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FRACTURE & DYNAMICS
PAPER NO. 46

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An Experimental Study of a Steel Lattice Mast under Natural Excitation

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Abstract: The natural frequencies and modal damping ratios of a 20 m high steel lattice mast subjected to natural excitation have been experimentally investigated. The undamaged mast as well as the damaged has been considered. For the damaged mast seven different damage states were considered. In these damage states a damage was assumed in one of the lower diagonals. These diagonals were cut and provided with a bolted joint implying that a damage could be simulated. Based on 20 periodical measurements during 6 months the sensitivity of the modal parameters, identified by an ARMA-model, to environmental conditions such as wind-direction, wind-speed and air-temperature have been investigated. These sensitivities have been compared with the changes of modal parameters due to a damage. It is found that the measured natural frequencies vary less than one per cent while the measured modal damping ratios vary more than twenty per cent due to different environmental conditions. The measured bending natural frequencies and the measured rotational frequency approximately decrease few per cent and more than ten per cents, respectively, due to a damage corresponding to a removal of one of the lower diagonals. This means that it is possible to detect such a damage using a system identification technique based on natural excitation. A damage corresponding to a fifty per cent reduction of the sectional area can also be detected.

Keywords. System identification, ARMA-model, damage detection, civil engineering application.

1. Introduction

Structural diagnosis by measuring vibrational signals of civil engineering structures is a subject of research which has received increasing interest during the last decades. The main impetus for doing vibrational based inspection (VBI) is caused by a wish to establish an alternative damage assessment method to the more traditionally methods such as e.g. visual inspection. Many research projects have concluded that it is possible to detect damages in civil engineering structures by

VBI, and some techniques to locate damages in civil engineering structures have also been proposed. However, much of the performed research has been based on numerical simulations and on laboratory models. A throughout review of VBI techniques can be found in Rytter [1].

In order to use VBI techniques it is necessary to be able to obtain reliable estimates of the dynamic characteristics, e.g. natural frequencies. Such quantities can be estimated from the resulting output caused by a known well-defined input. However, the estimates can also be estimated by using the so-called ambient testing, i.e. the only excitation on the structure is the natural excitation.

The aim of the research presented in this paper was to answer the following questions by using full-scale measurements based on natural excitation:

1) Is it possible to distinguish between changes in modal parameters due to effects produced by damages and those brought about as a result of changes in the ambient environmental conditions ?

2) How sensitive are measured modal parameters to a damage ?

In order to answer these questions a 20 m high steel lattice mast subjected to wind excitation was experimentally investigated. The experimental arrangement are described in section 2. In section 3 the system identification method (ARMA) used is described. In section 4 the experimental results are presented and discussed and at last in section 5 conclusions are given.

2. Experimental Arrangement

An elevation of the 20 m high steel lattice test mast is shown in fig. 1.1. The four chords K-frame test mast with a 0.9x0.9 m cross-section was bolted with twelve bolts, three for each chord, to a concrete foundation block founded on chalk and covered by sand. The mast was constructed with welded connections. At the top of the mast two plywood plates were placed in order to increase the wind-area.

The eight lower diagonals were cut and provided with a bolted joint. Each bolted joint consists of 4 slice plates giving the possibility of simulating a 1/4, 1/2, 3/4 and full reduction of the area of a diagonal. A damage was simulated by removing one or more splice plates in these bolted joints. Seven different damage states (1,2,5,6,9,10,11) were considered. The damage state 1,2,5 and 6 correspond to a removal of diagonal AB101, BC101, AB102 and BC102, respectively, see fig. 1.2. Damage states 9 and 11 correspond to fifty per cent reduction of the sectional area of diagonal AB101 and AB102, respectively. Damage state 10 corresponds to fifty per cent reduction of the sectional area of diagonal AB101, BC101, CD101 and DA101.

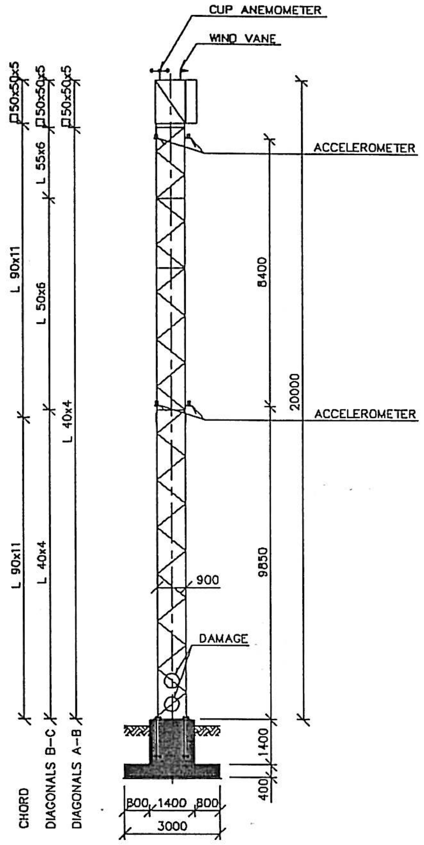

Fig. 1.1. Elevation of Mast.

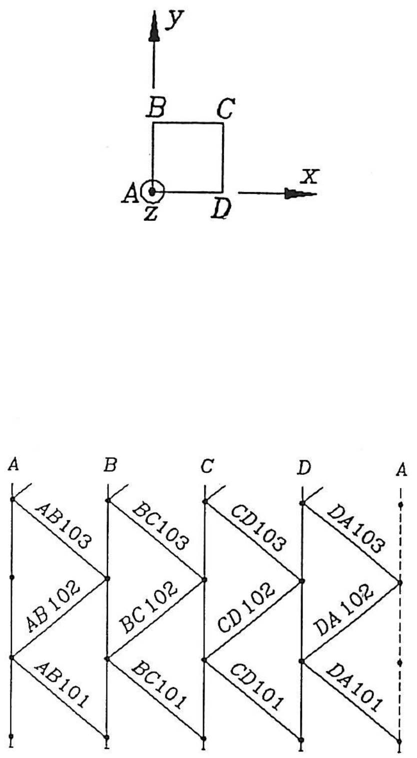

Fig. 1.2. Diagonals of the lower two sections of the mast.

The mast was instrumented with instruments to measure the accelerations, wind-direction (wind-vane) and wind-speed (cup-anemometer). Further, the ambient air temperature was measured. The data acquisition and the analyse of the sampled data were performed with the MATLAB, see PC-MATLAB [2], based on program to Structural Time Domain Identification, STDI, see Kirkegaard et al. [3]. A throughout description of the test arrangement can be found in Kirkegaard et al. [4].

3. System Identification

In this section it is described how the modal parameters were estimated by an ARMA-model. In recent years the application of ARMA models used in system identification, see e.g. Söderström et al. [5] and Ljung [6], to the description of structural systems has become more common, see e.g. Gersch et al. [7], Pandit et al. [8], Natke [9] and Kozin et al. [10].

An ARMA(n, m) model of order n, m describing the response at discrete time points y_t is given by

$$y_t = \sum_{i=1}^{n} \Phi_i y_{t-i} - \sum_{i=1}^{m} \mathcal{O}_i e_{t-i} + e_t \tag{3.1}$$

Φ_i is an Auto Regressive (AR) parameter, $\mathcal{O}_i$ is the Moving Average (MA) parameter and e_t is a time series of a white noise process. If an ARMA$(2n, 2n-1)$ model is used for a stationary Gaussian white noise excited linear n-degrees-of-freedom system it can be shown that the covariance of the response due to the ARMA-model and that of the white noise excited structure will be identical, see e.g. Kozin et al. [10]. The AR-parameters are obtained by minimizing an error function V_N expressing the variance of e_t

$$V_N = \frac{1}{N}\sum_{t=1}^{N} \epsilon_t^2 = \frac{1}{N}\sum_{t=1}^{N} \frac{1}{2}(y_t^M - \hat{y}_t)^2 \tag{3.2}$$

where N is number of data and ϵ_t is the prediction error. y_t^M and $\hat{y}_t$ are the measured response and the predicted response by (3.1), respectively. It may be noticed that the white noise assumption must be checked when the AR and MA parameters and the residuals have been estimated.

When the AR parameters have been estimated the dynamic parameters are found from the $2n$ roots, λ_i of the characteristic polynomial of the AR-parameters:

$$\lambda^{2n} - \Phi_1\lambda^{2n-1} - \cdots - \Phi_{2n-1}\lambda - \Phi_{2n} = 0 \tag{3.3}$$

In e.g. Pandit et al. [5] it is shown that the roots are related to the modal parameters through the $2n$ relations

$$\lambda_i = \exp(\mu_i \Delta t) \qquad i = 1, 2, .., 2n \tag{3.4}$$

where Δt is the sampling interval. μ_i has the following relation to the modal parameters

$$\mu_i = -\omega_i\zeta_i \pm i\omega_i\sqrt{1-\zeta_i^2} \qquad \zeta_i < 1.0 \tag{3.5}$$

From measurements of the response process it is possible to get estimates of the AR-parameters Φ_1 and Φ_2 where the estimates of the variance of the estimated parameters can be estimated by the Cramer-Rao lower bound. This implies that the covariance matrix of parameter estimates can be obtained by the inverse of the Fisher information matrix $\overline{\overline{J}}$ which can be written

$$\overline{\overline{J}} = \frac{N}{\lambda_\mathcal{E}} E[\frac{\partial\epsilon_t(\overline{\Phi})}{\partial\overline{\Phi}} \frac{\partial\epsilon_t(\overline{\Phi})}{\partial\overline{\Phi}}^T] \tag{3.6}$$

It is assumed that the variance of the noise process is $\lambda_\mathcal{E}$. N is the number of samples. $\overline{\Phi}$ is a vector including the AR-parameters. When the elements of the information matrix have been calculated the parameter covariance matrix $\overline{\overline{C}}_{\hat{\overline{\theta}}_N}$ of estimates of the parameter vector $\hat{\overline{\theta}}_N$ can be expressed in the following way

$$\overline{\overline{C}}_{\hat{\overline{\theta}}_N} = \overline{\overline{A}}\,\overline{\overline{J}}^{-1}\overline{\overline{A}}^T \tag{3.7}$$

where the transformation matrix $\overline{\overline{A}}$ is given by

$$\overline{\overline{A}} = \begin{bmatrix} \frac{\partial f_1}{\partial \Phi_1} & \frac{\partial f_1}{\partial \Phi_2} & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \frac{\partial f_1}{\partial \Phi_{2n}} \\ \frac{\partial \zeta_1}{\partial \Phi_1} & \frac{\partial \zeta_1}{\partial \Phi_2} & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \frac{\partial \zeta_1}{\partial \Phi_{2n}} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \frac{\partial f_n}{\partial \Phi_{2n}} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \frac{\partial \zeta_n}{\partial \Phi_{2n}} \end{bmatrix} \tag{3.8}$$

$\hat{\overline{\theta}}_N$ is an estimator of the parameter vector $\overline{\theta} = [f_1, \zeta_1, f_2, \zeta_2, ..., f_n, \zeta_n]^T$. The above estimation of $\overline{\overline{A}}$ will only be accurate if the function is sufficiently smooth since it corresponds to a linear approximation of the function describing the inverse transformation from AR- parameters to the parameters $\overline{\theta}$, see e.g. Kirkegaard [11] and Jensen et al. [12].

4. Experimental Results and Discussion

In the period from December 92 to June 93 twenty measurements sessions were performed with the undamaged mast . The dates of the sessions were selected in such a way that a data base containing measured responses due to different wind-directions and wind-speeds were created. At a measurement session 10 time series were recorded for each transducer, i.e. accelerometers as well as cup-anemometer and wind-vane. In the same period 2 measurement sessions were performed where damages were simulated at the mast. In the period the lowest and the highest air temperature were -5°C and 20°C, respectively.

From preliminary studies of response spectra, it was decided to concentrate the identification on the first two bending modes parallel to the x-axis and y-axis, respectively, and the first rotational mode. Prior to the identification the acceleration signals were detrended and removed from outliers. Further, the signals from the accelerometers were low-pass filtered with a cut-off frequency selected to 13.3 Hz corresponding to 70 % of the Nyquist frequency. The signals from the cup-anemometer and wind-vane were not filtered. Results obtained by a simulation study indicated that a sampling frequency equal to approximately 38 Hz will give the best reduction of bias of the modal parameter estimates. Further, by using this sampling frequency, it was shown that only a limited reduction of the variance of the modal parameter estimates could be obtained by using more than 8000 number of data points. This implied that 8000 points were sampled by 38 Hz from accelerations signals and signals from cup-anemometer and wind-vane. The signals were not high-pass filtered in order to remove low-frequency drifts in the data.

Prior to the system identification the validity of the assumptions for the ARMA model were investigated. It was found that the response could be assumed linear, stationary and approximately Gaussian, both for the undamaged mast as well as for the damaged. Based on different checks, it was concluded that an 6th-order ARMA-model for the mast was satisfactory. The model-order was estimated based on the Akaike Information Theoretic Criterion and an investigation of the poles and zeros with respect to a pole-zero cancellation in the dynamic model. The validity of the model of the ARMA-model was investigated by comparing the power spectrum obtained by a Fast Fourier Transformation and the spectrum obtained from the ARMA-model. Further, the investigation of the spectrum and the autocorrelation of the residuals indicated whiteness of the residuals and therefore validate the model. As a final test for model validity, a fairly good match was found between the model output and measured output.

4.1 Modal Parameters of the Undamaged Mast

As mentioned above it was the natural bending frequencies no. 1 and no. 4, the natural bending frequencies no. 2 and no. 5 and the natural frequency no. 3 corresponding to deflection parallel to the x-axis and deflection parallel to the y-axis and rotation, respectively, which were estimated.

The estimates of the natural frequencies and the modal damping ratios are shown as function of the measurement number in fig. 4.1. The 20 estimates in each figure have been obtained by combining the measured estimates of natural frequencies and modal damping ratios, respectively, from each measurement session by weighting with the standard deviations. At each measurement session 10 times series were recorded, implying 10 estimates of the natural frequencies and modal damping ratios, respectively.

The solid lines in fig. 4.1 indicate a mean value of the 20 estimates while the dashed lines give an interval between the mean value plus one per cent and the mean value minus one per cent for the natural frequencies. In the same way an interval corresponding to the mean value plus ten per cent and the mean value minus ten per cent is shown with dashed lines for the modal damping ratios. Fig. 4.1 shows that the measured natural frequencies vary approximately only few per cent while the modal damping ratios vary more than twenty per cent. It is seen that the bending natural frequencies are more sensitive than the rotational frequency. The standard deviation of the natural frequencies and modal damping ratios are approximately 0.003 Hz and 0.001, respectively. This indicates that the variation of the measured modal parameters is due to changes in the environmental conditions and only not due to randomness. In order to investigate the sensitivity of natural frequencies with respect to wind-direction and wind-speed the 200 estimates of the natural frequencies are shown in fig. 4.2a as function of the wind-speed. The estimates have been divided into 4 groups. Each group corresponds to a wind-direction interval of 90 degrees. Fig. 4.2a shows that the natural frequencies are sensitive to the wind-speed. However, it is most clear for the first and second natural frequency. Further, it is seen that the natural frequencies have an increase for a wind-speed corresponding to 7-8 m/s when the wind-direction is changed. However, this change can also be a consequence of a change in temperature. In fig. 4.2b the 200 estimates of the natural frequencies are shown as a function of the wind-speed. The estimates have been divided into 2 groups. corresponding to estimates obtained from measurements where the air temperature was lower than 0^oC and higher than 0^oC, respectively. It is seen that the increase in natural frequencies for a wind-speed corresponding to 7-8 m/s can be due to an air temperature below 0^oC and not necessarily a change in the wind-direction. However, more data most be obtained in order to investigate this problem.

4.2 Modal Parameters of the Damaged Mast

At two different measurement sessions, session 4 and 6, the natural frequencies and modal damping ratios were estimated for seven different damage states, see section 2. In fig. 4.3 the measured natural frequencies and modal damping ratios are shown as function of damage state. The solid lines indicate the mean value from fig. 4.1. Fig. 4.3 shows that the modal parameters are sensitive to a damage corresponding to a removal of one of the lower diagonals, i.e. damage states 1,2,5 and 6. It is seen that the change in the bending natural frequencies depends on the location of the damage. Fig. 4.3 also shows that the rotational frequency is more sensitive to a damage than the bending frequencies. Further, the modal parameters seem to be insensitive to damages corresponding to damage states 9,10 and 11. However, above it is shown that the modal parameters are sensitive to environmental conditions. Therefore, in order to distinguish between a change in the modal parameters due to a damage or the environmental conditions, modal parameters corresponding to the same environmental conditions have to be compared. In fig. 4.4a and 4.4b the measured natural frequencies from measurement sessions 4 and 6 are shown as a function of damage state, respectively. The solid lines in fig. 4.4a show the lower bound of the 95% confidence level of the natural frequencies from measurement session 3. The estimates are assumed Gaussian distributed. In the same way in fig. 4.4b the lower bound of the 95% confidence level of the natural frequencies from measurement session 5 is shown. The measurement sessions 3 and 5 (undamaged) correspond to measurement sessions 4 and 6 (damaged), respectively, with respect to environmental conditions, i.e. approximately the same wind-speed, wind-direction and air-temperature. This means that a change in the measured natural frequencies can be interpreted as a change due to a damage and not to a change in the environmental conditions. Fig. 4.4 shows that it is possible to detect a damage in the mast corresponding to a removal of one of the lower diagonals, damage states 1,2,5 and 6. Further, a damage, damage states 9 and 11, corresponding to a fifty per cent reduction of the sectional area can also be detected. However, if such a damage should be detected it is important to compare modal parameters from the damaged and undamaged mast, respectively, obtained under the same environmental conditions.

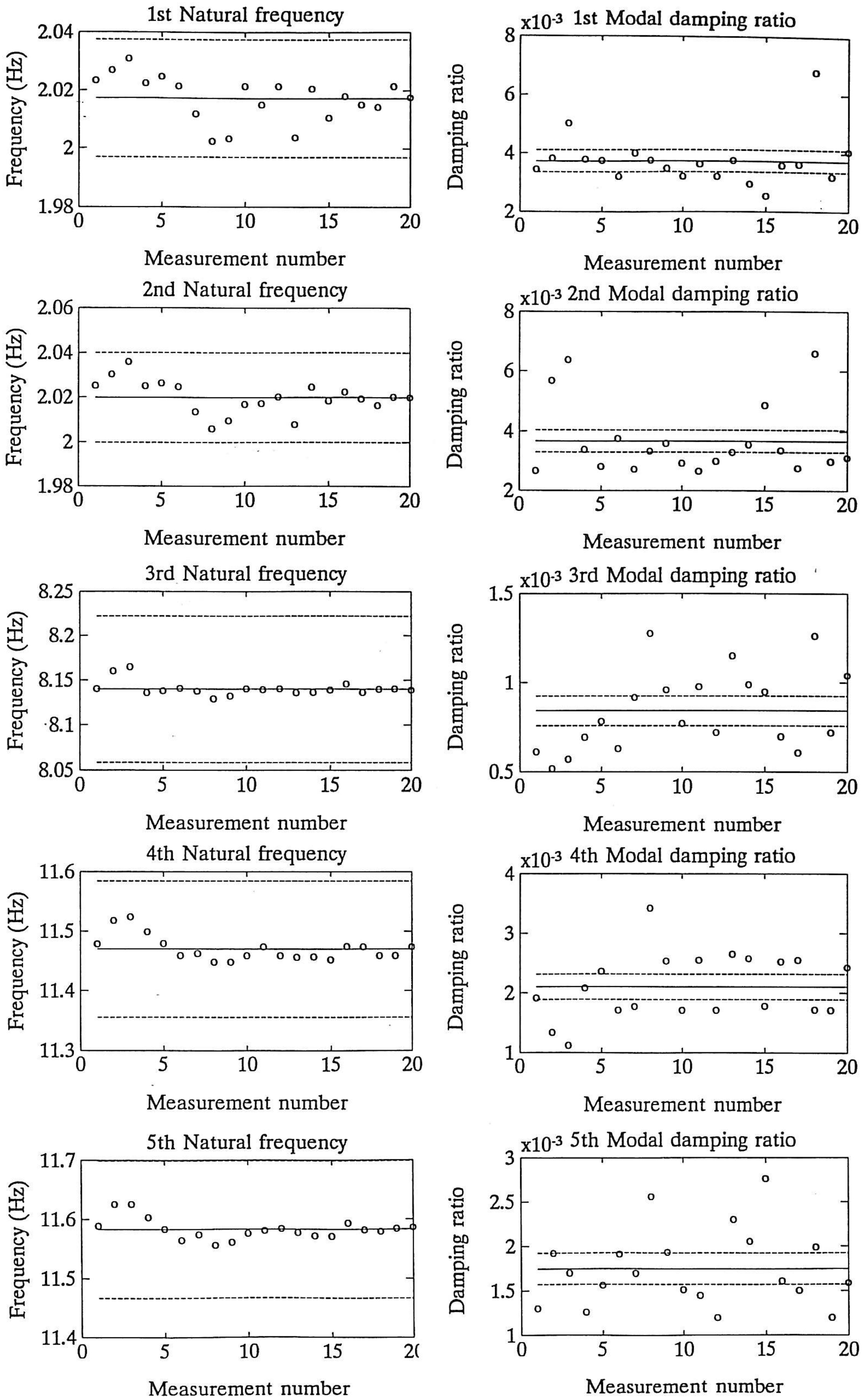

Fig. 4.1. Estimated natural frequencies and modal damping ratios as a function of measurement number. (Solid lines show the mean value and dashed lines show the mean value plus/minus one per cent and plus/minus ten per cent for the natural frequencies and the modal damping ratios, respectively).

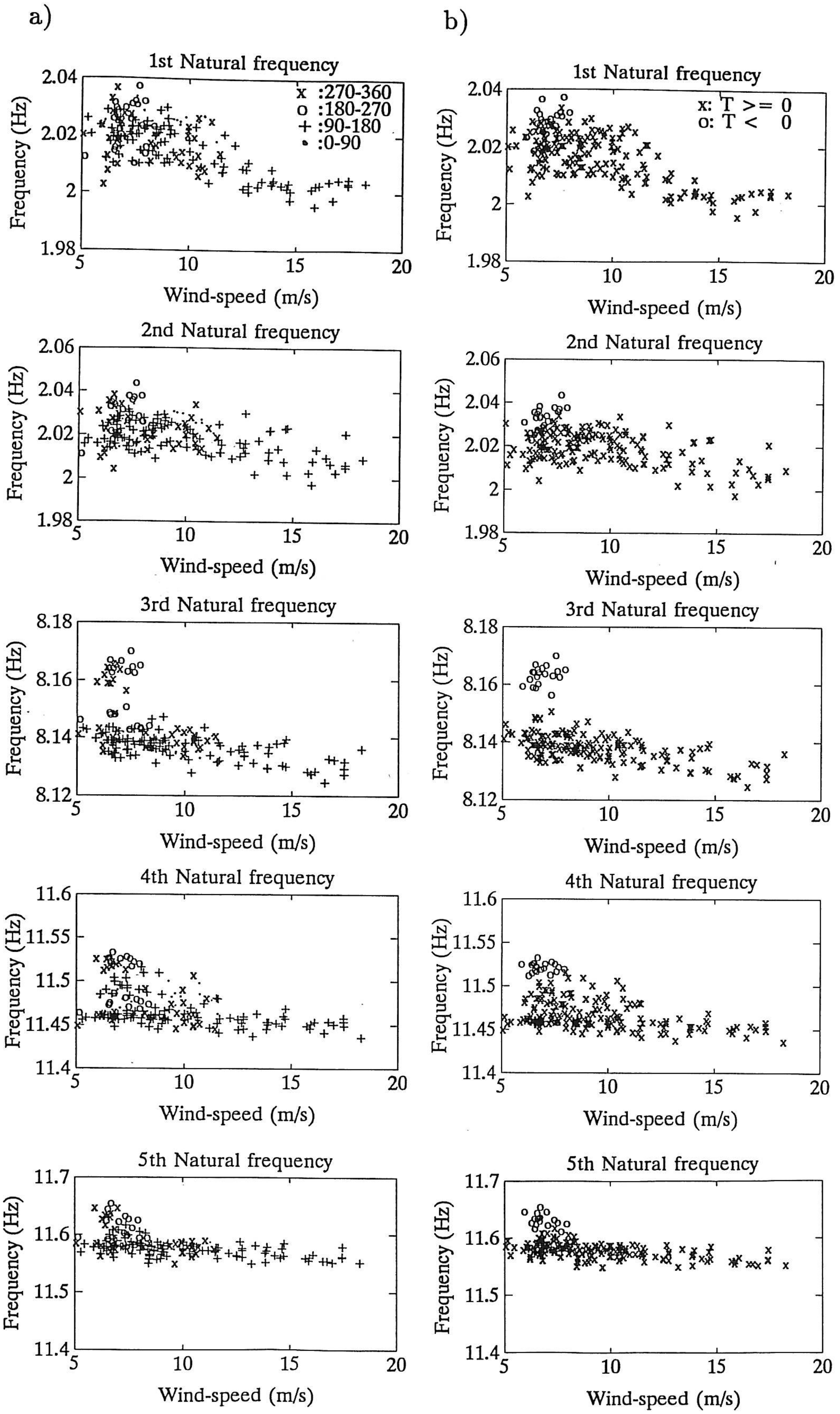

Fig. 4.2. Natural frequencies as a function of wind-speed and wind-direction (a) and as a function of wind-speed and air temperature (b).

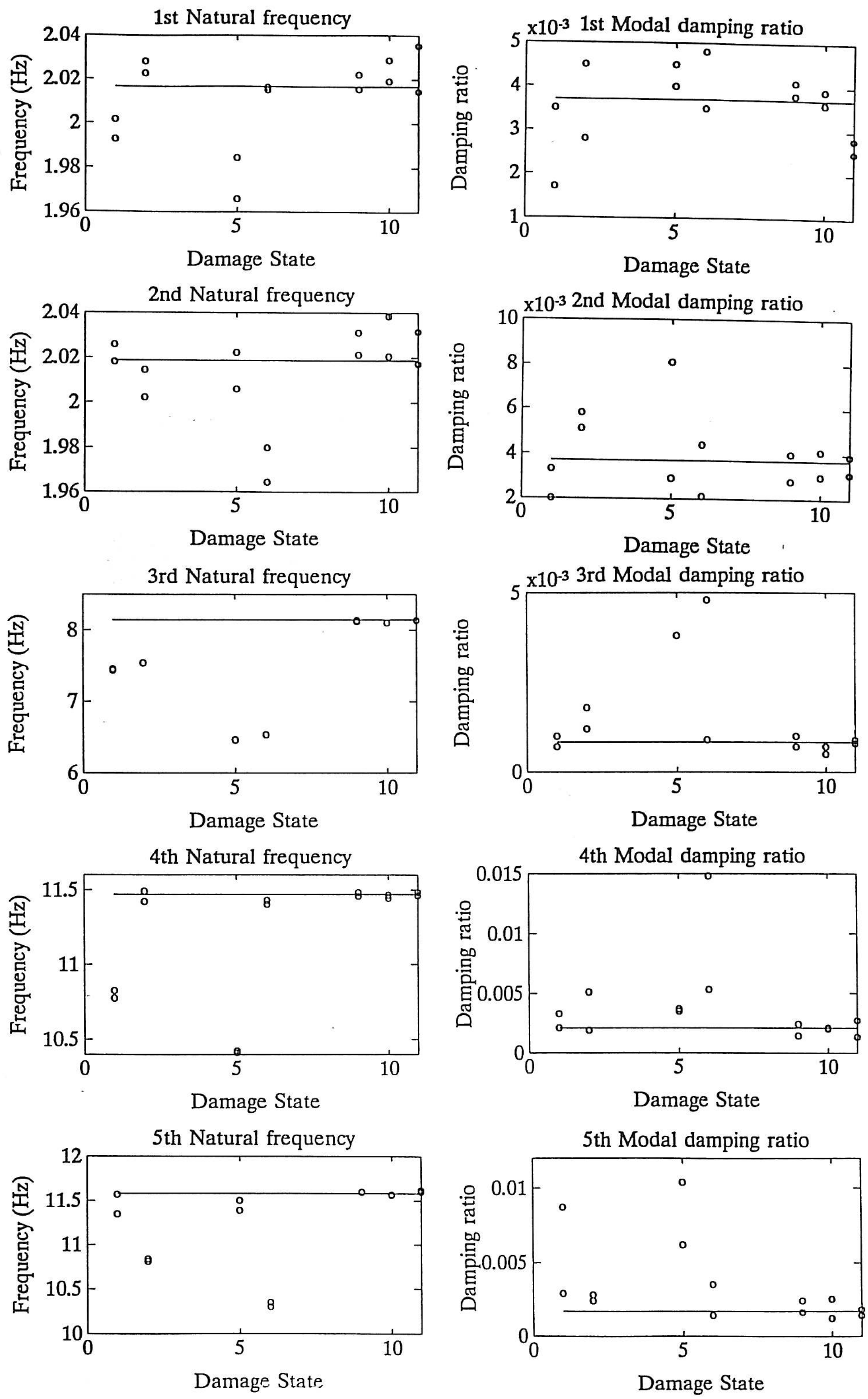

Fig. 4.3. Estimated natural frequencies and modal damping ratios as a function of damage state. (Solid line is the mean value from fig. 4.1)

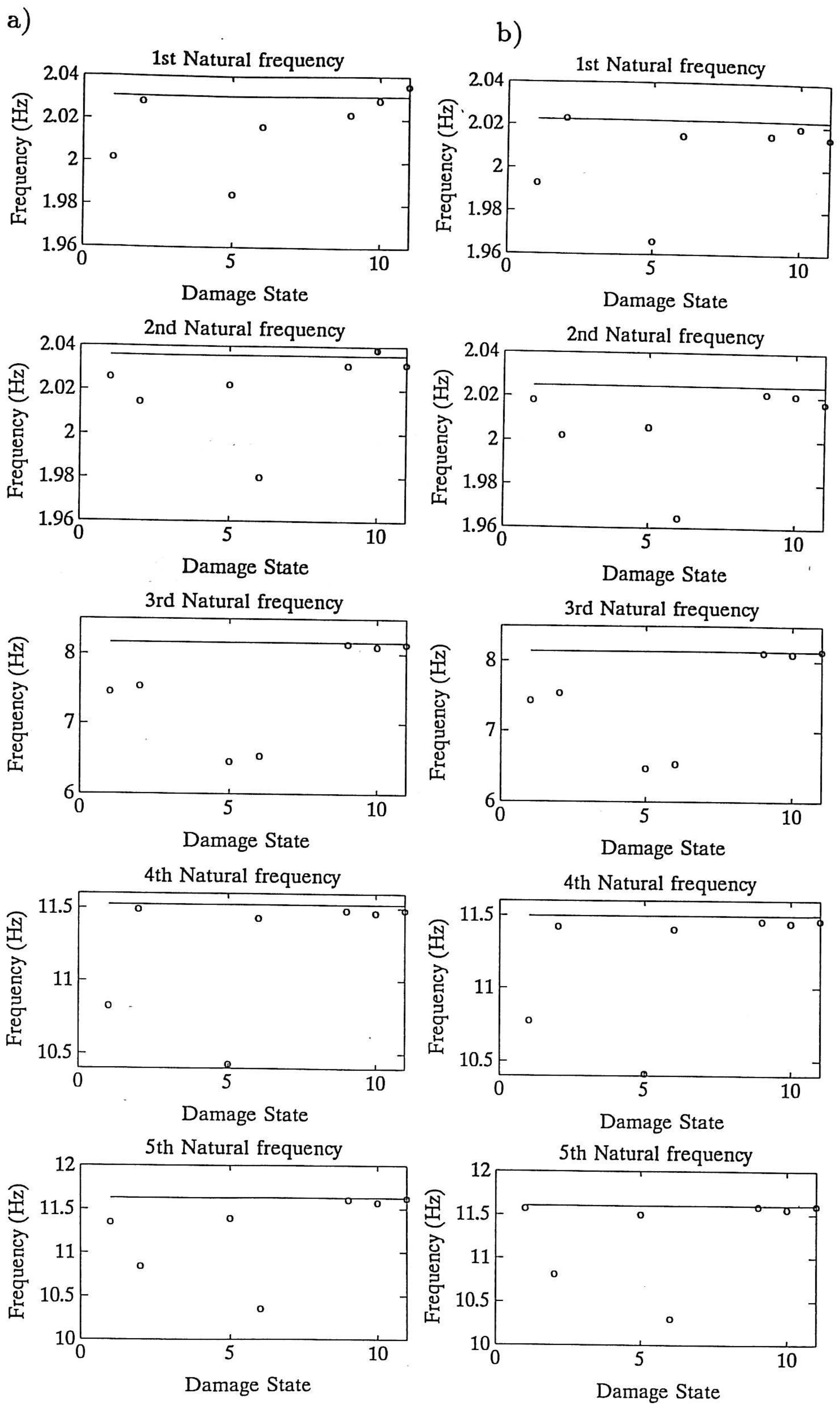

Fig. 4.4. Estimated natural frequencies from measurement session 4 (a) and 6 (b) as a function of damage state. (Solid lines are the lower bound of the 95% confidence level for estimated natural frequencies from measurement sessions 3 (a) and 5 (b), respectively)

4. Conclusions

In this paper the natural frequencies and modal damping ratios of a 20 m high steel lattice mast subjected to natural excitation has been experimentally investigated. The conclusions of the paper can be stated as follows:

- Measured natural frequencies vary less than one per cent while the measured modal damping ratios vary more than twenty per cent due to different environmental conditions, such as wind-speed and air-temperature
- The measured bending natural frequencies and the rotational frequency approximately decrease few per cent and more than ten per cent, respectively, due to a damage corresponding to a removal of one of the lower diagonals.
- It is possible to detect a damage corresponding to a removal of a diagonal using a system identification technique (ARMA) based on natural excitation. A fifty per cent reduction of the sectional area of a diagonal can be detected, if the measured modal parameters from the damaged mast and the undamaged mast, respectively, are obtained under the same environmental conditions.

References

[1] Rytter, A.: *Vibration Based Inspection of Civil Engineering Structures.* Ph.D thesis, Fracture and Dynamic Paper No. 44, University of Aalborg, 1993.

[2] PC-MATLAB for MS-DOS Personal Computers, The Math Works, Inc., 1989.

[3] Kirkegaard, P.H. & R. Brincker: *STDI: Program for Structural Time Domain Identification.* University of Aalborg, 1993.

[4] Kirkegaard, P.H. & A. Rytter: *An Experimental Study of the Modal Parameters of a Damaged Steel Mast.* Fracture and Dynamic Paper No. 45, University of Aalborg, 1993.

[5] Söderström, T. & P. Stoica: *System Identification.* Prentice Hall, 1987.

[6] Ljung, L.: *System Identification: Theory for the User.* Prentice Hall, Englewood Cliffs, 1987.

[7] Gersch, W. & R. Liu: *Time Series Methods for the Synthesis of Random Vibration Systems.* Journal of Applied Mechanics, Vol. 98, No. 2, 1976.

[8] Pandit, S. W. & N. P. Metha: *Data Dependent Systems Approach to Modal Analysis Via State Space.* ASME paper No. 85-WA/DSC-1, 1985.

[9] Natke, H. G.: *Einführung in Theorie und Praxis der Zeitreihen- und Modalanalyse.* ISBN 3-528-28145-6, Germany, 1993.

[10] F. Kozin & H. G. Natke: *System Identification Techniques.* Structural Safety, Vol. 3, 1986.

[11] Jensen, J. L., R. Brincker & A. Rytter: *Uncertainty of Modal Parameters Estimated by ARMA Models.* 9th International Conf. on Experimental Mechanics, Copenhagen, 1990.

[12] Kirkegaard, P.H.: *Optimal Design of Experiments for Parametric Identification of Civil Engineering Structures.* Ph.D-thesis, University of Aalborg, 1991.

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