Experimental determination of structural damping of a full-scale building with and without tuned liquid dampers

Tarpø, Marius; Georgakis, Christos T.; Brandt, Anders; Brincker, Rune

Published in:
Structural Control and Health Monitoring

Link to article, DOI:
10.1002/stc.2676

Publication date:
2021

Document Version
Peer reviewed version

Citation (APA):
Experimental determination of structural damping of a full-scale building with and without tuned liquid dampers

Marius Tarpare
PhD Student
Aarhus University
Inge Lehmanns Gade 10
Aarhus, Denmark

Christos Georgakis
Professor
Aarhus University
Inge Lehmanns Gade 10
Aarhus, Denmark

Anders Brandt
Professor
University of Southern Denmark
Campusvej 55
Odense, Denmark

Rune Brincker
Professor
Technical University of Denmark
Brovej, Bldg. 118
Kgs. Lyngby, Denmark

Abstract

The theory of vibration absorbers is well established but the literature lacks documentation of the actual performance of absorbers installed in tall buildings. This paper presents an experimental assessment of the dynamic characteristics of one of two identical high-rise towers of the European Court of Justice in Luxembourg, before and after the activation of tuned liquid dampers, tuned to the frequency of the first mode. The prime focus of this assessment is structural damping and the effect that the tuned liquid dampers have on this. Two different full-scale test methods were utilized; operational modal analysis, using ambient vibrations, and harmonic forced vibration tests using two centrifugal mass exciters. All three modes were excited at and around their natural frequencies of approximately 0.44, 0.57, and 0.82 Hz respectively. To determine the damping, the free decays of the acceleration signals after shutting off the forces were studied. A clear and unambiguous increase in damping was found after the activation of the tuned liquid dampers, with damping increasing from 0.8% to 3.8% for the first mode. Also, the damping of the second mode was increased, although only from approximately 0.8% to 1%. The damping of the third torsional mode is approximately 0.6% and it is unaffected by the activation of the dampers. Thus, the tuned liquid dampers mainly affect the first mode as intended where the damping ratio increases with at least 500%. The results, finally, strongly suggest nonlinear behavior of the tuned liquid dampers, with higher damping at higher vibration levels.

Keywords: operational modal analysis; tuned liquid damper; vibration absorber; free decay measurement; vibration damping

1. Introduction

The adoption of new materials, building methods, and technology enables the construction of high-rise buildings with striking and slender shapes. A consequence of the tall, slender structures is often, however, unfortunate sensitivity to wind-induced vibrations due to the natural frequencies and damping ratios of the first swaying modes. This article is protected by copyright. All rights reserved.
modes that can be detrimental to human comfort. Thus, the sensitivity of occupants to vibration is a concern for such buildings since prolonged exposure to vibrations affects task concentration and even trigger dizziness, migraine, and/or nausea [1].

In the design process of the erected twin towers, housing the Court of Justice of the European Union in Luxembourg [2], see Fig. 1, it was found through simulations and wind tunnel tests that wind-induced loads could potentially cause discomfort due to structural vibrations in serviceability limit state. Various remedies were considered to reduce the vibration levels like structural stiffening, mass alteration, aerodynamic features, and vibration absorbers [2]. After investigation of different mitigation means, Tuned Liquid Dampers (TLDs), also called Tuned Sloshing Dampers (TSDs) - tuned to the first mode of the building - were chosen to reduce in-operation vibration levels and improve serviceability [3]. The choice was primarily based on the following criteria: cost of implementation, maintenance, tuning flexibility in regards with the structural uncertainties, and a minimum change to the structural design or load-bearing structure [2].

A dynamic vibration absorber is a secondary system, which is attached to a main system, with the intention of reducing the vibrations of the main system [4, 5]. There is a wide range of absorbers with different working principles and they can be both passive and active [6]. TLD is, however, the main focus in this paper. TLDs use liquid as a damping mass and there exist various types and configurations of these absorbers [7]. TLDs have been thoroughly investigated analytically and by laboratory experiments, for example, [5, 8–13]. It is well established that TLDs perform well [14]. Also, the nonlinear behavior with increasing damping by increasing vibration levels is well established [8, 15], based on shake table tests. Studies of full-scale tall buildings equipped with TLDs, however, are rare and have mostly focused on steel towers and tall buildings [11, 14, 16–18]. Furthermore, Su et al. [19] reviewed field monitoring of high-rise structures and, in this review, reported studies of buildings equipped with TLDs are rare. In general, published studies of the full-scale performance of vibration absorbers are very rare although absorbers are implementation worldwide [16, 18]. In the work of Tamura et al. [14], the run-down (free decay) and random decrement techniques before and after installing TLDs were used, and it was reported that the
dampers increased the damping by a factor of about 4.5-7. Furthermore, the dampers decreased the acceleration response with a factor of one third to one half during strong winds compared to response without TLDs. [Tamura et al.] reported that the damping ratio increased from 1% to 7.6% during a storm (high vibration levels) for a steel tower with an installed TLD. Love et al. [16] studied the added effective damping on two tall buildings with vibration absorbers under ambient excitation and compared it to theoretical predictions and they found an high correlation. Love and Haskett [18] evaluated the performance of three buildings with vibration absorbers where the measured performance match well with the predictions. They found that the added effective damping from the absorbers depended on the level of vibration but, during larger wind events, the absorbers added 1.5-3% effective damping. Love et al. [17] studied the full-scale performance of multiple tuned sloshing dampers installed in a tall building before and after the installation. The study found a good agreement between the theoretical and the full-scale performance where the dampers reduced wind-induced acceleration of the building with approximately 50% when wind speeds exceed 5m/s.

After the two Luxemburg Court of Justice towers were erected, it was decided to evaluate the structural behavior before and after installing the TLDs, to gain knowledge about and document the behavior of the TLDs. The objective of this study was, thus, to experimentally assess the structural dynamic properties of one of the two twin towers, prior to and after filling the TLDs with water. These results document the efficiency of TLDs installed in a concrete high-rise building, evaluated through both forced and ambient vibration methods. To the best of the authors’ knowledge, this is the first time TLDs behavior is investigated thoroughly on a high-rise concrete building with controlled external excitation. Generally, the literature lacks documentation on the actual performance of vibration absorbers installed in tall buildings [16]. The intention of this paper is not to present the design and model of the TLDs in detail, which are covered in [2,3,20], but instead to compare the actual full-scale performance prior and subsequently to filling TLDs. The novelty of this paper lies in the quantification of the actual performance and effectiveness of the TLDs with ambient and forced vibration tests. Uniquely, the forced vibration tests enable measurements of root-mean-square (RMS) response of the structure before and after the activation of TLDs. This paper, therefore, adds important information to the database of tall building damping characteristics and full scale tests.

2. Structure

The two identical towers form part of the fourth extension of the European Court of Justice, located in Luxembourg, see Fig. 1. The architect of the towers was Dominique Perrault Architecte (Paris), while Ingenieurs Conseils Associs (INCA) undertook the structural design of the twin towers. The 27-story towers are 102.8 meters tall, each with a mass of about 21,000 ton and a plan section of 14.4 by 48.6 meters. The structural systems of the two towers are identical and the primary parts consist of two concrete shafts, one at each end of the plan section, several columns and concrete slabs.

Subsequent to the start of construction, it was found that the structural vibration, in the serviceability limit state, could cause discomfort. Due to this potential discomfort caused by wind-induced loads, it was decided to reduce the vibration levels for the serviceability performance of the east tower. Several criteria were considered for the vibration absorbers, such as cost of implementation, maintenance, tuning flexibility, and structural uncertainties.
Table 1 TLD design parameters

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLD dimension [m]</td>
<td>2.14 x 1.81 x 0.75</td>
<td>1.81 x 2.14 x 0.75</td>
</tr>
<tr>
<td>Liquid height [m]</td>
<td>0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>Optimal modal mass ratios [%]</td>
<td>2.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Damper frequency [Hz]</td>
<td>0.44</td>
<td>0.573</td>
</tr>
<tr>
<td>Damper internal damping [% of crit.]</td>
<td>7</td>
<td>7 %</td>
</tr>
</tbody>
</table>

Furthermore, a critical restriction in the design of the vibration absorber was that the absorber could not change the structural design or the load-bearing structure of the towers since they were already under construction. Different remedy measures were investigated and the TLDs (in form of tuned sloshing dampers) were chosen as the economical and technical solution for the first structural mode. The reader should note that the term “tuned sloshing dampers” is often used interchangeable with “tuned liquid dampers” [7] and this paper uses the term tuned liquid damper. Here the dead load of the TLDs was distributed over the rooftop, see Fig. 2 so the bearing capacity was not exceeded. The TLDs consist of four large tanks on the roof and they are filled with water. See Fig. 2 for the plan view of the TLDs and Fig. 3(A) for a picture of the installed TLDs. Each tank contains between one and 24 individual TLDs with baffles, see Fig. 3(B). In total, there are 38 TLDs with a size of 2.14 by 1.81 meters and a height of 0.82 meters, and four of half that size [2, 3]. Two baffles are positioned crosswise in the middle of each TLDs where the baffles have steel bars/lamellas with a width of 60 mm and thickness of 8 mm with 40 mm spacing. These types of TLDs work in both plane directions so the TLDs for the first and second mode share the water volume and they have the same water height. Since the peak acceleration for tower was calculated to be dominated by the first mode then the design of the TLDs is optimized to the first bending mode of the tower while a mismatch for the second mode was acceptable [3]. The design parameters of the TLDs are listed in Table 1. In the design of the TLDs, the optimal modal mass ratios of the TLDs are 2.2% for the first modes and 2.0% for the second mode [20]. The modal masses were estimated to $4.18 \times 10^6$ and $4.55 \times 10^6$ kg for the first and second mode. The sloshing frequencies of the TLDs were calculated to 0.44 and 0.573 Hz in each direction [3] where the calculation was based on the work of Warnitchai and Pinkaew [21]. The internal damping of the TLDs were designed to 7% of critical damping [3]. Based on the design, the dynamic amplification factor would decrease 82% for the first mode and the effective structural damping was calculated to be five-fold of the original damping ratio [20]. The reader is referred to [2, 3, 20] for an in-depth description and analysis of the TLDs.

It was decided to perform two tests of the structural dynamic behaviour of the building, namely; i) Operational Modal Analysis (OMA), using the ambient wind loading, and ii) forced vibration tests, utilizing two eccentric mass exciters applying sinusoidal forces tuned to one natural frequency at a time. In the second case, damping is estimated from the free decay after shutting the exciters off. Fig. 4 shows one of the exciters used for the forced vibration tests. For the forced excitation, the two exciters generated forces to excite either of the two first bending modes, when operating in-phase, or the first torsion mode with the exciters on opposite sides of the center of rotation and operating out-of-phase.
Forced excitation measurements were chosen to be able to excite the structure with higher vibration levels because the damping properties of the TLDs are known to be highly nonlinear. The OMA results, on the other hand, would give information on the natural frequencies for faster tuning of the sinusoidal forces for the forced tests, and were also anticipated to give damping values of interest based on typical low-level wind loading.

The time frame for both OMA and forced vibration measurements was limited to four days, where OMA tests were performed on the first day and forced vibration tests on the second day, without the TLDs activated. During the night between the second and third day, the TLD tanks were filled with water. On the third and fourth day, OMA and forced vibration tests were again performed in the same sequence, however, with the TLDs activated. The order of testing was established so the initial OMA results could be used as a guide for the first three natural frequencies at which the harmonic excitation should be performed.

3. Theory and methods

3.1. Experimental Modal Analysis (EMA)

Experimental Modal Analysis (EMA) is a term used for forced and free vibration tests [22]. There are two types of free vibration tests: 1) resonant excitation; the free decay after a sinusoidal load excites the structure at an excitation frequency around one natural frequency and the excitation stops. 2) impact excitation or imposed displacement: followed by an estimation of the frequency response between force and response. The forced vibration tests, conducted on the European Court Building, is of the resonant excitation type.

In the beginning of a free decay from resonant excitation, different effects might affect the free decay - like exciter shutdown effect and dissatisfactory tuning of the excitation frequency. In reality, the exciter shutdown is not immediate and the excitation force will diminish over a small period of time. In the case of dissatisfactory tuning, the structure will, however, still seek to decay with its modal parameters [23]. Thus, when the excitation of a structure has a forcing frequency slightly different than the natural frequency, the free decay changes from the forcing to the natural frequency in a transient phase. This phase is called the "phase correction" and an identification process should exclude this phase.
At the end of a free decay, the vibrations are of a low level, thus, the ambient vibrations and measurement noise start to dominate the free decay. Hence, an identification process should exclude free decay when the
signal-to-noise ratio becomes small [22].

To exclude the phase correction and the ambient/noise dominated parts, only the middle part of the free vibrations - in the range 20 – 90% of the maximum amplitude [24] - are applied in the identification process of modal parameters. Fig. 5 A) illustrates the typical noise in EMA.

When applying excitation in EMA, the contribution of residual modes should be included or analyzed due to the fixed spatial distribution of the excitation [25]. The vector product between the mode shapes and the spatial distribution can lead to the contribution of modes far from the excitation frequency.

3.2. Operational Modal Analysis (OMA)

OMA uses operational or ambient excitation of structures to estimate the modal parameters [26]. When the excitation is white noise and the system is stationary and linear, then the correlation function matrix of the response is equivalent to free decays of the system [27].

\[
R_y(t + \tau) \triangleq E[y(t)y^\top(t + \tau)]
\]

where \(E[\cdot]\) is the expectation operator, \(y(t)\) is the system response, \(\tau\) is the continuous time lag, and \((\cdot)^\top\) denotes the transpose.

In reality, the correlation function matrix is estimated with finite data and this introduces statistical errors, thus, the estimated correlation function matrix is a stochastic process [28,29]. In general, the estimated correlation function matrix has a physical part, which has persistent features in the beginning and a noise dominated part, which behaves erratically, in the tail region. The width of the persistent part is called the correlation time and the noise part is called the noise tail [29,30]. The noise tail has a biased envelope [29], which must be excluded from an identification process to minimize bias errors on the damping estimates. Generally, increasing the time length of the measured response decreases the statistical errors, thus, the time length of the measurement series is an important parameter in OMA [29]. Brincker and Ventura [26] recommend \(T_{\text{min}} = \frac{10}{f_0\zeta_0}\) as the minimum time length where \(T_{\text{min}}\) is the minimum time length, \(f_0\) is lowest natural frequency, and \(\zeta_0\) is the damping ratio.

Measurement noise is, however, located differently in operational modal analysis than experimental modal analysis, since the system response is converted into the estimated correlation function matrix. Any uncorrelated broadband noise appears in the first few discrete time lags of the estimated correlation function [31].

To sum up, the first few discrete time lags must be excluded and the noise tail of the estimated correlation function matrix must be reduced. Fig. 5 B) shows the typical behavior of noise in OMA.

3.3. Identification techniques

This section presents the techniques that are used for identification of the modal parameters in the forced vibration tests and the ambient vibration tests.
3.3.1 Ibrahim time domain

The Ibrahim Time Domain (ITD) identification technique was developed as one of the first techniques for identification of multiple-output systems using free decays [32], but it has been extended to correlation function matrix used in OMA [33]. Therefore, this technique is applicable to all the tests on the European Court Towers.

Two block Hankel matrices, \( H_1 \) and \( H_2 \), are formed using the measured (discrete) system response, \( y(k) \), and the two Hankel matrices are delayed a single time step from each other.

\[
H_1 = \begin{bmatrix}
    y(1) & y(2) & \ldots & y(n-na) \\
    y(2) & y(3) & \ldots & y(n-na+1) \\
    \vdots & \vdots & \ddots & \vdots \\
    y(na-1) & y(na) & \ldots & y(n-1)
\end{bmatrix}, \quad H_2 = \begin{bmatrix}
    y(2) & y(3) & \ldots & y(n-na+1) \\
    y(3) & y(4) & \ldots & y(n-na+2) \\
    \vdots & \vdots & \ddots & \vdots \\
    y(na) & y(na+1) & \ldots & y(n)
\end{bmatrix}
\]  

(2)

where \( n \) is the number of utilized data points and \( na \) is the model order of the identification technique, or the number of block rows in the Hankel matrix. In this implementation, a high model order is applied along with principle component analysis on the Hankel matrices to reduce the dimension to the decided size. The reduced dimension is often referred to as the model order [34]. This implementation is called the Multiple-reference Ibrahim time domain (MITD). Regardless of the implementation, \( H_2 \) is equal to \( H_1 \) but delayed one discrete time step.

The discrete system model, \( A \), calculates the next time step of a transient system response [33]. This matrix holds all the modal parameters of the system.

\[
AH_1 = H_2
\]  

(3)

Based on this equation, the discrete system matrix is estimated.

\[
\hat{A} = \frac{H_2H_1^\top (H_1H_1^\top)^{-1} + H_2H_2^\top (H_1H_2^\top)^{-1}}{2}
\]  

(4)

The modal parameters are extracted by eigenvalue decomposition of the estimated discrete system matrix.

The extension of this identification method to the correlation function matrix used in OMA is given in [33]. In this paper, a version of the MITD based on the ABRAVIBE toolbox [22] is used and this implementation is based on [34].

3.3.2 Hilbert transformation

The Hilbert transformation has been applied to structural dynamics in numerous ways [35]. The Hilbert transformation can estimate modal parameters from a free decay of a Single-Degree-of-Freedom (SDOF) system [36]. This identification technique requires that each measured channel contains a single free decay of an SDOF system. Furthermore, it does not account for noise or residual modes, unlike other identification techniques.

The free decay is given by the following equation

\[
y(t) = Ce^{-\alpha(t)t} \cos(\omega_d(t)t - \beta)
\]  

(5)

Using the Hilbert transformation on the free decay, the analytic signal is obtained [22].

\[
y_a(t) = Ce^{-i\beta(t)}e^{(-\alpha(t)+i\omega_d(t))t}
\]  

(6)

The logarithmic function is applied to "unwrap" the analytic signal and obtain a first-order polynomial.

\[
\log(y_a(t)) = \log(C) - i\beta + (-\alpha(t) + i\omega_d(t))t
\]  

(7)

The slope of this first order polynomial is found by two points with \( t_0 \) between them.

\[
-\alpha(t) + i\omega_d(t) = \frac{\log(y_a(t + t_0)) - \log(y_a(t))}{t_0}
\]  

(8)
The undamped frequency and the damping ratio are calculated as

$$\omega(t) = \sqrt{a(t)^2 + \omega_d(t)^2}, \quad \zeta(t) = \frac{a(t)}{\sqrt{a(t)^2 + \omega_d(t)^2}}$$

In discrete form, $a$ and $\omega_d$ are estimated as the difference between any data point and the succeeding data point of the logarithmic analytic signal. The median value is used to obtain a single estimate of the frequency and damping ratio for the entire decay.

### 3.3.3 Enhanced Frequency Domain Decomposition (EFDD)

Brincker et al. [37] made the frequency domain decomposition technique for OMA. It uses the spectral density matrix for ambient system response excited by white Gaussian noise. The spectral density matrix is defined as

$$G_{yy}(\omega) = \mathcal{F}\{\mathbb{E}[y(t)y^\top(t+\tau)]\}$$

where $\mathcal{F}(\cdot)$ denotes the Fourier transformation.

The frequency domain decomposition uses the modal superposition, which states that the response of a linear system is a linear combination of its mode shape.

$$y(t) = \Phi q(t)$$

where $\Phi$ is the mode shapes and $q(t)$ is the modal coordinates (the time-dependent linear combination).

Eq. (10) is rewritten by applying the modal decomposition, Eq. (11)

$$G_{yy}(\omega) = \Phi G_{qq}(\omega) \Phi^H$$

where $G_{qq}(\omega)$ is the autospectral density matrix of the modal coordinates and $(\cdot)^H$ denotes the Hermitian transpose or the conjugate transpose. A similar expression as Eq. (12) is found by applying the singular value decomposition to the definition of the spectral density matrix, Eq. (10), for each angular frequency.

$$G_{yy}(\omega) = U(\omega)S(\omega)U(\omega)^H$$

where $U(\omega)$ is the singular vectors as a function of frequency, $\omega$, and $A(\omega)$ is the singular values as a function of frequency, $\omega$.

Near the frequency of a particular mode, the adjacent vectors in $U(\omega)$ are dominated by the local mode $i$, and are all essentially equal to the actual mode shape, $\phi_i$. The frequency domain decomposition approximates a mode shape by assuming, it is analogous to the first singular vector near the frequency of a mode [37]. The Enhanced Frequency Domain Decomposition (EFDD) [38] method uses this to select a number of frequency bins corresponding to those vectors in $U(\omega)$ with Modal Assurance Criterion (MAC) values close to unity, which relates to the equivalent single-degree-of-freedom system in the modal coordinates. These frequency bins are then used in an inverse discrete Fourier transform, producing a free-decay time signal, from which the natural frequency and damping can be obtained.

In this paper, a version of the EFDD from the OMAtools [26] is used.

### 4. Ambient vibration tests - operational modal analysis

#### 4.1. Setup of test

The measurement system used for the ambient vibration tests was a digital geophone based system consisting of a client/computer, a sensor base, and a measurement chain of sensor nodes. CAP2 ApS process the sensors. The sensors were glued directly on top of the concrete in the two staircases of the building, see Fig. 6. A roving sensor scheme was utilized to obtain higher spatial resolution of the estimated mode shapes where some sensors are kept at the same locations as references sensors while the remaining sensors the rowing sensor that are moved to new locations after each test [26]. Two of these systems were used, one recording the x- and y-directions in a reference point on the 24th floor, and one station which was moved to different floors, recording three horizontal measurements in two sensor nodes on each floor, see Fig. 7. Five data sets were recorded using a sampling...
Fig. 6 Representative plan view of the structural system of the towers and the positioning of the sensors, the center of rotation, and exciters

Table 2 Natural frequencies and damping estimates from operational modal analysis test prior to the activation of the TLDs. Results from the enhanced frequency domain decomposition and Multiple-reference Ibrahim time domain analysis are tabulated where $\mu$ is the sample mean and $\bar{\sigma}$ is the sample coefficient of variation.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Enhanced frequency domain decomposition</th>
<th>Multiple-reference Ibrahim time domain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency [Hz]</td>
<td>Damping ratio [%]</td>
</tr>
<tr>
<td></td>
<td>$\mu$</td>
<td>$\bar{\sigma} \cdot 10^{-2}$</td>
</tr>
<tr>
<td>1</td>
<td>0.449</td>
<td>0.175</td>
</tr>
<tr>
<td>2</td>
<td>0.582</td>
<td>0.115</td>
</tr>
<tr>
<td>3</td>
<td>0.828</td>
<td>0.0845</td>
</tr>
</tbody>
</table>

4.2. Data processing

Two methods were used for modal parameter extraction; the EFDD method and MITD method in the modified version, see Section 3.3. Since the two methods use different numerical approaches, a comparison between estimates from the two methods can be used for assessing the reliability; the closer the estimates are, the more reliable they are likely to be. In the MITD, a total of 40 block rows are used in the Hankel matrices and maximum model order of 30 is applied in the identification process.

The data were decimated to a new sampling rate of 5 Hz and data segments of 512 data points were applied in the calculation of the correlation function matrix and spectral density matrix. Due to the short time length, the algorithm from [30] is applied to reduce statistical errors on damping estimates.

4.3. Results and discussion

Since the TLD was primarily designed to affect the first mode of the building, and to have some slight impact also on the second mode, it was considered sufficient to estimate the modal parameters of the first three modes.
Fig. 7 Data set 1-5 from left. The data were recorded at the 5th, 10th, 15th, 20th and 24th floor.

Table 3 Natural frequencies and damping estimates from operational modal analysis test after the activation of the TLDs. Results from the enhanced frequency domain decomposition and Multiple-reference Ibrahim time domain analysis are tabulated where $\mu$ is the sample mean and $\tilde{\sigma}$ is the sample coefficient of variation.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Enhanced frequency domain decomposition</th>
<th>Multiple-reference Ibrahim time domain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency [Hz]</td>
<td>Damping ratio [%]</td>
</tr>
<tr>
<td></td>
<td>$\mu$</td>
<td>$\tilde{\sigma} \cdot 10^{-2}$</td>
</tr>
<tr>
<td>1</td>
<td>0.442</td>
<td>0.12</td>
</tr>
<tr>
<td>2</td>
<td>0.59</td>
<td>0.124</td>
</tr>
<tr>
<td>3</td>
<td>0.826</td>
<td>0.114</td>
</tr>
</tbody>
</table>

Fig. 8 Singular values with logarithmic y-scale of the principal component matrix for the OMA test prior to activating the TLDs (data set 2) and the identified modes for the enhanced frequency domain decomposition.
Fig. 9 Stabilization diagram from the OMA test after TLD activation (data set 3) using the Multiple-reference Ibrahim time domain method. The vertical axis shows the model order as the number of eigenvalues in the model. Red circles indicate stabilized modes and black squares indicate spurious modes. The green bar indicates the model selected for analysis and the black ‘x’ indicate the chosen stable modes.

Fig. 10 Cluster diagram from the OMA test after TLD activation (data set 3) using the Multiple-reference Ibrahim time domain method. Red circles indicate stabilized modes and black squares indicate spurious modes. The black crosses indicate the chosen stable modes corresponding to the green bar from Fig. 9.
Fig. 11 Singular values with logarithmic y-scale of the principal component matrix for the OMA test after TLD activation (data set 3) and the identified modes for the enhanced frequency domain decomposition.

Fig. 12 The first three merged mode shapes from the Ibrahim time domain identification from the OMA test prior to activating the TLDs.

Fig. 13 Cluster diagram for all identified modes throughout all data sets.
The results of the parameter extraction using the EFDD and MITD methods are presented in Table 2 prior to the activation and Table 3 post to the activation of the TLDs. Fig. 12 shows the merged mode shapes for the five data sets prior to the activation of TLDs for the MITD method.

Prior to the activation of the TLDs, the natural frequencies using both analysis methods were found to be near identical, whereas the damping ratios varied somewhat more, however, within a difference of 10%. In OMA, this amount of uncertainty in the damping estimates is within the expected accuracy of the method due to the statistical errors. The principal component plot from the EFDD analysis is shown in Fig. 8.

Post to the activation of the TLDs, the modal parameters from the EFDD and MITD analysis are presented in Table 3. The natural frequency estimates are very similar between the two analysis methods, whereas the damping estimates of each mode are within 15%. A stability diagram from the MITD analysis is shown in Fig. 9, where it can be seen that the stability diagram is clean for the three modes of interest. The cluster diagram shows that stable clusters are formed for each mode, see Fig. 10.

The spectral densities show that the peak for the first modes slightly splits into two peaks around 0.44 and 0.46 Hz, see Fig. 9. This is consistent with theory of the TLDs (the two-peak-curve according to Den Hartog [5]) where a mode is split into two; where the structural mode is in or out of phase with TLDs. Furthermore, the pure structural mode - without the effect of the TLD - is located in between the two peak. The MITD primarily estimates the most dominating mode of these closely spaced, split modes, while the other mode is less stable. The mode shapes from both peaks are similar, therefore the EFDD cannot decorrelate them into two modes, but the technique estimates a mean between the two dominating frequencies of the peaks as seen Fig. 11. The second peak is difficult to estimate throughout all five data sets.

To analyse the effect of the TLD, Fig. 13 shows all estimated frequencies and damping ratios for both prior and post activation of the TLDs in a cluster diagram. It shows the increase in damping ratio for the first and second mode due to the TLDs. The first mode decreases its natural frequency while the second mode increases. This indicates that the TLDs are properly tuned for the first mode while they are inadequately tuned for the second mode - though they add damping to the mode. The third mode has no change in either frequency nor damping ratio. Furthermore, no notable changes were observed in MAC values between the mode shapes - prior and post activation of TLDs.

5. Forced vibration tests - experimental modal analysis

5.1. Setup of test

Two centrifugal mass exciters, Fig. 4, were employed to produce sinusoidal forces in the three directions of interest. Each exciter produces a rotational frequency dependent load with force amplitude

\[ f_F = m r \omega^2 \] (14)

where \( m \) is the rotating mass in kg, \( r \) is the radius from the center of rotation in meters, and \( \omega \) is the angular frequency of the exciter in rad/s. A mass of 350 kg was mounted on each exciter at a distance of \( r = 0.524 \) m from the center of rotation. With 1 Hz rotation, each exciter can produce a maximum harmonic load of approximately 7.4 kN.

The mass of the exciters is 409 kg each, they have a service range of 0 to 1.6 Hz and 0.8 m diameter wheel which can carry a maximum attached mass of 350 kg. The control boxes were connected to a personal computer (PC) in order to control the exciter’s frequency and start/stop of the experiments. The control circuitry allows the two exciters to be accurately synchronized for operation either in-phase or out-of-phase.

The exciters were installed at the 25th story, which is the technical floor of the buildings (95.2 m height) and positioned as shown in Fig. 6. They were positioned in three different configurations, one for each mode, and programmed to operate in-phase and out-of-phase for the tower’s primary bending modes and torsional modes, respectively. The exciters produce both a horizontal and vertical load, and to prevent the exciters from sliding and lifting, they were placed on rubber sheets and the supporting frame was covered with one metric ton of sandbags.

The accelerations of the building during the forced vibration testing were recorded by a GeoSIG AC-63 accelerometer, with a sensitivity of 10 V/g. The tri-axial accelerometer was placed on the platform in the stairwell between TB and TC and connected to a PC, which collected the measured data. The positions of the different sensors are shown in Fig. 6.

The natural frequency of each mode was found by fine-tuning the frequency of the forced response excitation around the initial estimates found by the OMA results, and observing when the beating in the amplitude envelope
of the forced acceleration response disappeared. After finding the natural frequency, data were recorded with a sampling frequency of 10 Hz and observed online. When steady-state vibration was observed, the exciters were abruptly shut down and the acceleration signals continued to be recorded until ambient vibration levels were obtained.

5.2. Data processing

The data were first detrended, after which they were bandpass filtered with narrow filters around the natural frequency of interest. A Butterworth filter of order 5 is applied around the frequency of the decay to reduce noise and residual modes.

Two methods are used for the identification process; the Hilbert transform and ITD method, see Sections 3.3.2 and 3.3.1. Since the free decay is filtered and assumed to contain a single free decay of an SDOF system, then a low model order of 2 is used for the ITD method.

5.3. Results and discussion

Table 4 presents the results of the analysis of forced response measurements prior to activating the TLDs. In the last two columns, also the Root Mean Square (RMS) and the maximum acceleration levels during the steady-state condition just prior to shutting the exciters off are listed.
Fig. 16 Second mode time-history and free decay without (A) and with (B) the TLDs activated.

Fig. 17 Second mode linear damping in both the non-damped (A) and damped (B) case.
Table 4 Estimated frequencies, damping and acceleration levels during the various forced vibration tests

<table>
<thead>
<tr>
<th>Mode</th>
<th>Hilbert transform</th>
<th>Ibrahim time domain</th>
<th>Steady-state acc.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency [Hz]</td>
<td>Damping Ratio [%]</td>
<td>Frequency [Hz]</td>
</tr>
<tr>
<td>1</td>
<td>0.443</td>
<td>0.755</td>
<td>0.443</td>
</tr>
<tr>
<td>1 with TLDs, part 1</td>
<td>0.436</td>
<td>3.96</td>
<td>0.439</td>
</tr>
<tr>
<td>1 with TLDs, part 2</td>
<td>0.441</td>
<td>0.368</td>
<td>0.439</td>
</tr>
<tr>
<td>2</td>
<td>0.573</td>
<td>0.859</td>
<td>0.572</td>
</tr>
<tr>
<td>2 with TLDs</td>
<td>0.581</td>
<td>0.981</td>
<td>0.582</td>
</tr>
<tr>
<td>3</td>
<td>0.821</td>
<td>0.627</td>
<td>0.82</td>
</tr>
</tbody>
</table>

The measurement signals for the first mode are plotted in Fig. 14 - both prior and post to the activation of the TLDs. Prior to the activation of the TLDs (Fig. 14 A), the response is an exponential decay down to the ambient vibration level, see Fig. 14 A. With the TLDs activated, the free decay, however, splits into two regions; one with a high decay rate (high damping) followed by a lower decay rate (low damping). This is visualized in Fig. 15. Therefore, the analysis of the first mode - after activating the TLDs - was divided into two areas, for which separate damping estimates were obtained, see Table 4. The first damping ratio estimated at high acceleration levels is four to five times (dependent of the identification technique) higher than in the case prior to activating the TLDs in Table 4 whereas the second value is closer to the damping ratio found without the TLDs. Furthermore, the RMS acceleration level decreased with 63% after the activation of the TLDs. A similar reduction is observed in the maximum acceleration levels that dropped 64%. The effective damping for the first structural mode is 2.06% using Table 4. The reason, the acceleration level did not decrease proportionally to the increase of the damping ratio, is likely due to nonlinear behavior of the TLDs, where increasing levels of vibrations are associated with increased damping ratios. The sloshing model used for the TLDs was, however, linear [20].

The second mode had an increase in both frequency and damping ratio due to activation of the TLDs. Corresponding time history and zoom on the decay are shown in Figs. 10 and 11 for the second mode. As can be seen in these figures, there is only a single exponential decay in this case and the same was the case for mode 3. For the second mode, both the RMS and the maximum acceleration levels dropped 44% by the activation of the TLDs. Due to time restrictions and the fact that the OMA analysis had shown that the damping of the third mode was unaffected by activating the TLD, it was decided not to excite this mode after activating the TLDs.

The results from OMA show that the first two mode shapes are not pure bending modes in the global directions, see Fig. 12. Thus, the exciters have a fixed spatial distribution for each configuration that does not fit completely to the mode of interest. Residual modes likely contribute with some quasi-static response in the free decay and it is a potential error in the modal parameter estimation. ITD has the advantage that it takes residual modes and noise into account by fitting more poles to the free decay.

6. Discussion

In this section, the results of the OMA - both before and after activating the TLDs - will be compared and discussed with the corresponding analysis from the forced response analysis, EMA. Generally, the estimated frequencies are slightly lower and the estimated damping ratios are higher for the forced vibration tests than the ambient OMA test.

Prior to the activation of TLDs, there are no notable differences in the damping estimates from the ambient and forced vibrations tests when one takes the inaccuracies in the estimates into account, see Table 2 and Table 4. Since the vibration levels were significantly larger in the forced response test, it thus seems that the structure behaved approximately linearly before the TLDs were activated.

With the activated TLDs, the OMA analysis yielded significantly lower damping estimates than the forced response, see Table 3 and Table 4. This, again, could be attributed to the nonlinear behavior of the TLDs, since the OMA measurements were made at significantly lower vibration levels than the forced response measurements.

A comparison of the damping estimates for the first mode from the OMA analysis, see Tables 2 and 3 and the forced response test, see Table 4 shows that the OMA damping estimate - with the TLDs inactive - is nearer to the damping estimates found by the latter part of the forced response analysis. This indicates that the TLD has little
effect at the end of decay, which can be attributed to the nonlinear sloshing motion of TLDs [41], which causes a lower threshold below which there is little damping generated by the TLD.

In the OMA test, a characteristic splitting of the first natural frequency into two is observed at approximately 0.44 and 0.46 Hz. Thus, the first mode splits into an approximated frequency shift of ±0.01 Hz. This is expected when the secondary system is tuned to the frequency of the first mode of the structure. In the forced vibration tests, the frequency of the exciters was tuned to the frequency of the first peak for the first mode.

The damping ratio of the second mode is less affected by the TLDs than that of the first mode, which agrees with the fact that the TLDs were designed to affect predominantly the first mode. It should be noted also, that some of the increased damping ratios in the OMA results in the case of the TLD activation, could be attributed to stronger wind conditions on the day of the test with the TLDs activated than on the day of the test prior to activating the TLDs. For both tests, the second mode has a slight increase in natural frequency after the activation of TLDs. This could be caused by an insufficient tuning of the TLDs in regards to this mode. The associated acceleration levels for the second mode dropped with 44% during the forced response steady-state condition, when the TLDs were activated.

Furthermore, the damping ratio for the second mode is higher in the OMA tests than in the force response test. In this study, the OMA and force response tests are associated with low and high levels of vibration, respectively. Due to nonlinearities in TLDs, increased level of vibration should correspond to higher damping ratio [8,15], which was also the case for the first mode but the opposite is the case for the second mode. These results could be caused by the nonlinearities in the TLDs which are frequency-energy dependent. The higher vibration level seems to slightly decrease the frequency of the second mode, 0.58 Hz, compared to the OMA tests, 0.59 Hz. This potential decrease in frequency at a high level of vibration could result in a further detuning of the TLDs in regards to the second mode.

The damping ratio of the third mode (taken from the OMA tests, as no forced response test was done after the TLDs had been activated) did not change significantly when the TLDs were activated. This is consistent with the fact that the TLDs were not designed to affect this mode.

7. Conclusion

The natural frequencies and relative (viscous) damping ratios of the first three modes of a high-rise building were experimentally determined before and after tuned liquid dampers (TLDs) were activated. Two different test methods were used, partially to ensure testing using sufficiently high excitation levels because of the known nonlinear behavior of TLDs. Firstly, Operational Modal Analysis (OMA) was used to find both natural frequencies and damping factors. Secondly, free decays after exciting the building with a harmonic excitation at each natural frequency were used to estimate the damping ratios. Tests were performed with both methods prior and post to activation of the TLDs.

Prior to activating the TLDs, OMA using natural (predominantly wind) excitation resulted in natural frequencies of approximately 0.45, 0.58, and 0.83 Hz, respectively. Two modal parameter extraction techniques were used which resulted in somewhat different damping estimates. The relative damping factors were, thus, found to be approximately 0.57 % for the first mode, 0.56 % for the second mode, and 0.57 % for the third mode. The natural frequencies found by tuning the forced response harmonic excitation until no beating occurred, were consistent with the frequencies found by OMA. Corresponding results for the damping factors found by the forced response and free-decay method were slightly higher at approximately 0.80, 0.83, and 0.64 %, respectively.

For the case with the TLDs activated, the natural frequencies did not change significantly. The OMA test yielded damping ratio estimates of 1.6, 1.3, and 0.57 %, for the three modes, respectively. Corresponding values from the forced response tests were approximately 3.8 % for the first mode and 0.95 % for the second mode. No forced response measurement was made for the third mode with the TLDs activated. For the first mode, the damping ratio increased with a factor of 4 times compared to damping prior to TLDs.

For the first mode, to which the TLDs were tuned, a threshold was found in the free decay from the test with the TLDs activated. After the initial high damping, the damping significantly decreased to approximately 0.35 %, which was consistent with the OMA result and approximately the same damping as was obtained without the TLDs. This is attributed to the nonlinear sloshing motion of TLDs, which causes a lower threshold below which there is little damping caused by the TLD. The higher damping factors found by the forced response tests, which overall were using higher vibration levels than the OMA tests, strongly suggest nonlinear behavior of the TLDs, with higher damping at higher vibration levels.

The theoretical level of effective damping differs slightly from the experimentally observed damping effects.
The theoretical reduction of the vibration levels was 82% in the design while the measured reduction was approximately 64% based on the forced vibration tests. The theoretical added effective structural damping was expected to be five-fold of the original damping ratio and the experimental amplification were four to five-fold. The theoretical effective damping correlates well with the experimental results while there is an incongruence in the reduction of vibration between theory and full-scale tests. This could be contributed to the nonlinearity in TLDs where an increase in the level of vibration results in higher damping ratios. It is concluded that the TLDs worked as they were designed to, with a strong effect on the first mode and some, but a lower effect on the second mode, whereas the third mode was unaffected by the TLD.

Furthermore, it is concluded that OMA is applicable to structures with TLDs. All identification techniques, used for OMA in this paper, were able to capture the characteristics of the TLDs and they show increased levels of damping. Without sensors directly on the TLDs, the OMA identification techniques, however, struggle with separation of the split modes - where the TLDs move in or out of phase with the structural mode. The EFDD could not separate the two modes and it identified an average between the two while the MITD could distinguish the split modes for some model orders.

Acknowledgements

The authors express their gratitude to Ingenieurs Conseils Associés (INCA), and in particular to Dietmar Schilz, for assistance in planning and arranging the experiments. We also acknowledge the work carried out in connection with the experiments by Dr. Einar Thor Ingolfsson, Krabbenhoft Consulting Engineers ApS, Copenhagen, Denmark, Mads Christiansen, Øllgaard Rådgivende Ingeniører A/S, Hellerup, Denmark, and Dr. Robert Bolton.

REFERENCES


This article is protected by copyright. All rights reserved.


This article is protected by copyright. All rights reserved.
Singular Values of Spectral Densities of Test Setup:
Dataset2

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>dB</th>
<th>(1 m/s²)² / Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>120</td>
<td></td>
</tr>
</tbody>
</table>

This article is protected by copyright. All rights reserved.
This article is protected by copyright: All rights reserved.
This article is protected by copyright. All rights reserved.
fig6b.eps
This article is protected by copyright. All rights reserved.
This article is protected.
This article is protected by copyright.
This article is protected by copyright. All rights reserved.
Hilbert transformation
Ibrahim time domain

This article is protected by copyright. All rights reserved.
mode_2_passive_2.eps
This article is protected by copyright. All rights reserved.
This a
This article is protected by copyright. All rights reserved.
1.5 Configuration of the dampers

The Tuned Liquid Dampers (TLDs) which are installed on the roof of the towers are a system of in total four cages that contains in total 38 TLDs of equal size and 4 half size of the latter, see Figure 1.5. The TLDs are designed as liquid tanks which are divided into four sections by screens in order to increase the internal damping, see Figure 1.6 and the liquid height is controlled in order to tune the TLDs especially for Mode 1.

<table>
<thead>
<tr>
<th>Center of stiffness</th>
<th>Direction to geographic north</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y = 6.17 m</td>
<td>Φ(y) = 135°</td>
</tr>
<tr>
<td>X = 18.80 m</td>
<td>Φ(x) = 225°</td>
</tr>
</tbody>
</table>

Table 1.3: Properties for the towers.

![Figure 1.5: Plan view for placement of the TLDs. Measures in meters.](image)

<table>
<thead>
<tr>
<th>Cage no.</th>
<th>Height</th>
<th>Depth</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-4</td>
<td>0.82</td>
<td>1.81</td>
<td>2.14</td>
</tr>
</tbody>
</table>

Table 1.4: Dimensions for internal parts of the Tuned Liquid Dampers for a) the internal sections and b) the screens.