forces depending on relative displacements of adjacent floors only (Luz 1991). Numerical studies, however, have shown that additional beams have to be included due to rather stiff cores like a staircase running through the whole height of the building (Obermüller 1992).

For optimization purposes the model can be reduced to a multibody system with four degrees of freedom by summarizing four and three stories to single bodies, respectively, Fig. 1. The inertia is then represented by four rigid bodies while the stiffness is modeled by absolute and relative springs. The absolute springs resulting in a moment proportional to the absolute rotation of a single body are related to the elastic columns in each story, the relative springs are related to stiff cores.

The masses M_i and moments of inertia I_i with respect to the center of gravity of each body can be found from mass distribution and geometrical data whereas the stiffness coefficients c_{abs} and c_{rel} may be identified via an eigenvalue analysis. It turns out that for this special combination of

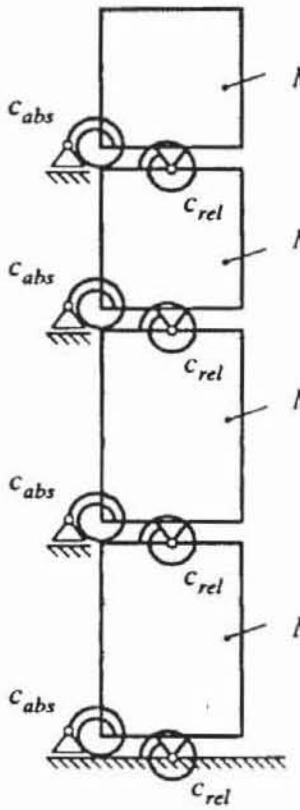

Fig. 1: Multibody system model of a 14–story building

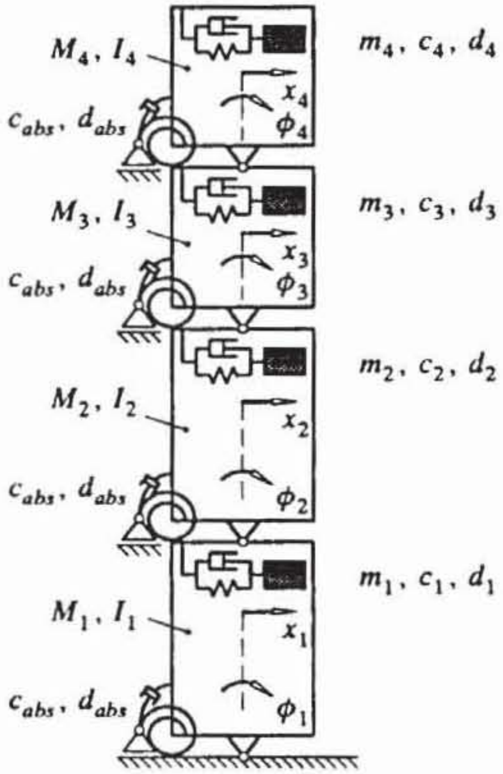

Fig. 2: Multibody system model with mass dampers

stories to rigid bodies the relative springs can be neglected (Reichert 1992). For considering damping effects absolute dampers in parallel to the springs are added.

Tuned mass dampers are most effective if they are mounted to the top of each body. The resulting model with eight degrees of freedom is shown in Fig. 2. The kinematics of the multibody system is described by absolute angles ϕ_i and relative displacements x_i of the tuned mass dampers which are summarized in a vector $y \in \mathbb{R}^8$ of generalized coordinates. Due to small displacements the equations of motion can be linearized with respect to the equilibrium position (Schiehlen 1986):

$$M(p)\,\ddot{y} + D(p)\,\dot{y} + K(p)\,y = h(t) \qquad (1)$$

where the mass matrix M, damping matrix D, and stiffness matrix K depend on the design parameters p.

Generation of equations of motion for such multibody systems can be automated by computer formalisms (Schiehlen 1990). In particular, a symbolic formalism like NEWEUL (Kreuzer and Leister 1991) offers great advantages in the subsequent optimization step.

3 OPTIMIZATION APPROACH

The comfort of the residents of a multi–story building may be evaluated by the horizontal accelerations of the individual stories. For the reduced model an integral type criterion can be formulated as

$$\psi(p) = \int_0^T \sum_{i=1}^{4} w_i\,\ddot{y}_i^2\,dt \qquad (2)$$

where $\ddot{y}_i$ are the horizontal accelerations at the top of each body, w_i are weighting factors, and T is a finite time of interest. Via the equations of motion kinematic quantities like the accelerations are completely determined by the parameters of the model. Therefore, the objective function can be considered as a function of the design variables only.

The task of finding optimal values for the design variables may be formulated as a nonlinear programming problem which has to be solved in an iterative process starting with a given design. In each iteration step at least one function evaluation has to be performed which is a time–consuming numerical simulation of the dynamic behavior of the structure due to wind excitation. To reduce the number of iteration steps sequential quadratic programming (SQP) methods can be used, e.g. Fletcher (1987). The remaining problem with these algorithms is the requirement of gradients of the objective function with respect to the design variables.

In principal, there are two different approaches for computing gradients: numerical differentiation via finite differences and analytical sensitivity analysis via the adjoint variable approach (Haug 1987). Numerical studies have shown the adjoint variable method to be superior to numerical differentiation with respect to reliability, accuracy and efficiency (Bestle and Eberhard 1992). Therefore, the latter approach is used for optimizing the tuned mass dampers. Based on symbolical equations of motion the sensitivity analysis can be performed on the computer automatically.

4 NUMERICAL RESULTS

In the following, the tuned mass dampers are optimized with respect to the performance function (2) for typical wind loadings. If a single gust, Fig. 3, is applied to the building without additional damping devices it will respond with low–damped vibrations almost in its first eigenmode, Fig. 4. Installing tuned mass dampers and optimizing them with respect to the accelerations at the top of the building, i.e. $w_1 = w_2 = w_3 = 0$, $w_4 = 1$, helps to damp out long term vibrations drastically, Fig. 4.

If we choose all mass dampers to be identical, i.e.

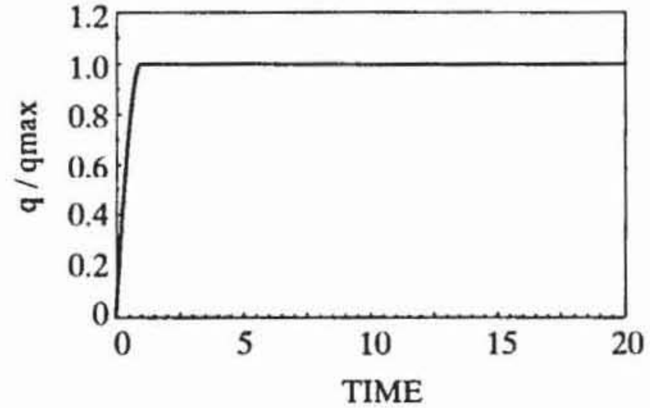

Fig. 3: Specific wind loading for a single gust

$$m_1 = m_2 = m_3 = m_4 ,\quad c_1 = c_2 = c_3 = c_4 ,\quad d_1 = d_2 = d_3 = d_4 \tag{3}$$

we have to minimize criterion (2) with respect to three design variables. It turns out that the mass of the additional damping devices has to be bounded for obtaining reasonable results. For upper bounds of 1%, 5% and 10% for the ratio of the total weight of the tuned mass dampers and the total weight of the building we find $\psi_{1\%}/\psi_0 = 0.33$, $\psi_{5\%}/\psi_0 = 0.17$, and $\psi_{10\%}/\psi_0 = 0.12$, respectively. In all cases, like in the 5%–case in Fig. 4, long term vibrations can be damped out whereas the first acceleration peak cannot be influenced very much by mass dampers.

If only the mass of the additional damping devices is chosen to be identical and the stiffness and damping coefficients are optimized individually, the additional increase of the performance is not significant: $\psi_{5\%}/\psi_0 = 0.15$, $\psi_{10\%}/\psi_0 = 0.11$.

In both cases, the comfort of the building is improved by increasing the weight of the mass dampers. This dependence changes for a more realistic broad band excitation, Fig. 5, where a local minimum of the performance function (2) with $w_i = 1$, $i = 1(1)4$, exists for the mass ratio

$$\frac{\sum m_i}{\sum M_i} \approx 2.25\% \tag{4}$$

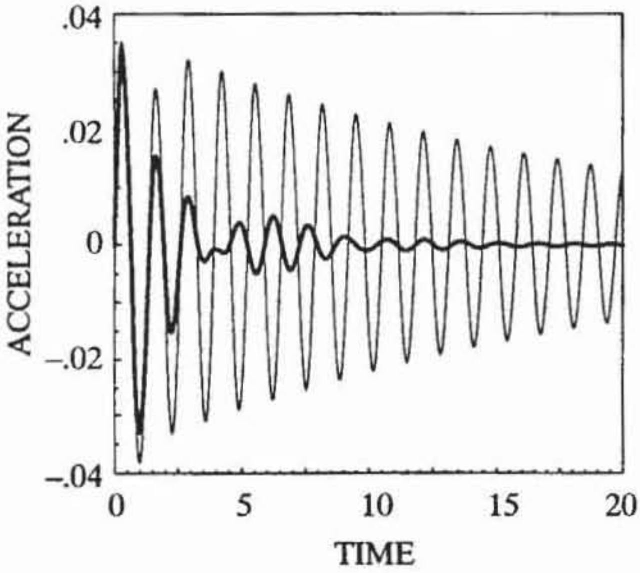

Fig. 4: Acceleration of the top of the building due to a single gust with (—) and without (—) tuned mass dampers

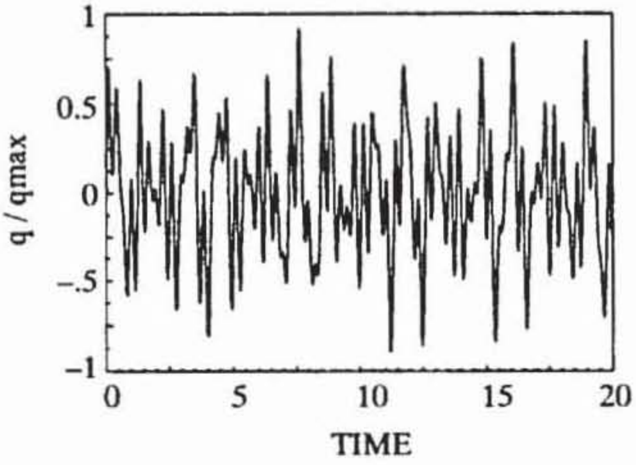

Fig. 5: Broad band excitation

as shown in Fig. 6. If the mass ratio is limited to less then about 10% optimization will automatically provide this optimal value.

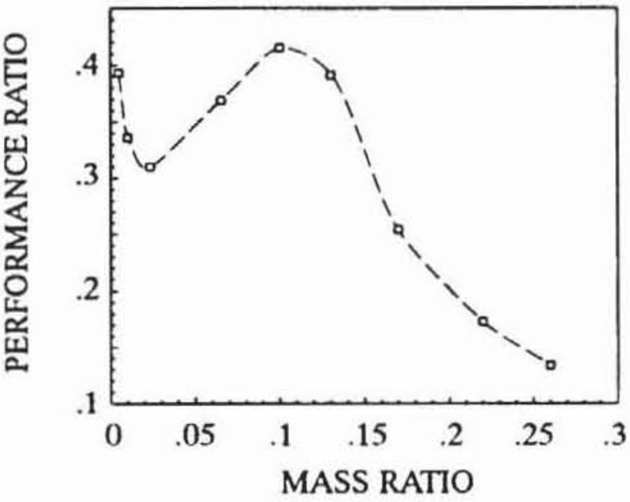

Fig. 6: Ratio of the performance values with and without mass dampers for broad band excitation

5 CONCLUSIONS

The multibody systems approach and optimization methods are well suited for a computer–aided design of tuned mass dampers. Such additional damping devices improve the comfort of the residents of high–rise buildings with respect to long term vibrations although they cannot reduce the first acceleration peak due to single gusts. For broad band excitation there exists a local minimum of the performance function with respect to the mass ratio of the total weight of the tuned mass dampers and the total weight of the building. Further numerical studies have to show the influence of excitation frequencies on this minimum.

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