Wind tunnel test of an active mass damper for bridge decks

R. Körlin & U. Starossek

Structural Analysis and Steel Structures Institute, Hamburg University of Technology, Denickestr. 17, 21073 Hamburg, Germany

Abstract

An active mass damper is implemented to a bridge section model test in a wind tunnel to enhance the flutter stability. Servo motors controlling the rotational motion of control masses serve as actuators. The torque generated by rotational acceleration is used to control the angular motion of the section model. The mechanical parameters of the uncontrolled and the controlled structures are identified by the Modified Ibrahim Time Domain Method (MITD). The deterioration of the control performance through control loop time delay is determined. The critical wind speeds are determined experimentally by wind tunnel tests and numerically by flutter analysis. The experimental and numerical results are in good agreement. The experimental results underline the applicability of an active mass damper and can be seen as a first step towards an implementation in real bridges.

Keywords: vibration control, active mass damper, bridge, flutter, buffeting, real-time implementation, wind tunnel test, Modified Ibrahim Time Domain Method

1 Introduction

Bridge deck flutter is an aeroelastic instability phenomenon and leads to dangerous self-excited coupled, vertical and torsional vibration. The bridge may collapse without advance warning. Until now, active flutter control for bridges has not been implemented in real structures. It can be assumed, however, that effective and robust active control devices will be needed for future ultra-long-span bridges to prevent flutter onset. Active mass damper devices change the dynamic properties of the bridge structure to enhance flutter stability. The active stabilizing moments can be generated, for instance, by a variable eccentric weight or by changing the rotational speed of a control mass using rotational actuators [1]. Another class of active control measures to avoid flutter vibrations is the aerodynamic control by active control surfaces or movable girder edges [2]. Active aerodynamic countermeasures modify actively the flow around the bridge deck and generate stabilizing aerodynamic forces. Contrary to aerodynamic methods, active mass dampers can be assembled and can operate completely inside the bridge girder. The applicability of an active flutter control in bridge building is highly determined by constructional requirements, power demand, questions concerning safety and reliability as well as consequences arising out of control loop time delays. For evaluating these issues, wind tunnel tests are suitable and necessary.

As far as the authors are aware, no wind tunnel testing has been carried out concerning bridge girder models equipped with an active mass damper. In [3], experiments with an active flutter control by means of active stay cables with displacement actuators are described. These experiments were not carried out in a wind tunnel. External vibration excitation was used instead to simulate flutter instability at overcritical wind speed. With the help of wind tunnel tests, the applicability of active tendon control for damping

NOTICE: this is the author’s version of a work that was accepted for publication in Journal of Wind Engineering and Industrial Aerodynamics. Changes resulting from the publishing process, such as peer review, editing, structural formatting, and other quality control mechanisms may not be reflected in this document. A definitive version was subsequently published in Journal of Wind Engineering and Industrial Aerodynamics, Vol. 95, Issue 4, April 2007, doi:10.1016/j.jweia.2006.06.015.
of vertical vibrations of a bridge girder model has already been proved [4]. In flutter
tests, various passive mechanical dampers, such as tuned mass dampers [5] or gyroscopic
dampers [6], have already been tested. Wind tunnel tests concerning active aerodynamic
methods have been carried out several times. A number of tests done by Kobayashi [7]
and others are described in [8]. Another account on wind tunnel testing of an active
aerodynamic flutter control can be found in [9].

Considering the number of practical implementations for high-rise buildings, the active
mass damper seems to be practicable for flutter control in real bridge structures. In an
analytical study, the variable eccentric mass damper and the rotational actuator were
compared by the authors [1]. The variable eccentric mass damper has a lower energy
consumption. But, undesired horizontal motion would be induced by this device in a
bridge structure. Therefore, rotational actuators are implemented in an experimental
test using servo motors. The proposed wind tunnel test is a first step towards finding
solutions of active mass dampers that will be both satisfying and reliable.

In this paper, details of the experimental set-up and results of the wind tunnel tests of
a sectional bridge model controlled by a rotational mass damper are shown. For iden-
tification of mechanical system parameters the Modified Ibrahim Time Domain Method
(MITD) is used [10]. In the flutter test, the enhancement of critical wind speed through
the active control is of interest. For evaluating the experimental results, the critical wind
speed has also been determined numerically by flutter analysis using the Hurwitz crite-
ron. The aerodynamic parameters of the cross section under consideration, i.e., the flutter
derivatives are taken from [11]. The applicability of an active mass damper for bridge
deck flutter is demonstrated. The effects of control loop time delays are determined.

2 Experimental set-up

2.1 Section model test

The experimental testing was carried out in the wind tunnel of the Institute of Fluid
Dynamics and Ship Theory, Hamburg University of Technology. The test section is 3.5
m long. The air stream has a cross section of 1.05 m x 1.75 m. The wind velocity has
a maximum of 50 m/s with full stream cross section. The degree of turbulence is 0.2%.
Fig. 1 shows the aerodynamic profile of the bridge girder inside the area of wind flow.
The cross section is rectangular with a height of 37.5 mm and a width of 300 mm. It is
790 mm long. The sectional model is connected to an H-shaped frame outside the area of
wind flow. The frame is supported by eight springs, see Fig. 2.

The sectional model moves in the two degrees of freedom of vertical displacement \(h\) and
rotational displacement \(\alpha\) around the horizontal axis perpendicular to the wind direction.
The horizontal movement of the test section in wind direction is prevented by horizontal
springs. The horizontal movement perpendicular to the wind direction is possible but
negligible. The test section allows testing of free vibrations. The initial displacements
are fixed to the outer ends of the H-shaped suspension frame via magnetic contact elements.
It is possible to remove the magnetic contacts simultaneously by means of a control
unit. The mass inertias of the vibrating model including the mass of the installed active
vibration damper are as follows: weight \(m = 7.39\) kg, mass moment of inertia \(I = 0.136\)
kgm². Each of the eight springs have a spring constant of 0.26 N/mm. The spring and
damping parameters of the model are identified experimentally.

2.2 Servo actuators

Two brushless 48 V DC servo motors 3564K048B of Dr. Fritz Faulhaber GmbH are used
for the control. They are fixed without a relative movement on the H-shaped frame in the
symmetrical axis of the model on both sides outside the wind tunnel, see Fig. 2. Note,
the position of the actuators is not restricted to the symmetrical axis of the cross section for the wind tunnel test and for an implementation of rotational actuators on real bridge girders.

One of the two servo motors has a maximum continuous torque of up to 44 mNm with a rotational speed of 58 s\(^{-1}\). The torque constant is 37.02 mNm/A. The maximum rotational speed is 72 s\(^{-1}\). With a continuous current of 1.36 A the servo motor has an output power of 101 W. Gears for torque enhancing are not implemented. Power is supplied by a 360 W power supply unit for each motor. According to the data sheets the degree of efficiency of the servo drive amounts to 0.82.

Optical encoders HEDS5540A of Dr. Fritz Faulhaber GmbH with 500 lines per revolution are used for measuring the angular position \(\gamma\) of the servo motors. The encoders fulfil yet another task: being mounted on top of the motors they measure the angular accelerations \(\ddot{\gamma}\) which are determined through the measured angles by means of two-time differentiating. For servo motor control the servo drive BLD 7010 of Dr. Fritz Faulhaber GmbH is used. For the torque control, the input value is an analogue signal of \(\pm 10\) V. The relation between motor current and motor torque being linear to a great extent is a characteristic feature of the internal control loop of the servo drive in this test.

The motors’ load discs have a weight of 56.1 g each. The additional entire driven control mass is complemented by the servo motors’ rotors with a weight of approximately 47.0 g each. The comparatively small mass of the optic pulse generator rotating disc is neglected. The control mass \(m_c\) of both servo actuators therefore is 206.2 g. The mass moment of inertia of rotor and pulse generator rotating disc is 34.6 gcm\(^2\). Under the assumption of material homogeneity the mass inertia of the load disc can be determined by means of geometry; it is nearly 55 gcm\(^2\). For the experimental identification of the mass moment of inertia of the motor load the servo motors are run at their maximum torque mentioned above. The resulting angular velocities are measured. The experimentally identified moment of mass inertia of the motor load is 116.5 gcm\(^2\) for each motor. By measuring the current of the servo motor and thus the motor’s torque constant it is possible to verify these results. Rotating in the same direction, the entire mass moment of inertia \(I_c\) of both servo actuators is 233.0 gcm\(^2\).

The mass ratio of the damper mass \(m_c\) and the mass \(m\) is 2.8 %. Considering the rotating degree of freedom, the mass moments of inertia, \(I_c\) and \(I\), yield a mass ratio of 0.02 %. The relative small value can also be achieved in an implementation of rotating actuators on real bridge girders. But, the practicability of flutter control via a motors’ torque \(M_c = I_c \dot{\gamma}\) is not only determined by the mass ratio but also by other characteristic values.
like maximum angular velocities and accelerations. Analytical results indicate a higher energy demand when using a lower mass ratio for rotational actuators [1].

2.3 Real-time implementation of control

The active vibration controller determines the control force, that is the servo motors’ torque, from the measured structural response (Fig. 2). The movements of the sectional model are measured with four inductive position encoders of Hottinger Baldwin Messtechnik GmbH. Energy input for the position encoders and the measuring amplifier system is regulated by the measuring amplifier device MGCPplus of the same company. For realizing the required inputs and outputs of the data processing in the computer the I/O-card MF 614 of the company Humusoft is used. The real-time implementation of the control is run by software Real Time Windows Target of The Math Works, Inc, offering an interface to Matlab Simulink.

The angular velocity $\dot{\alpha}$ of the bridge section model is controlled. The control force $u$ is the servo motors’ torque $M_c$. The control law is

$$M_c := k_4 \dot{\alpha}.$$  \hspace{1cm} (1)

The single feedback of $\dot{\alpha}$ can be explained by the fact that first, a control of the conditions $h$ and $\dot{h}$ through vibration damping is not planned and second, a displacement of the equilibrium point in $\alpha$ shall not lead to a continuous motor torque. The control parameter $k_4$ is identified experimentally.

3 System identification

For identification of mechanical parameters free vibration tests of the uncontrolled and controlled structures are used. In these initial tests no wind forces are acting on the bridge deck. The wind velocity is $v = 0$. Fig. 3 shows the measured structural response and time series of the control force $u$. 
The time required for the response to decline and stay at 5% of its final value is referred to as settling time. The active mass damper reduces the settling time of the rotational vibration $\alpha$ from 3.16 s to 2.03 s. Since the settling time of the vertical vibration $h$ is also reduced by the control, in this case from 5.41 s to 3.45 s, there is a mechanical coupling between the two degrees of freedom already referred to above. Furthermore, looking at the course of the vertical vibration $h$, a clear frictional impact can be noticed. The main reason for this are the sliding contacts of the inductive position encoders. Removed position encoders were filmed with 25 pictures per second. Simultaneously, the vibration series of structural response were measured via a background scale. The video data were then analyzed with a result of a damping ratio of $\zeta_h = 0.005$. The settling time of the vertical vibration makes up 35.29 s and is significantly higher than that of the in-built inductive position encoders.

![Figure 3: Uncontrolled (−−) and controlled (−−) free vibration response](image)

Introducing the state vector $z^T := (h, \alpha, \dot{h}, \dot{\alpha})$, the state space model of the mechanical system reads

$$
\dot{z} = \begin{pmatrix}
0 & I \\
-K_{\text{eff}} & -C_{\text{eff}}
\end{pmatrix} z, \quad \text{with} \quad C_{\text{eff}} = M^{-1} C, \quad K_{\text{eff}} = M^{-1} K,
$$

where the matrices $M$, $C$, and $K$ are the inertial, damping, and stiffness matrices of the mechanical system, respectively. The 2x2-matrices $C_{\text{eff}}$ and $K_{\text{eff}}$ are experimentally determined with regard to all elements. For system identification the Modified Ibrahim Time Domain Method (MITD) is used [10]. The method makes use of the free vibration response $z$ for identifying the modal natural circular frequencies $\omega_h$ and $\omega_\alpha$ and the damping ratios $\zeta_h$ and $\zeta_\alpha$ as well as the elements in $C_{\text{eff}}$ and $K_{\text{eff}}$. For sake of brevity, a detailed description of the identification method will not be given here. Further information can be found in [12].

Table 1 contains the identified mechanical system parameters for the uncontrolled and controlled set-ups. Comparing the system matrices of the uncontrolled and controlled systems, the impact of an active mass damper can be shown. It alters the mechanical system parameters, in this case especially the damper matrix parameters in $C_{\text{eff}}$.  

5
Table 1: Identified system parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncontrolled</th>
<th>Controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_h$</td>
<td>16.88 sec$^{-1}$</td>
<td>16.87 sec$^{-1}$</td>
</tr>
<tr>
<td>$\omega_\alpha$</td>
<td>30.22 sec$^{-1}$</td>
<td>30.19 sec$^{-1}$</td>
</tr>
<tr>
<td>$\zeta_h$</td>
<td>0.0124</td>
<td>0.0214</td>
</tr>
<tr>
<td>$\zeta_\alpha$</td>
<td>0.0215</td>
<td>0.0508</td>
</tr>
<tr>
<td>$C_{\text{eff}}$</td>
<td>$\begin{pmatrix} 0.4190 &amp; -0.0195 \ -1.3352 &amp; 1.2941 \end{pmatrix}$</td>
<td>$\begin{pmatrix} 0.7309 &amp; -0.1026 \ -5.2563 &amp; 3.0522 \end{pmatrix}$</td>
</tr>
<tr>
<td>$K_{\text{eff}}$</td>
<td>$\begin{pmatrix} 284.86 &amp; -1.84 \ 61.47 &amp; 914.29 \end{pmatrix}$</td>
<td>$\begin{pmatrix} 284.22 &amp; -2.26 \ 68.41 &amp; 915.12 \end{pmatrix}$</td>
</tr>
</tbody>
</table>

Corresponding to the control law, the servo motor torque is proportional to angular velocity $\dot{\alpha}$ of the bridge model. The time delays of the actuator and control valve have an impact on this proportional relation. In this case, the time delay between the measurement signals $\dot{\alpha}$ and $M_c$ is 0.01 s. According to the manufacturer time delays of the measurement unit are less than 1 ms and are therefore negligible. The rising regression line with all sets of values confirming a linear regression $(\dot{\alpha}, M_c)$ corresponds to the control parameter $k_4$ if the time delay between the two signals is neglected. In this initial test the following value was calculated:

$$k_4 = 0.0373 \text{ Nms.} \quad (3)$$

If the time delay of 0.01 s is taken into account in the calculation above the control parameter $k_4$ is reduced to 0.0350 Nms. The reduction by 6% of $k_4$ indicates that the time delay reduces control performance. For practical implementations in real bridge girders, the deterioration of control performance due to time delay have to be considered.

### 4 Flutter test

The critical wind speeds for both systems (the uncontrolled $k_4 = 0$ and the controlled $k_4 = 0.0350$) are determined experimentally in the wind tunnel. The wind speed is raised incrementally in the wind tunnel and free vibrations are measured. With the help of the described identification method the modal frequency and the damping ratios of both degrees of freedom for all test series are determined. The experimentally identified system parameters are plotted over wind speed, Fig. 4. The wind speeds of the intersection points of the curves of the damping ratios $\zeta_\alpha$ of both systems and the axis of abscissa are the respective critical flutter wind speeds.

The critical wind speed of the uncontrolled system is 13.57 m/s. The experimentally determined critical flutter wind speed of the controlled system is 15.81 m/s. The critical wind speed is thus increased by 16.5 % due to the control. A video of a flutter-control experiment in wind tunnel can be downloaded from [http://www.sh.tu-harburg.de/forschung/Flutter Control (Starossek, Germany).avi](http://www.sh.tu-harburg.de/forschung/Flutter Control (Starossek, Germany).avi). The control remained linear and showed no saturation effects during all experiments, see Eq. (1).

In addition, an amplifier $k_4 = 0, 141 \text{ Nms}$ was chosen to demonstrate the possibilities of the set-up. The controlled system can be stabilized for wind speeds up to 22 m/s which corresponds to an increase of 62 % compared to the uncontrolled set-up. During this additional test, the control showed significant nonlinearities. There are two reasons for this. First, there are differences concerning the input tracking of the internal control of the servo drive BLD 7010, and second, the saturation of the actuators is achieved very fast even with small-scale girder displacements. Using the same $k_4$, saturation deteriorates the control performance in comparison to the linear unsaturated case.

An analytical determination of critical wind speeds was also done and the results were compared to the experimentally obtained results. The critical wind speed is calculated
Figure 4: Structural parameters $\omega_h$, $\omega_\alpha$, $\zeta_h$, and $\zeta_\alpha$ plotted over wind speed for the uncontrolled ($k_4 = 0$) and the controlled system ($k_4 = 0.0350$).

Numerically by means of the Hurwitz criterion [13]. The Hurwitz stability criterion is based on the coefficients of the characteristic polynomial

$$\det[\lambda I - A(k)] = a_4 \lambda^4 + a_3 \lambda^3 + a_2 \lambda^2 + a_1 \lambda + a_0,$$

(4)

with the system matrix

$$A(k) = \begin{pmatrix} 0 & I \\ -K_{\text{eff}} + \pi \rho b^2 v^2 M^{-1} A_K(k) & -C_{\text{eff}} + \pi \rho b v M^{-1} A_D(k) \end{pmatrix},$$

where

$$A_K(k) = \begin{pmatrix} c'_{hh} & bc'_{h\alpha} \\ bc'_{h\alpha} & b^2 c'_{\alpha\alpha} \end{pmatrix},$$

$$A_D(k) = \begin{pmatrix} c''_{hh} & bc''_{h\alpha} \\ bc''_{h\alpha} & b^2 c''_{\alpha\alpha} \end{pmatrix},$$

$$M = \begin{pmatrix} m & 0 \\ 0 & I \end{pmatrix},$$

$\rho$ is the air density, $v$ is the mean velocity of the oncoming flow, and $b$ is the half width of the bridge deck. The nondimensional reduced frequency $k$ is defined as $k = \omega b/v$, where $\omega$ is the circular frequency of structural motion. The $c_{mn} = c'_{mn} + ic''_{mn}$ are dimensionless complex aerodynamic force coefficients (complex flutter derivatives) where $c'_{mn}$ and $c''_{mn}$ are real numbers and $i$ is the imaginary unit [14], [15]. The first index $m$ refers to the direction of the force, the second index $n$ indicates the motion causing the force. The complex force coefficients are functions of the reduced frequency $k$ and depend on the cross section under consideration. Alternatively, following the real notation approach by Scanlan in its latest form [16], eight real aerodynamic force coefficients $H_j^*$ and $A_j^*$.
\begin{align*}
c'_{hh} & = \frac{2}{\pi} H' \gamma, \quad c''_{hh} = \frac{2}{\pi} H' \gamma, \quad c'_{ah} = \frac{4}{\pi} A' \gamma, \quad c''_{ah} = \frac{4}{\pi} A' \gamma, \quad (5) \\
c'_{ha} & = \frac{4}{\pi} H' \gamma, \quad c''_{ha} = \frac{4}{\pi} H' \gamma, \quad c'_{aa} = \frac{8}{\pi} A' \gamma, \quad c''_{aa} = \frac{8}{\pi} A' \gamma. \quad (6)
\end{align*}

The flutter derivatives for a rectangular profile with an edge relationship of 1 : 8 are taken from [11].

The closed loop has an asymptotic stability if the following two conditions are satisfied:

1. All coefficients \( a_i \) are positive:
\[
a_i > 0, \quad i = 0, 1, 2, 3, 4. \quad (7)
\]

2. The following determinants are positive:
\[
\begin{vmatrix}
a_1 & a_3 & 0 & 0 \\
a_0 & a_2 & a_4 & 0 \\
0 & a_1 & a_3 & 0 \\
0 & a_0 & a_2 & a_4
\end{vmatrix} > 0, \quad \begin{vmatrix}
a_1 & a_3 & 0 \\
a_0 & a_2 & a_4 \\
0 & a_1 & a_3
\end{vmatrix} > 0, \quad \begin{vmatrix}
a_1 & a_3 \\
a_0 & a_2
\end{vmatrix} > 0. \quad (8)
\]

The wind speed is varied in an iterative procedure until the stability border is found. The procedure is repeated for modified reduced frequencies until the smallest and governing critical wind speed is identified. Table 2 contrasts the experimentally and numerically determined results. The results obtained for the critical wind speeds are in good agreement for both the uncontrolled and the controlled system. The differences between the experimentally determined reduced frequencies and their numerical equivalences is somewhat larger, though.

<table>
<thead>
<tr>
<th>k_4 = 0 \hspace{1cm} (uncontrolled)</th>
<th>Flutter test</th>
<th>Flutter analysis</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.57 m/s \hspace{1cm} k = 0.32</td>
<td>13.00 m/s</td>
<td>-4.2 %</td>
<td>-9.9 %</td>
</tr>
<tr>
<td>15.81 m/s \hspace{1cm} k = 0.27</td>
<td>16.99 m/s</td>
<td>+7.5 %</td>
<td>-10.2 %</td>
</tr>
</tbody>
</table>

5 Conclusions

Active mass dampers are implemented in a bridge section model. Servo motors serve as actuators. Their torques are controlled dependent on measured movements of the section model. The real-time implementation of the control uses software Real Time Windows Target in combination with Matlab Simulink. The damping and stiffness parameters as well as the control parameter are determined through initial tests followed by system identification of measured free vibrations of the uncontrolled and the controlled sectional model. Control loop time delays are measured and their impact on control quality is clarified.

The critical wind speed of the uncontrolled and the controlled structures are determined experimentally by wind tunnel tests. With linear control, the measured critical wind speed of the sectional model rises by about 16.5 %. The experimentally determined critical wind speed is compared with the numerical results. The Hurwitz criterion is used in the flutter analysis to determine the critical wind speed numerically. The experimental and numerical results are in good agreement.
Summarizing, an active mass damper with rotational servo actuators has, as it seems for the first time, successfully been implemented and used for flutter suppression of a bridge deck sectional model in a wind tunnel. Considering the number of practical implementations of active mass dampers for high-rise buildings, the experimental and analytical results indicate that active mass damper can be implemented also for flutter control in real bridge structures in the future.

The large energy demand of the proposed active mass damper in combination with linear control has been discussed in analytical studies before. Consequently, alternative active mass devices and/or control laws should be a topic of further research. The proposed wind tunnel tests are a first step towards finding solutions of active mass dampers that will be both satisfying and reliable.

Acknowledgements

This research is supported by funds from the Free and Hanseatic City of Hamburg, Germany, under scholarship HmbNFG of the Hamburg University of Technology.

References


