Experimental verification of the container crane natural frequencies

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Abstract

Experimental verification of a container crane structure modal parameters which are numericaly obtained by using the Finite Element Method is presented. To validate the numericaly calculated natural frequencies and vibration mode shapes, and to define the modal damping values, a full-scale forced vibration experiment was performed. The simplest possible experiment was chosen to obtain these objectives. Some kind of intersection between forced vibration test, with the control of the input (forcing function), and step relaxation test, with the release of the structure from a statically deformed position, was made. Instead of releasing the deformed structure, the crane was forced into the specific vibration mode with limited operational movements, using inertial forces of the masses in motion. Therefore, the input excitation was not directly controlled, but was more or less under control. Ambient vibration testing, due to wind loading and due to forcing with crane motion, was also performed and is briefly presented.

1. Introduction

The objective of the research is a container crane structure with optimal dynamic characteristics. The scope of interest is only the structure of the crane and not the dynamic system of the structure, the sway and the load.

The primary part of the dynamic optimisation process is a reliable mechanical dynamic model. As far as reliability is concerned in dynamics of structures, experimental verification of the model is necessary in most cases.

Dynamic optimisation in our case means:

- as high as possible natural frequencies, especially the first and the two most important for service operation (mode 2 and 3 in Fig. 2 and Fig. 3)
- small amplitudes of displacements, velocities and accelerations
- minimal weight of the structure

Fig. 1 shows the container crane with the load carrying capacity of 500 kN (dead weight 5500 kN, height 73.4 m), product of Metalna Maribor, stationed in Koper port in Slovenia. On this crane the experiment was conducted.

Numerical model of the crane structrue on Fig. 1 is made with line-beam finite elements with the properties of Timoshenko beam and the second order theory is used to take the geometric nonlinearity into account.
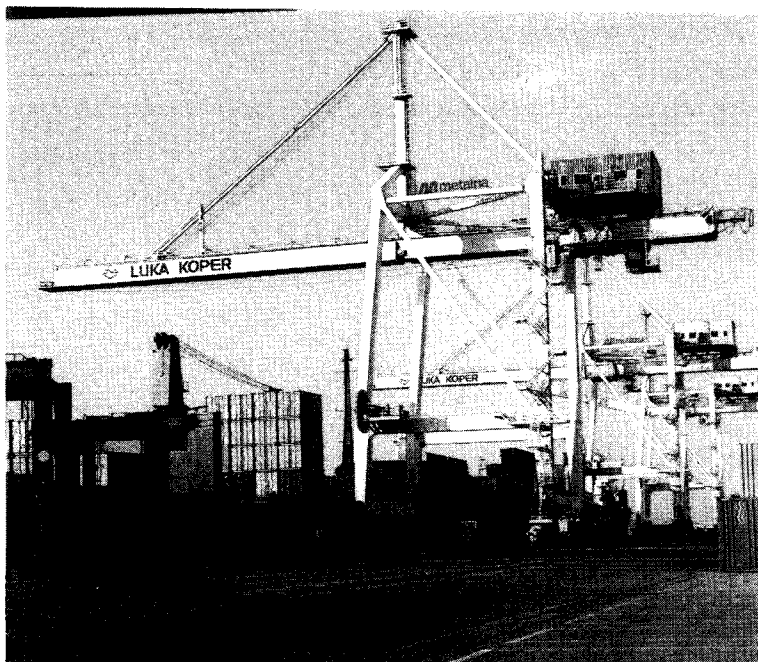

Figure 1. Analysed container crane in Koper port, Slovenia

Finite element model of the container crane structure has 79 line and 4 point mass elements. The model has 66 nodes and 396 degrees of freedom. The number of elements is the result of several trials and is the least possible for a satisfactory accuracy.

The vibration mode shapes and natural frequencies of the crane, as a result of the finite element analysis, are on Fig. 2 and Fig. 3. Mode 2 and 3 are the most important ones for the operational features of the crane, because they are directly excited with a hoisting motion of the load (mode 3) and the sway (with the load) horizontal motion and the load swinging (mode 2). The mode 1 is important because it's lower limit is usually prescribed.
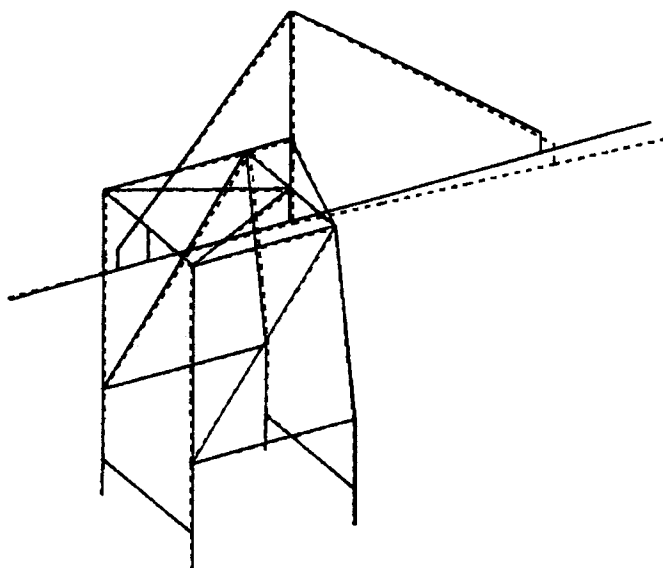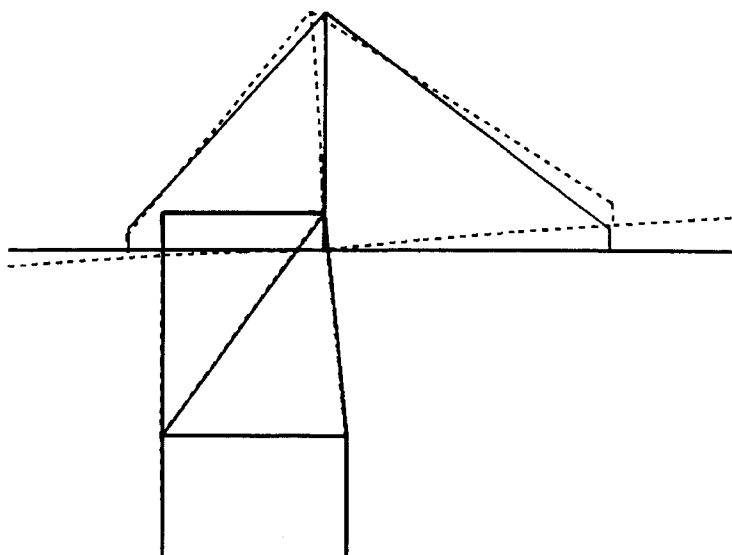
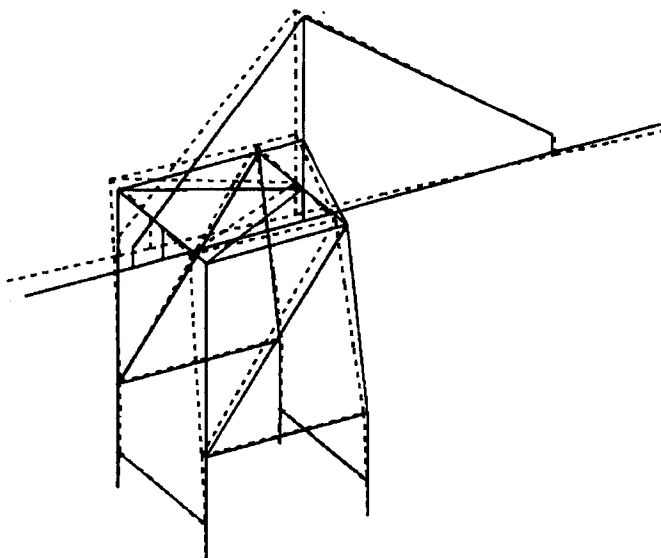MODE NO. = 1   FREQUENCY = 5.07880E-01 Hz
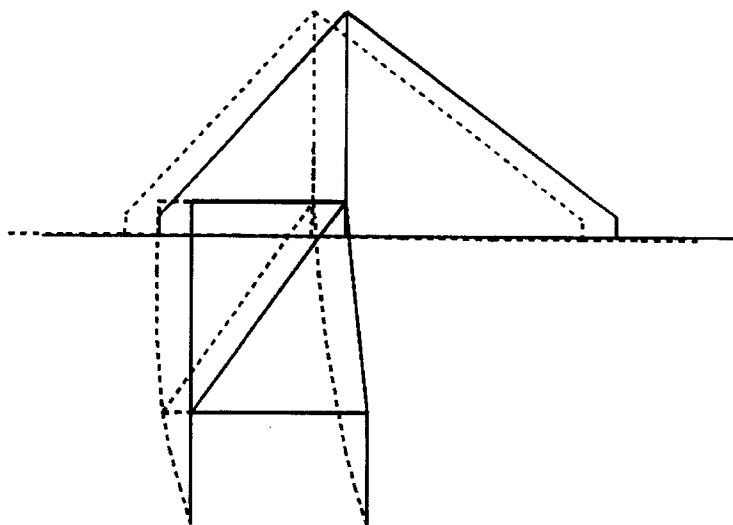
MODE NO. = 2   FREQUENCY = 7.62034E-01 Hz

Figure 2. Computed vibration modes and natural frequencies of the crane structure

MODE NO. = 3   FREQUENCY = 8.28301E-01 Hz

MODE NO. = 4   FREQUENCY = 9.23180E-01 Hz

Figure 3. Computed vibration modes and natural frequencies of the crane structure

2. Full-scale forced vibration test on the crane structure

The purpose of the experiment was the verification of the crane mechanical model; therefore, the determination of natural frequencies and modes of vibration and the definition of structural damping. The estimation of dynamic load level (and the shape of load function) encountered in the operating environment was the second goal of the full-scale testing.

The simplest possible experiment was chosen to obtain these objectives. Some kind of intersection between forced vibration test, with the control of the input (forcing function), and step relaxation test, with the release of the structure from a statically deformed position, was made. Releasing the deformed structure is mechanically difficult to implement in dealing with structures of such dimensions and stiffness. Instead of doing this, we tried to force the structure to the specific vibration mode with limited operational movements, using inertial forces of the masses in motion. For example, instead of deforming the crane in vertical direction at the position where the load was being lifted we lifted the load and then halted the motion without significant excitation of the structure in any other direction. The effect of the relaxation was in this way more or less achieved. Therefore, the input excitation was not directly controlled, but was more or less under control.

The structure was forced into basic eigenmodes and transient response (acceleration) of the event was measured. Afterwards, spectral analysis with Fourier transformation was made to obtain the frequency response.

The transient response of the structure due to service operation was also measured, which provides necessary data for other analyses (service operation, ship transport simulation, fatigue analysis, dynamic optimisation). Spectral frequency responses due to wind load and due to operation of the crane were also measured.

2.1. Setting up of the acceleration meters

The placement and monitoring direction of acceleration meters is presented in Fig. 4. The four applied meters should give all the necessary data for the described purpose. The testing is made easier, because the investigated range of frequencies is in the scope of human perception, and the amplitudes of displacements for the relevant modes are great enough to be approximately determined by simple observation. For the higher eigenfrequencies and vibration modes, this is not possible, nor the four meters are sufficient.
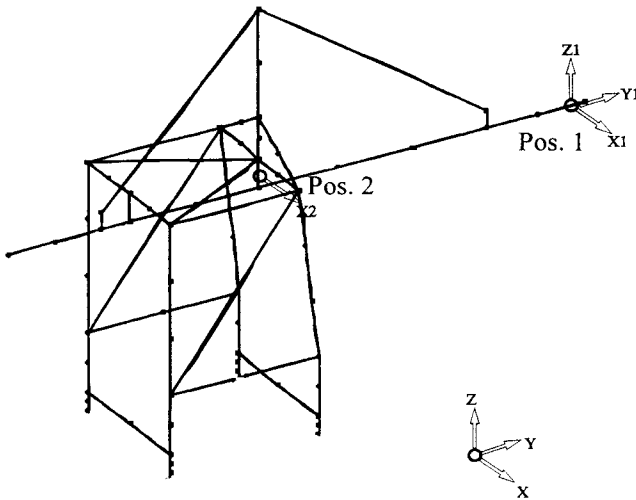
Figure 4. Acceleration meters positions and directions of monitoring

2.2. Mode No. 3 test - vertical forcing at pos. 1

Already mentioned forcing motion into the investigated mode (Fig. 3) with lifting the load and halting the lifting motion of the load on the spreader (440 kN) at the end of the arm - at pos. 1. was implemented

The measured signal on the meter Z1 is in Fig. 5. The halting effect took place from 14th till 17th second.
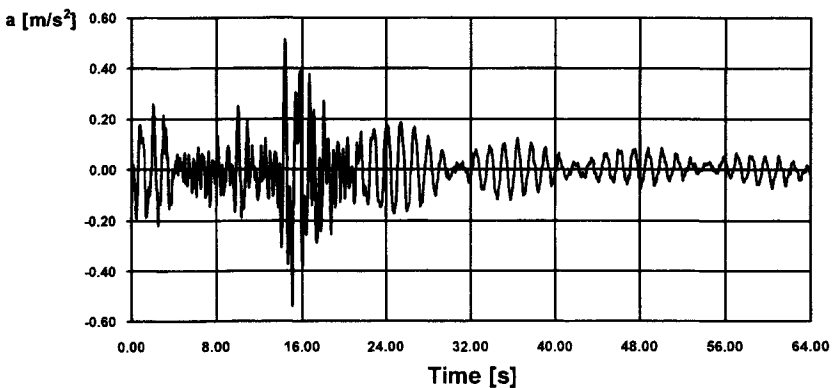
Acceleration at pos.1 in dir.Z (rec10)

Figure 5.

The analysed part of the monitored signal is from 20th till 64th second and its Fourier transform gives us the frequency spectrum in Fig. 6.
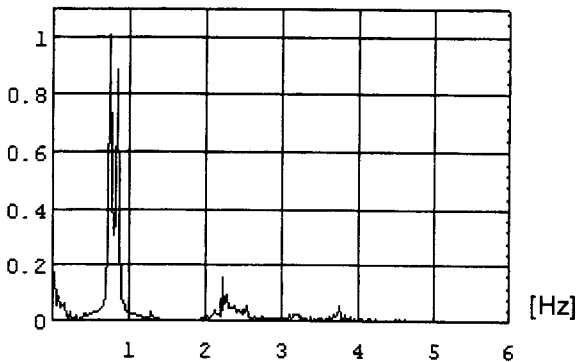
Figure 6. Frequency spectrum of Rec10 (20 s < t < 64 s)

The two dominant frequencies are: F1 = 0.75 Hz   F2 = 0.84 Hz

Carefully analysing other measured responses we found out that the frequency of the mode 3 is: $F_{mode\ 3} = 0.84\ Hz$
and the F1 is the mode 2 frequency. Mode 2 was obviously significantly excited with the forcing which produces the vibration also in Z1.

The average damping measured for this mode is: $\xi = 0.0085$ which is 0.85% of critical damping.

2.3. Mode No. 2 test - horizontal forcing at pos. 2

Forcing into mode No. 2 (Figure 2) was done with halting the horizontal motion of the sway, together with the full load at upper position. The sway was moving from the sea side towards the earth side and was halted after passing pos.2 (to avoid excessive vibration arm). The spectrum is in Fig.7.
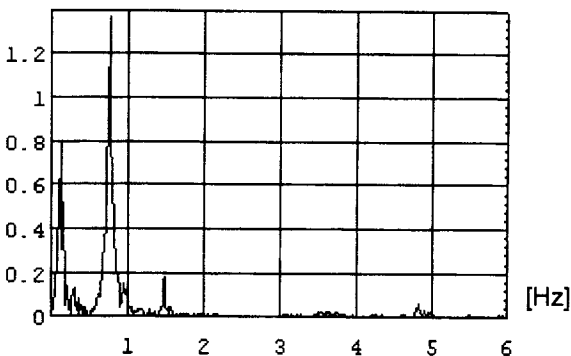

Figure 7. Frequency spectrum of Mode No. 2 test

The two dominant frequencies are: F1 = 0.15 Hz   F2 = 0.75 Hz

The frequency F1, which is very low and therefore less interesting for the scope of the work, is probably the effect of bearing clearance in the crane legs. The F1 has minimal damping.

The frequency of mode 2 is: $\qquad$ $F_{mode\ 2} = 0.75$ Hz

The average damping measured for this mode is: $\xi=0.010$ which is 1.0% of critical damping.

2.4. Mode No. 1 and mode No. 4 test - forcing with motion along rail tracks

Forcing into modes No.1 and No.4 (Fig. 2 and Fig. 3) was done with halting the crane travelling motion along rail tracks with two different sway and load positions:
a) the sway without the load was on the earth side of the crane (to expose mode 4)
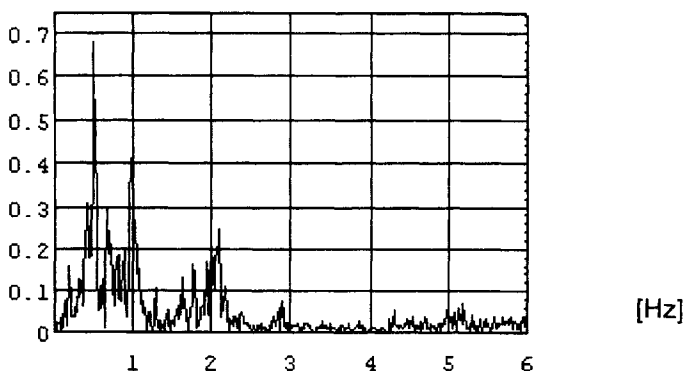b) the sway with full load in upper position was at pos. 1 (to expose mode 1)

Figure 8. Frequency spectra diagram at pos. 1 as a result of b) forcing

Analysing all responses we conclude: $F_{mode\ 1} = 0.50$ Hz, $\quad F_{mode\ 4} = 0.97$ Hz

The average damping measured for both modes is: $\xi=0.010$ which is 1.0% of critical damping.

2.5. Frequency spectra due to ambient excitation

The frequency spectra was measured due to:
a) wind loading
b) crane motion along rail tracks (where low frequency range vibration modes have large amplitudes)
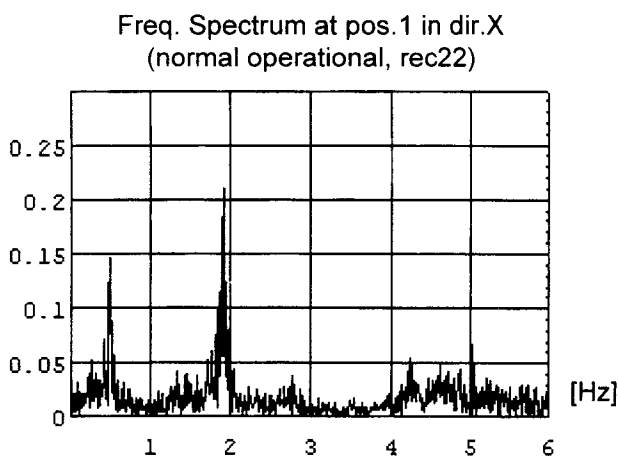c) service operational procedure (Fig. 9)

Freq. Spectrum at pos.1 in dir.X
(normal operational, rec22)

Figure 9.

3. Conclusions

Experimentally measured values of crane natural frequencies are in very close agreement with numerical results of the FEM mechanical model (Table I.).

frequency	FEM result	Experimental	difference
1st	0.508 Hz	0.50 Hz	-1.6 %
2nd	0.762 Hz	0.75 Hz	-1.6 %
3rd	0.828 Hz	0.84 Hz	1.4 %
4th	0.923 Hz	0.97 Hz	4.8 %

Table I. FEM and experimental Eigenfrequencies comparison

The first numerical results (prior to the experiment) were notably different only for the fourth vibration mode where a smaller value was computed. The difference was the result of inappropriately modeled bearings and inner reinforcement ribs in the beams above the bearings but, before the comparison with the experimental results, we were not aware of the mistake we had made.

Conclusions are:

■ the mechanical dynamic model of a container crane and related structures (heavy lifting appliances) which are in general steel-box-beam welded structures can be successfully made on the basis of Finite Element Method

■ experimental verification of the model, or at least of the model of a closely related structure, is required when accuracy and reliability of the model is important (for example, when one wants to perform extended dynamic analyses and not only the first natural frequency is of interest),

■ dynamic experiment (experimental modal analysis) can be simplified when low-frequency range is investigated. In our case, four acceleration meters (in combination with simple observation and previously made numerical analysis) turned out to be enough to establish the first four natural frequencies and proximate mode shapes. Simple forcing into basic eigenmodes, using inertia of the load or inertia of the structure itself, was also successful.

The conclusion is that the mechanical model of the container crane is reliable in the scope of our requirements and can be used for analysing other events concerned with dynamics of the structure such as service operation analysis (the deformation time history due to operational procedures and its improvement), ship transport simulation, stress analysis and fatigue analysis.

References:

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3. Salawu,O.S., C., Williams, 'Review of full-scale dynamic testing of bridge structures', Engng Struct. 1995, Volume 17, Number 2, 113-121