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Damping estimation of large wind-sensitive structures

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Abstract

The adequacy of two identification techniques to accurately estimate the modal damping ratios (MDRs) from ambient vibration records is assessed for long-span suspension bridges with eigen frequencies close to or below 0.1 Hz. The first method is an automated covariance driven stochastic subspace identification (SSI-COV) algorithm and the second one is an automated Frequency domain decomposition algorithm (AFDD). The bias and the dispersion of the identified MDRs are first assessed using simulated bridge vibration records and then investigated using full-scale acceleration data obtained on the Lysefjord Bridge, Norway.

The simulated data showed that record durations of 60 min provided up to three times more accurate estimates of the MDRs than if the more common record duration of 10 min is used. For the full-scale acceleration records and a duration of 60 min, the MDR estimates showed a relatively large dispersion with a non-Gaussian distribution, suggesting that the median value of the MDR may be more reliable than the arithmetic mean. The AFDD algorithm was observed to estimate the MDRs with a larger bias than the SSI-COV method. This suggests that the frequency-domain based approach is not well suited for the modal parameters identification of long suspension bridges with eigen-frequencies around and below 0.1 Hz.

Keywords: Long-span bridge, Damping ratio, Full-scale measurements, Operational modal analysis, System identification

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1. Introduction

The studies of the modal parameters of a long-span suspension bridge often show that the structural modal damping ratios (MDRs) increase for decreasing eigen frequencies, especially when the latter approach 0.1 Hz [1, 2]. This can be a natural behaviour, for instance caused by increasing vibration amplitudes, but also a bias due to signal processing errors, which are generally larger for low vibration frequencies. The duration of the records used in the analysis is known to affect the accuracy and the precision of the damping estimates [1, 3]. To estimate MDRs associated with low frequencies with a reasonable accuracy, the data records used need to be long enough. This has been pointed out in the literature [4], but without any specific recommendations for long-span suspension bridges. Typically, the wind and the associated bridge response are analysed over a period ranging from 10 min [5] to 60 min [6]. An increasing record duration involves an increasing probability of non-stationary wind and acceleration records [7]. For a wind-sensitive

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structure, for which a significant part of the total damping is due to the aeroelastic effects, this will imply a limited accuracy of the estimated aerodynamic damping as a function of the mean wind speed.

The present paper aims therefore to investigate what time series duration is best suited for an accurate estimation of the structural MDRs of the vibration modes characterised by a low eigen-frequency.

This paper is organized as follows: first, the MDRs are studied statistically using simulated wind-induced acceleration records of two single-span suspension bridges. The data are generated by applying a zero mean Gaussian white noise load process in the time domain to a simple computational model of the structure. The identification method relies first on an automated covariance driven stochastic subspace identification (SSI-COV) algorithm and an Automated Frequency Domain Decomposition (AFDD) algorithm. The automated SSI-COV method is inspired from Magalhães et al. [8] which has been observed to be well suited for long-span suspension bridges [9, 10]. The AFDD is based on the combination of the classical Frequency Domain Decomposition method [11] and the peak-picking algorithm proposed by Liutkus [12]. Magalhães et al. [4] applied both the FDD and SSI-COV methods to estimate the MDRs of a variety of large civil engineering structures, but not a suspension bridge, which is precisely the type of structure for which the eigen frequencies can be close or below 0.1 Hz. In some ways, therefore, the present study complements the works of Magalhães et al. [4]. Secondly, a similar investigation is conducted for six months of full-scale wind and acceleration data, obtained from continuous recordings between July 2015 and December 2015 on a 446 m long single span suspension bridge located in South-Western Norway.

2. Instrumentation and methods

2.1. *The Simplified Bridge Model (SBM)*

The estimation of the bias of the MDRs of a long-span suspension bridge is first illustrated for a simplified bridge model (SBM). The bridge deck is modelled as a horizontal line discretized into 75 nodes. The mode shapes and eigen frequencies are estimated using the method proposed by Sigbjörnsson and Hjorth-Hansen [13] and Strømmen [14], which was observed to apply well for a narrow single-span suspension bridge [15].

Two single-span suspension bridges with similar layout and the back-stays directly anchored to the rock, in the mountainous areas in Norway, are studied. The Lysefjord Bridge, which has a main span of 446 m is used as an example of "medium span" suspension bridge with well separated modes. The Hardanger Bridge, which has a main span of 1310 m is used as an example of "long span" suspension bridge with closely spaced modes. The bridge response is computed in the time domain by considering the first 6 modes for the lateral, vertical and torsional motions.

The present study investigates the MDRs of vibration modes with an eigen-frequency close or below 0.1 Hz. In the case of the Lysefjord Bridge, only the first symmetric lateral mode (HS1) possesses a natural frequency close to 0.1 Hz equal to 0.13 Hz. For the Hardanger Bridge, the frequencies associated with HS1, VA1 (first asymmetric vertical mode) and VS1 (first symmetric vertical mode) are equal to 0.05 Hz, 0.10 Hz and 0.14 Hz respectively.

2.2. *Full-scale measurements*

The influence of the record duration T on the MDR estimation is also illustrated using full-scale data from the Lysefjord Bridge, which has been instrumented with a Wind and Structural Health monitoring system since November 2013. The instrumentation of the deck relies on 7 tri-dimensional sonic anemometers and 4 pairs of tri-axial accelerometers (Fig. 1). More details about the instrumentation are given in Cheynet et al. [10]. In the present study, only bridge acceleration records corresponding to a mean wind velocity $\overline{u}$ lower than $5\,\mathrm{m\,s^{-1}}$ are considered. This criteria should ensure that the aerodynamic effect on the MDRs remains small, but at the same time that the number of samples remains large enough to conduct a statistical analysis. The distribution of the MDR for the period July 2015 to December 2015 is therefore studied using a number of samples ranging from 3.3×10^3 for a record duration of 60 min to 17×10^3 for a record duration of 10 min, with a sampling frequency reduced to 5 Hz.

2.3. *Identification procedure*

To simplify and speed up the identification of the MDRs, the wind velocity histories are not simulated following a target power spectral density and wind coherence. Instead, an uncorrelated white noise process with zero mean and unit

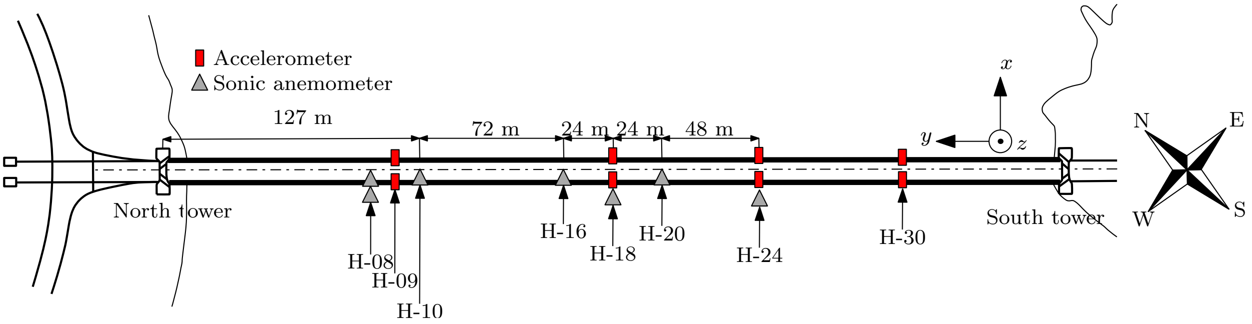

Fig. 1. Instrumentation of the Lysefjord Bridge deck using sonic anemometers and accelerometers synchronized by GPS time.

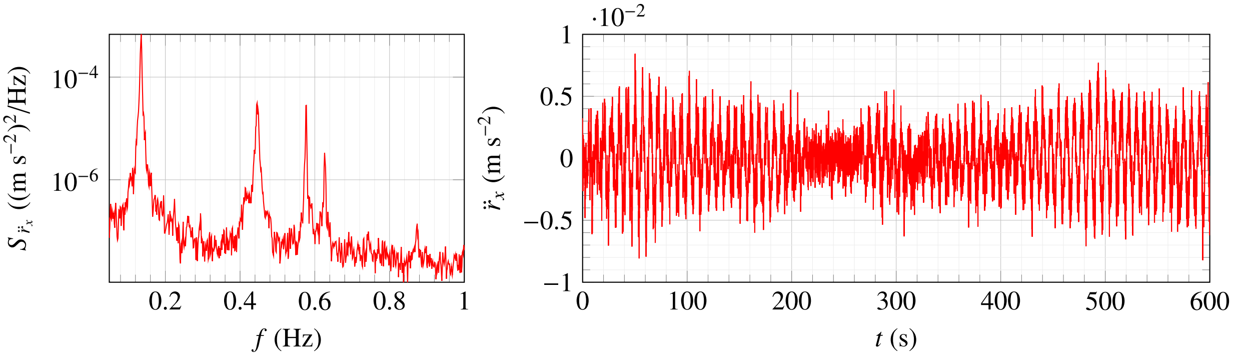

Fig. 2. Left: power spectral density of the lateral bridge acceleration response near hanger 24 recorded on 2015-10-28, from 00:30 to 01:30, with a hourly mean wind velocity component normal to the bridge deck of 3.6 m s^{-1}. Right: corresponding acceleration record from 01:20 to 01:30.

variance is used. In total, 1000 bridge acceleration responses are simulated in the time domain with a duration ranging from 10 min to 60 min. The standard deviation (STD) of the simulated displacement and acceleration response are ca. 1.3×10^{-3} m and 1.9×10^{-3} ms^{-2} respectively, which is the same order of magnitude as full-scale acceleration records at low wind velocities (Fig. 2). For the sake of brevity, only the SSI-COV algorithm is applied to identify the modal properties of the SBM. To use data sets of a comparable size to those acquired in the field monitoring campaigns, this algorithm uses the information provided by response "records" in 8 nodes uniformly spaced along the span instead of the 75 nodes. For the full-scale data, both the AFDD and SSI-COV approaches are used. To reduce the influence of outliers on the statistical description of the MDRs, any MDR value above the 95th percentile is disregarded.

2.3.1. SSI-COV and AFDD algorithms

A SSI-COV algorithm inspired from the one proposed by Magalhães et al. [8] is applied to identify the structural MDRs. For the sake of brevity, this method will not be described explicitly in the present paper, but can be found in e.g. [8, 16]. A relatively large number of parameters need to be defined for an efficient application of the automated SSI-COV algorithm. The most important parameter is likely the time-lag τ of the correlation functions. Brownjohn et al. [9] used a maximal time-lag corresponding to 2.23 times the longest natural period, whereas Magalhães et al. [8] used a time-lag corresponding to 6.4 times the largest eigen-period. In the present study, we used a time lag τ corresponding to 3 to 3.5 the largest eigen-period. The identification of the state-space model relies in our case on an increasing order from $N_{\mathrm{min}} = 2$ to $N_{\mathrm{max}} = 30$. The accuracy thresholds for the modal frequency variations and MDRs variations are denoted ϵ_{fn} and ϵ_{ζ} respectively. The variation of the minimum Modal Assurance Criterion (MAC) between mode shapes [17] is denoted ϵ_{MAC}. The cluster analysis, used for the automatic selection of the modes, relies on an additional accuracy threshold ϵ_{d}, referred to as the "distance between two modes" by Magalhães et al. [8]. The values of these parameters used in the present study are given in Table 1.

The AFDD relies on a much smaller number of parameters. The spectral matrix containing both the auto-spectral densities and cross-spectral densities of the bridge acceleration response if first built using Welch's method of spectral

Table 1. Parameters used in the automated SSI-COV method applied on the full-scale and simulated acceleration records.

Bridge	Motion	Data type	τ (s)	ϵ_{fn}	ϵ_{ζ}	ϵ_{MAC}	ϵ_{d}
Lysefjord	Lateral	Simulated and full-scale	25	1×10^{-2}	3×10^{-2}	5×10^{-3}	2×10^{-2}
Hardanger	Lateral	Simulated	60	1×10^{-2}	3×10^{-2}	5×10^{-3}	2×10^{-2}
Hardanger	Vertical	Simulated	30	1×10^{-2}	3×10^{-2}	5×10^{-3}	2×10^{-2}

estimation [18] using 4 segments with 50 % overlapping. Then the singular values of the spectral matrix are calculated as done in the classical FDD [11]. The different resonant peaks of the first singular vector are identified using the automated peak-picking algorithm proposed by Liutkus [12]. For each mode, the autocorrelation function is estimated based on the spectral values around each identified eigen-frequency f_n. A frequency range of $0.9 f_n - 1.1 f_n$ is used for this purpose. As the autocorrelation function generated that way has the same properties as the Free Decay Response (FDR) [19, 20], an exponential decay is fitted to the envelop of the FDR of each mode to determine the MDR. The time lag τ for the computation of the autocorrelation function is the only parameter used for the AFDD. In the present study, the value of τ is the same as for the SSI-COV algorithm (Table 1).

3. Results and discussions

3.1. MDR estimation using the automated SSI-COV algorithm with the SBM

The structural MDR of the mode HS1 for the computational model of the Lysefjord Bridge is arbitrary set to 1.0×10^{-2}. The mean value, median value and the STD of the identified MDR associated with HS1 for duration records T ranging from 10 min to 60 min are summarized in Table 2. As expected, a larger duration record leads to a lower bias and reduced dispersion of the damping estimation. For $T = 10$ min, the mean value of the identified MDR is 35 % larger than predicted but if $T = 60$ min, the overestimation is only 11 %, which is satisfying given the low amplitude of simulated vibrations. The dispersion of the MDR is also reduced by 2.5 when the duration record increases from 10 min to 60 min.

For the computational model of the Hardanger Bridge, the target structural MDRs are set to 1.0×10^{-2} for the mode HS1 and to 5×10^{-3} for the modes VS1 and VA1. The identified MDRs are summarized in Table 3. For HS1 and

Table 2. Mean value ($\overline{\zeta}$), median value ($\widetilde{\zeta}$) and STD (σ_{ζ}) of the identified MDR for the mode HS1 of the Lysefjord Bridge computational model, with $\overline{\zeta}_{\mathrm{target}} = 1.0 \times 10^{-2}$.

T (min)	$\overline{\zeta} \times 10^2$	$\widetilde{\zeta} \times 10^2$	$\sigma_{\zeta} \times 10^2$
10	1.35	1.27	0.51
20	1.21	1.18	0.35
40	1.14	1.14	0.24
60	1.11	1.10	0.20

Table 3. Mean value ($\overline{\zeta}$), median value ($\widetilde{\zeta}$) and STD (σ_{ζ}) of the identified MDRs for the modes HS1, VA1 and VS1 of the Hardanger Bridge, with $\overline{\zeta}_{\mathrm{target}} = 1.0 \times 10^{-2}$ for HS1 and $\overline{\zeta}_{\mathrm{target}} = 5 \times 10^{-3}$ for VA1 and VS1.

T (min)	HS1			VA1			VS1		
	$\overline{\zeta} \times 10^2$	$\widetilde{\zeta} \times 10^2$	$\sigma_{\zeta} \times 10^2$	$\overline{\zeta} \times 10^2$	$\widetilde{\zeta} \times 10^2$	$\sigma_{\zeta} \times 10^2$	$\overline{\zeta} \times 10^2$	$\widetilde{\zeta} \times 10^2$	$\sigma_{\zeta} \times 10^2$
10	1.63	1.53	0.67	1.19	1.08	0.56	0.98	0.91	0.41
20	1.30	1.20	0.55	0.92	0.89	0.33	0.74	0.71	0.23
40	1.17	1.13	0.37	0.78	0.77	0.21	0.69	0.67	0.17
60	1.16	1.14	0.32	0.74	0.73	0.17	0.66	0.65	0.13

$T = 10$ min, the average value of the MDR is 63 % larger than predicted but if $T = 60$ min, then the bias is only larger than predicted by 16 %, with a STD correspondence to ca. 32 % the value of the target MDR. As expected, a larger bias is observed for decreasing frequencies. For $T = 60$ min, the bias of the MDR associated with VS1 and VA1 are still relatively large, with values ranging from 16 % to 24 % in average. The distributions of the identified MDRs show however a relatively low dispersion, with STD values lower than 20 % the value of the target MDRs.

In summary, the identification of the MDRs using simulated acceleration bridge responses and different record durations shows similar results for the Lysefjord Bridge and the Hardanger Bridge: The MDRs are identified with a large bias and a large dispersion if the record time of 10 min is used. However, the dispersion and the bias are reduced by a factor of 2 to 3 if a record duration of 60 min is used instead. These observations are consistent with the study of Magalhães et al. [4] who focused on structures with eigen frequencies down to 0.28 Hz only.

3.2. Ambient vibration testing of the Lysefjord Bridge

The design value of the structural MDR of the Lysefjord Bridge for the mode HS1 is 0.5 %. The empirical formula proposed by Larsen and Larose [2] to estimate the MDRs of box girder suspension bridges suggests however that a value bounded between 0.5 % and 1 % may be more realistic.

3.2.1. System identification using the automated SSI-COV algorithm

For the full-scale data from the Lysefjord Bridge, the mean value, median value and STD of the identified MDR are displayed in Table 4 for the mode HS1. When T increases from 10 min to 60 min, the estimated MDR decreases by 0.27×10^{-2} in average, which is relatively close to the value of 0.24×10^{-2}, found for the simulated acceleration response (subsection 3.1). For $T = 60$ min, the standard deviation of the MDR identified using full scale data is 0.37×10^{-2}, which is much larger than the STD found using the simulated data. The acceleration response recorded in

Table 4. Mean value ($\overline{\zeta}$), median value ($\widetilde{\zeta}$) and standard deviation (σ_ζ) of identified MDR for HS1, obtained using the full-scale acceleration records from July 2015 to December 2015 on the Lysefjord Bridge and the automated SSI-COV algorithm.

T (min)	$\overline{\zeta} \times 10^2$	$\widetilde{\zeta} \times 10^2$	$\sigma_\zeta \times 10^2$
10	1.34	1.13	0.81
20	1.21	1.09	0.56
30	1.14	1.06	0.48
40	1.11	1.06	0.43
60	1.07	1.00	0.37

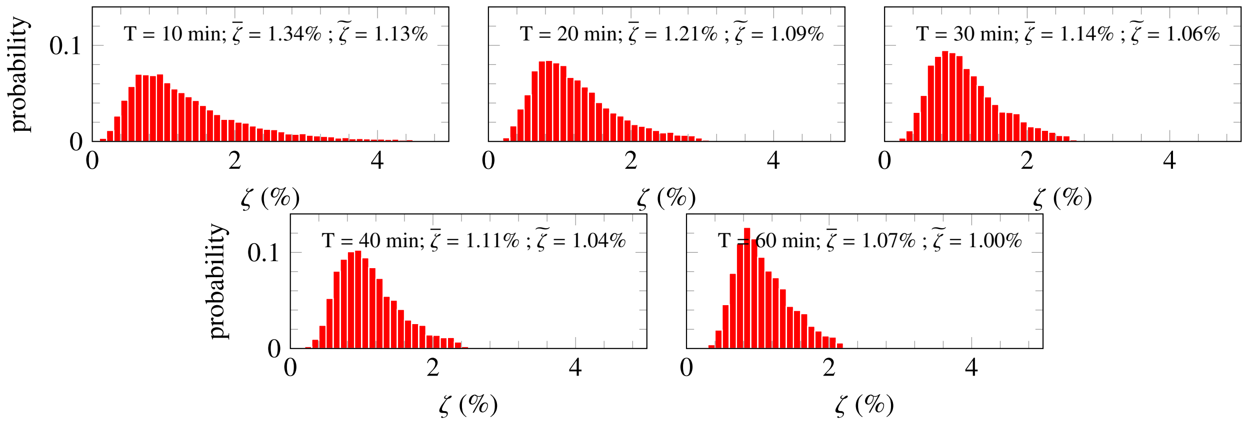

Fig. 3. Probability distribution of MDR of the mode HS1, identified using the automated SSI-COV algorithm to Lysefjord Bridge acceleration data from July 2015 to December 2015.

full scale is actually affected by environmental effects such as temperature fluctuations, non-stationary wind loads and traffic induced vibrations, which are sources of variation that are not accounted for in the SBM.

As shown in Fig. 3, the distribution of the identified MDRs is actually not Gaussian. The non-symmetry of the distribution is particularly pronounced for short record durations. Differences between $\overline{\zeta}$ and $\widetilde{\zeta}$ are also observed for the SBM, but they are much lower than in full-scale. This indicates that the use of the first two statistical moments to describe the accuracy and the precision of the identified MDRs may not be sufficient in full-scale. For a record duration increasing from 10 min to 60 min, the median of the MDR decreases by only 0.13×10^{-2} against 0.27×10^{-2} for the mean value, suggesting that the median of the MDR distribution is a more accurate estimator to estimate the “average” MDR than the arithmetic mean, especially if large record durations are not available.

Let’s assume that the bias of the estimated MDR for HS1 and for $T = 60$ min is 0.1×10^{-2} (Table 2). For $\overline{u} = 5\,\mathrm{m\,s^{-1}}$, the quasi-steady theory predicts an aerodynamic MDR of 0.17×10^{-2} for the mode HS1. The structural damping ratio of HS1 for the full-scale Lysefjord Bridge may therefore be around 0.8×10^{-2}.

3.2.2. System identification using the automated frequency domain decomposition

If the AFDD algorithm is used instead of the autmoated SSI-COV method, the average value of the MDR of HS1 for $T = 60$ min is 1.23×10^{-2} with a STD of 0.21×10^{-2}. Although the average value is much larger than the one estimated using the automated SSI-COV algorithm, the standard deviation of the MDR is lower (Fig. 4), which also explain why the differences between the median values and mean values are less obvious with the AFDD than with the SSI-COV algorithm. When the AFDD method is used, the bias of the MDR estimate increases considerably for records of decreasing durations. The overestimation of the average value of the MDR is mainly due to a lower frequency resolution in the low frequency range responsible for a broader spectral peak. An increasing signal to noise ratio is also observed for short acceleration records, leading to a larger number of spurious modes. This suggests that a frequency domain approach may not be appropriate to identify the MDRs of super long span suspension bridge, for which eigen frequencies down to 0.01 Hz can be expected.

Table 5. Mean value ($\overline{\zeta}$), median value ($\widetilde{\zeta}$) and standard deviation (σ_ζ) of identified MDR for HS1, obtained using the full-scale acceleration records from July 2015 to December 2015 on the Lysefjord Bridge using the AFDD algorithm.

T (min)	$\overline{\zeta} \times 10^2$	$\widetilde{\zeta} \times 10^2$	$\sigma_\zeta \times 10^2$
10	2.85	2.79	0.33
20	1.72	1.67	0.25
30	1.36	1.31	0.25
40	1.33	1.30	0.22
60	1.23	1.20	0.21

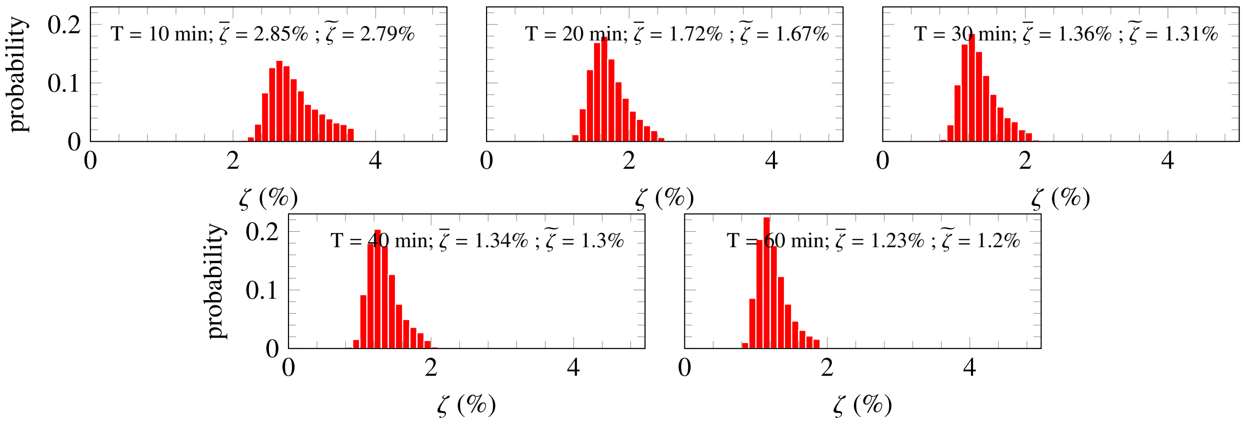

Fig. 4. Probability distribution of MDR of the mode HS1, identified using the automated AFDD algorithm to Lysefjord Bridge acceleration data from July 2015 to December 2015.

4. Conclusions

The modal damping ratios (MDRs) of a suspension bridge with eigen-frequencies close or below 0.1 Hz have been studied, using first a simple computational model subjected to a Gaussian white noise with zero mean, and then using full scale acceleration records. The accuracy of two different identification techniques to estimate the MDRs was investigated, in a similar fashion as by Magalhães et al. [4]. According to both the simulated and full-scale bridge responses, record durations of 60 min are recommended for estimation of the MDRs, although a measurement bias corresponding to 10 % to 20 % the real value of the MDR is still observed. The distribution of the identified MDR for the first lateral symmetric mode of the Lysefjord Bridge was not Gaussian, suggesting that the median value of the MDR should be used instead of the arithmetic mean to provide an estimation of the average MDR with an increased accuracy. Although the automated SSI-COV algorithm leads to identified MDRs with an increasing bias for decreasing eigen frequencies, the latter bias remains much lower than the one obtained using the Automated Frequency Domain Decomposition (AFDD). More generally, identification techniques based on a frequency-domain approach are not recommended for identification of MDRs of long-span or super-long span suspension bridges.

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