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Damage Assessment of a Steel Lattice Mast under Natural Excitation

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Abstract: In this paper the possibility of detecting and locating damages in a 20 m high steel lattice mast subjected to natural excitation has been investigated. 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. The results also show that a neural network trained with simulated data is capable for detecting location of a damage in the steel lattice mast when the network is subjected to the experimental data.

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

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 ?

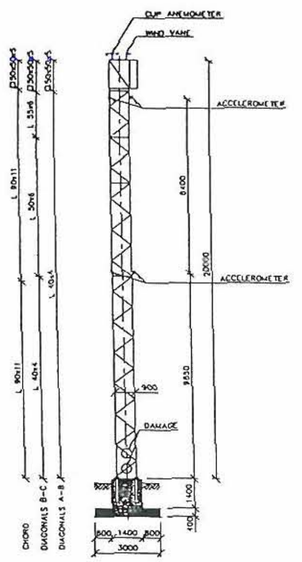
3) Can the location of the damages be estimated ?

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 experimental results are presented and discussed and at last in section 4 conclusions are given.

2. Experimental Arrangement

An elevation of the 20 m high steel lattice test mast is shown in fig. 2.1. 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. 2.2. 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.



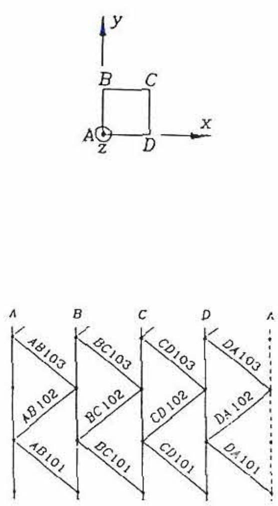


Fig. 2.1 Elevation of Mast. **Fig. 2.2** Diagonals of the lower two sections

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 by an ARMA-model 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. 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 dåmages were simulated at the mast. In the period the lowest and the highest air temperature were -5^{o}C and 20^{o}C, respectively.

3.1 Modal Parameters of the Undamaged Mast

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. 3.1. 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. 3.1 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. 3.1 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. 3.2a 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. 3.2a 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. 3.2b 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.

3.2 Modal Parameters of the Damaged Mast

In fig. 3.3a and 3.3b the measured natural frequencies from measurement sessions 4 and 6 are shown as a function of damage state, respectively. The solid lines in fig. 3.3a 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. 3.3b 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. 3.3 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.

3.3 Estimation of Damage Location by use of Neural Network

The applicability of a neural based damage assessment method, see e.g Hertz et al. [5] and Kirkegaard et al. [6], is investigated by training a neural network with the relative changes of the natural frequencies of the 5 lowest modes. These changes were estimated for a 20, 40, 60, 80 and 100 per cent reduction of the sectional area of diagonal AB101, BC101, AB102 and BC102, respectively. Further, the relative changes of the frequencies also were estimated for the undamaged mast. By a trial-and-error approach it is found that a 4 layers neural network with 5 input nodes, 5 nodes in each of the two hidden layers and 4 output nodes gave the network with smallest output error. Each output node corresponds to a damage in one of the diagonals AB101, BC101, AB102 and BC102, respectively. The value for a single diagonal adopts the value 1 when not damaged, the value 0 when totally damaged and 0.2 corresponds to a 80 per cent reduction of a sectional area etc.

The network was tested by subjecting the simulated input data corresponding to a 100 per cent reduction of the sectional area of the four diagonals AB101, BC101, AB102 and BC102, respectively, to the network. It was found that the neural network was capable of reproducing the location and size of a damage used in training (Damage state 1,2,5,6). Table 1 shows the outputs from the network subjected to experimental data.

Output Node No.	Damage State					
	1	2	5	6	9	10
1(AB101)	0.1	0.8	0.9	0.9	0.5	0.8
2(BC101)	0.8	0.1	0.8	1.0	0.7	0.4
3(AB102)	0.6	1.0	0.1	1.1	0.2	0.2
4(BC102)	0.9	0.9	0.9	0.0	0.9	1.1

Table 1: Results from network subjected to experimental data.

The results in table 1 show that it is possible to detect a damage corresponding to a removal of a diagonal (Damage state 1,2,5,6) by the neural network approach. It is also seen that a damage corresponding to 50 per cent reduction of the sectional area of a diagonal AB102 can be detected, but not quantified.

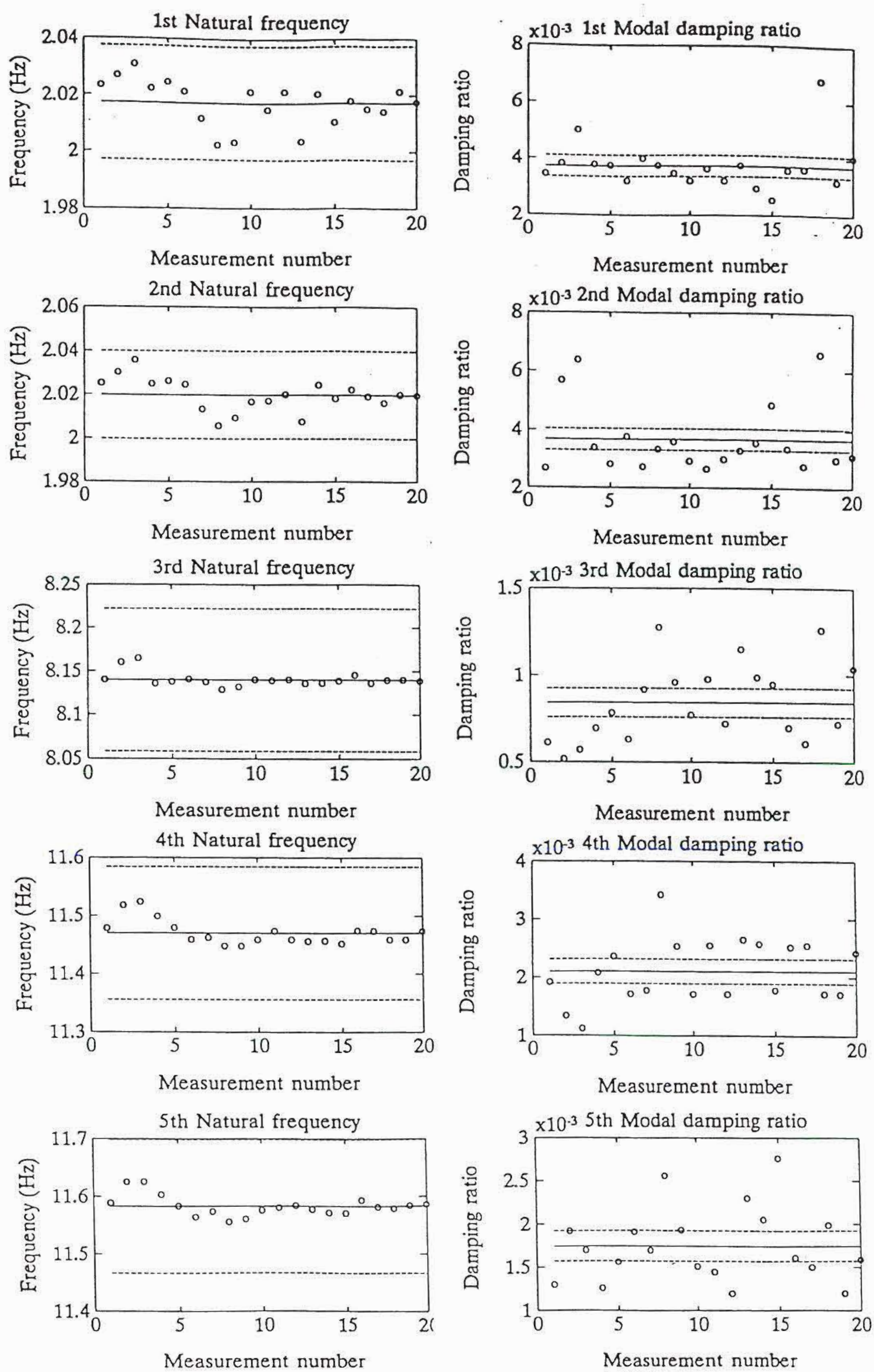


Fig. 3.1. Estimated natural frequencies and modal damping ratios as a function of measurement number. (Solid lines show the mean value and dashed lines show the mean value plus/minus one per cent and plus/minus ten per cent for the natural frequencies and the modal damping ratios, respectively).

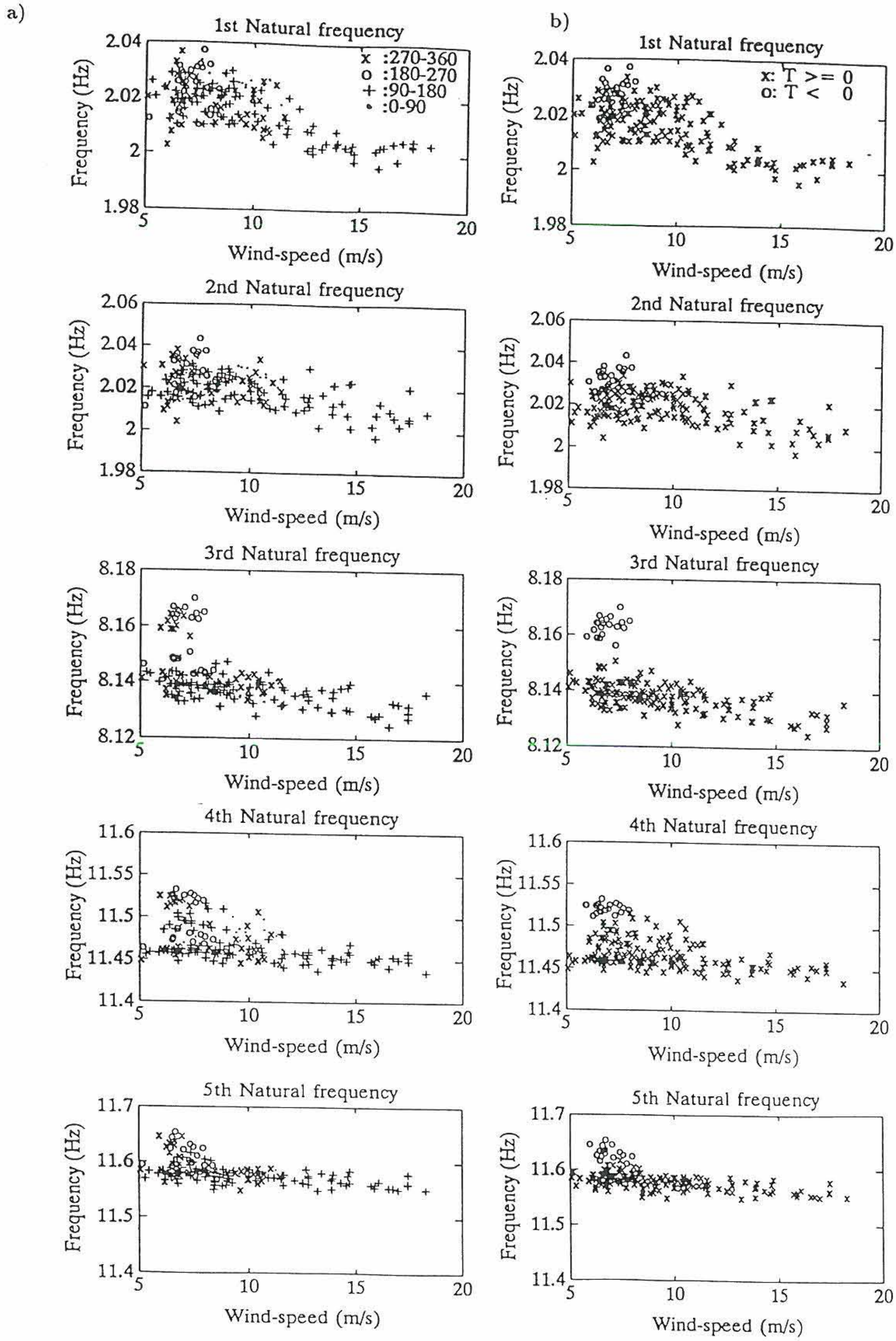


Fig. 3.2. Natural frequencies as a function of wind-speed and wind-direction (a) and as a function of wind-speed and air temperature (b).

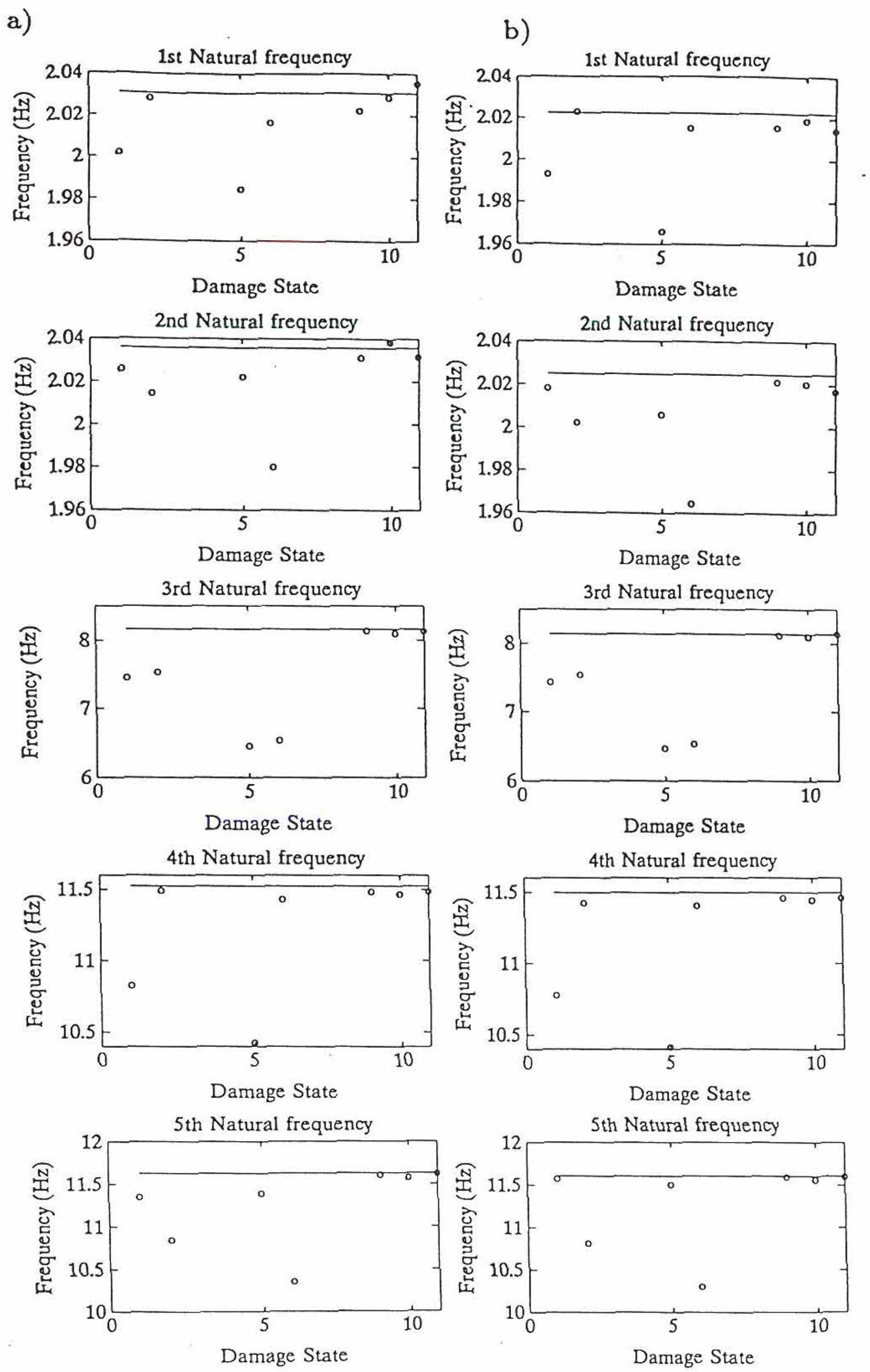


Fig. 3.3 Estimated natural frequencies from measurement session 4 (a) and 6 (b) as a function of damage state. (Solid lines are the lower bound of the 95% confidence level for estimated natural frequencies from measurement sessions 3 (a) and 5 (b), respectively)

4. CONCLUSIONS

In this paper the natural frequencies and modal damping ratios of a 20 m high steel lattice mast subjected to natural excitation have 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.
- A neural network trained with simulated data is capable for detecting location of a damage, corresponding to a removal of a diagonal when the network is subjected to experimental data.

4. REFERENCES

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