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ANALYSIS OF DYNAMIC LOADS OF THE LATTICE TYPE MAST STRUCTURE OF A TOWER CRANE USING SIMULATION METHOD

András PRISTYÁK

Department of Building and Materials Handling Machines
Technical University of Budapest
H-1521 Budapest, Hungary

Abstract

The oscillations of the crane, especially the pendulum motion of the lifted load suspended from rope, makes the load positioning operation difficult, endangers the potential stability of the crane and the dynamic forces, due to their oscillating feature, lead to fatigue damage of structure components. On the other hand, it is not possible to perform a fatigue analysis without the knowledge of the so-called *stress-time histories*. All this requires the application of dynamic analysis methods.

This paper is intended – through the analysis of transient motions and loading of a lattice type mast structure of a tower crane – to show the possibilities of computer simulation of dynamic loads and stresses and in promotion of the crane design.

Keywords: crane, dynamics, stress-time-histories, simulation.

1. Developing of the Dynamic Model

It is known that the tower cranes belong to the group of intermittent duty equipment. It is characteristic for them, too, a tall and slender mast or tower, a long jib, a complicated load lifting, jib holding and luffing rope system, and, furthermore, that they commonly have four autonomous driving systems which can be started independently one by one, and two or three instationary motions can exist at the same time (*Fig. 1*). Under the lifting and crane or trolley travelling motions, combined with slewing motion of the crane, the load is subjected to spatial pendulum motion that has significant influence to the loads of the mast, to support forces and to the potential stability of the crane.

For determination of loads and stresses in the mast structure it is necessary to analyse the cross-section where the maximum effects are expected. For the crane investigated (a KB 160/2 type crane) this cross-section is located in the vicinity of the lower fixation of the mast in the portal: the cross-section $I-I$ in *Fig. 1*, or this is the plane of truncation in *Fig. 2*. For this cross-section we can determine a system of 6 loading vectors (*Fig. 2*):

$$\mathbf{F} = f\left(\mathbf{F}_z, \mathbf{M}_z, \mathbf{F}_x, \mathbf{F}_y, \mathbf{M}_x, \mathbf{M}_y\right),$$

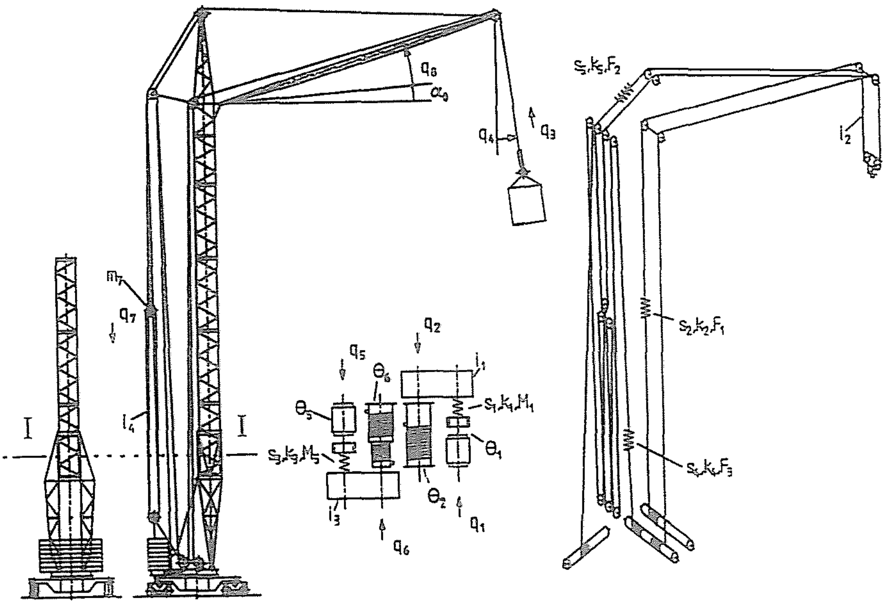

Fig. 1. Tower crane structure

that can be used for load or stress calculation in all the 8 rods 'cut' by that plane of truncation.

Since we need the loads and stresses in structure as the functions of time, this fact requires the application of *dynamic modelling and mathematical simulation methods.*

Description of combined crane motions requires complicated dynamic models and due to coincidence of straight-line and slewing motions it is necessary to count with the developing of centrifugal and Coriolis forces, too, that makes difficult the drafting of equations of motions for such systems.

For investigation of dynamic behaviour of tower cranes we have developed 3 dynamic models: one for analysis of stability [1], [2], [3], one for calculation of support forces [4], [5], and another one for determination of loads and stresses in the mast structure [6], [7], [8].

By the aid of the third model mentioned the effect of simultaneous start and braking of lifting, travelling and slewing motions can be simulated, or the same can be done with some time delay, or so can be simulated the independent start of each of them, the start of lifting motion with slacken rope, or the sudden release (dropping) of the lifted load.

A variation of these dynamic models can be seen in *Fig. 3*, which was elaborated and is used for studying the effect of combined raising, travelling

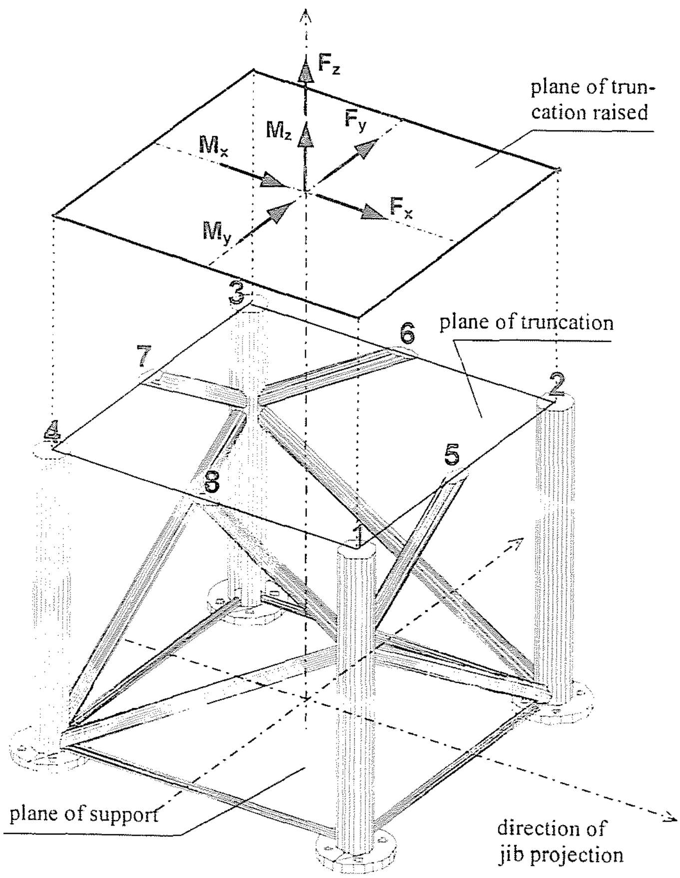

Fig. 2. Forces and moments in the cutting plane

and slewing motions.

Our model, used for investigation of the effect of combined motions on the mast structure, has 14 degrees of freedom, among which the mast itself has 3 degrees: two against bending (in its two main vertical planes) and one against torsional action around its longitudinal axis.

In these models the generalised co-ordinates are: q_1, q_8, q_{13}, q_{14} – the angular displacements of the axes of driving motors for slewing, lifting, travelling and luffing motions, respectively, q_2 – the angular displacement of rotating table, q_3 – the torsional deformation of the mast around its main (vertical) axis, q_6 and q_7 – the bending deformations of the mast under horizontal forces measured on the level of jib hinge point in the direction of the jib (q_6) and perpendicularly to the jib (q_7), q_{12} – the vertical displacement of the moving block of the luffing rope system (behind the mast, and having

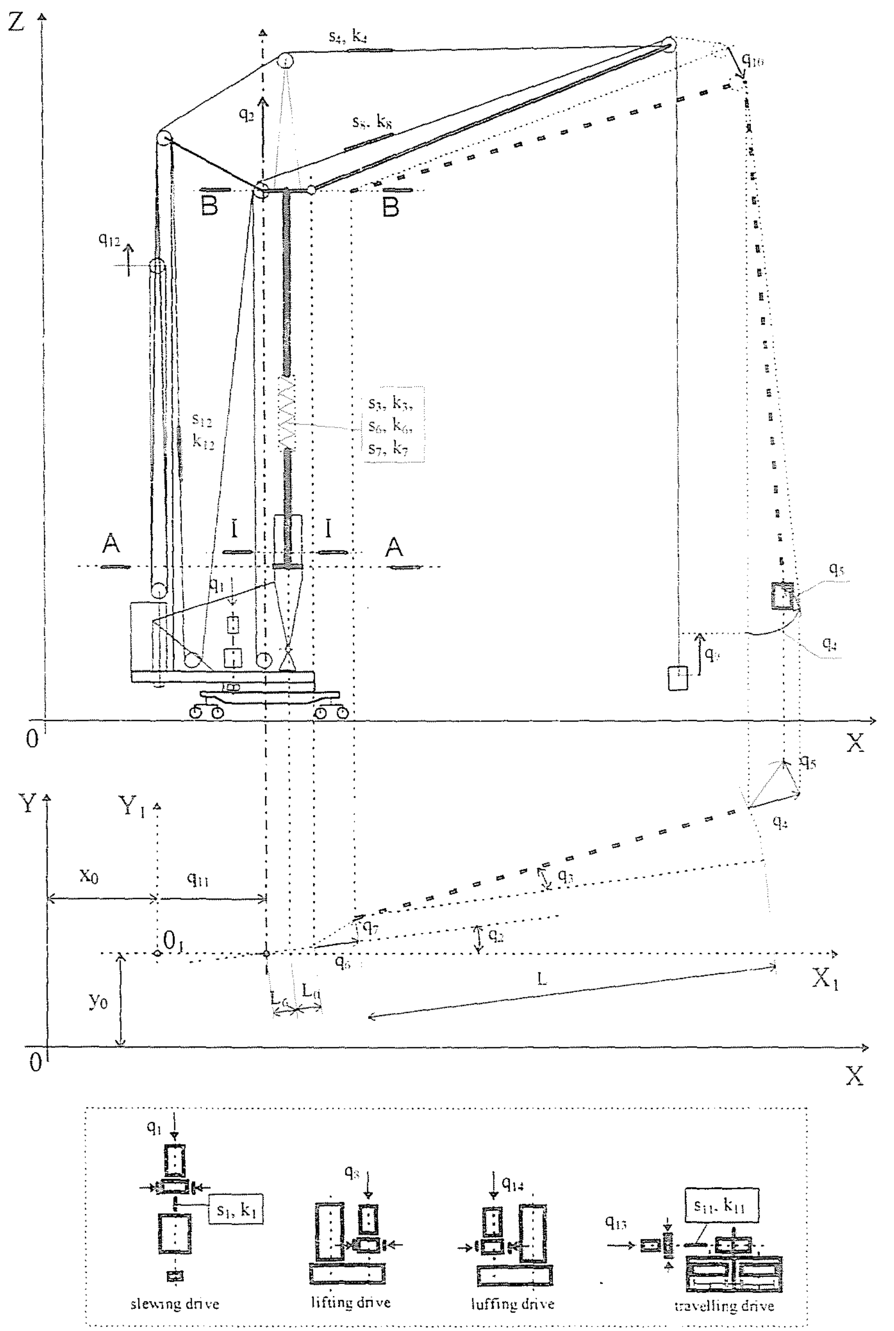

Fig. 3. Dynamic model variations

a mass m_1), q_{10} – the displacement of the jib outside end (due to relative rotation around its hinge point), q_{11} – the horizontal motion of the whole crane on its track, q_4 and q_5 – the horizontal displacements of the load in the direction of jib projection and perpendicularly to it, q_9 – the displacement of the load in the direction of the lifting rope.

The load lifting, jib holding and luffing rope system (*Fig. 1*), which is considered elastic, plays determining role in the loading of the mast. This system of ropes with different elasticity and the spatial pendulum motion of the load make the dynamic model rather difficult.

For checking of the quality of these models it was necessary to make a complex measuring experiment which was carried out on a real crane in 1995 (*Fig. 4*). Some results will be shown below.

2. Experimental Investigation for Elasticity and Damping Parameters

The rigidity of an elastic member is nothing else than the rat: of an action to the deformation caused by this action: N/m or Nm/rad, depending on the kind of action (force or moment) and on the deformation caused (elongation, deflection, torsion, etc.). The rigidity of simple elements can be determined by the equations of basic statics, but the same in case of girders with compound and varying cross-sections require instrumental static measurements. Determination of damping characteristics of structures requires exclusively oscillatory measurements, and the damping constants can be determined from the diagrams of free damped oscillations and on the basis of so-called logarithmic decrement.

It is known by specialists that to carry out an instrumental measurement and to evaluate the registrations is a rather difficult and responsible task, which is definitely true for an equipment with big geometric measures, especially if it is to be experimented at a construction site.

In the field experiment we have measured the quantities listed below:

- the displacements of different points of the structure under different static loads (to determine the deformations), using theodolits,
- the support forces under a whole rotation of the crane, using ring type load cells,
- the 6 loading vectors in the cross-section $I - I$ of the mast (*Fig. 2*), using a specially developed strain gauge system,
- the force in the lifting rope, using a load cell,
- the oscillations on the load, on the outside end of the jib (in 3 directions), in cross-sections of the mast at different levels (with 4 accelerometers in a cross-section in two horizontal directions to measure the bending and torsional oscillations of the mast),
- the vertical oscillations of the rotating platform and of the bogies.

During this experiment the crane was subjected to the possible most extreme static and dynamic load tests: to sudden pull-up of the load (raising at slacken rope), to raising the load from suspended position, to starting and braking of the raising, travelling and slewing motions at the same time, to action of sudden release of the load rope from pulling force at vertical and inclined directions (imitation of dropping of the load). In the last case the rope inclination was arranged perpendicularly to the jib horizontal projection to cause a mast torsional deformation.

It is not possible in this paper to describe this experiment wholly, nevertheless it will be shown that the dynamic models and their system equations and mathematical algorithms we have elaborated are workable and suitable for solving the problems aimed for the analysis of loads and stresses of the mast.

3. Some Experimental and Simulation Results

As it was mentioned above, the loads in the mast cross-section $I-I$ (*Fig. 1* and *Fig. 2*) were experimented by a system of strain gauges, and the same system of 6 cross-sectional vectors for the same crane were determined by mathematical simulation, too.

The mathematical simulation provides us with the time functions of these vectors that makes it possible to create the *load- or stress-time-histories* for different loading and operating conditions of the crane.

The *simulated stress-time-histories* can be seen in *Fig. 5* for the corner bar 4 (σ_4) and for the lattice bar 6 (σ_6). The simulation cases are: raising the load (R), travelling motion with the jib, standing in the direction of the crane track (T), slewing motion (S), and the simultaneous raising, travelling and slewing motions ($R+T+S$), all with the nominal load and with the simulation time of 20 seconds in every case. The diagrams are plotted at the same rate (0 ... −85 MPa for σ_4 and 90 ... −70 MPa for σ_6) for different working conditions, that provides an easy visual comparison.

The analysis of these diagrams makes us possible to draw conclusions listed below:

1. In the developing of dynamic forces, in excess of static ones, the slewing motion of the crane plays the determining role. The dynamic effects of lifting and travelling motions can nearly be neglected in the stress analysis.
2. The extreme values of stresses are developing always during the first 3 – 4 seconds following the start of the crane operations, that is important for the duration of simulation time.
3. Three dominant frequencies of oscillations can be observed in the stress-time diagrams. One of them has a relatively long period of time and big amplitude which is clearly determined by the length of load

rope suspended from the jib end (at the length of 40 m $f_1 = 0.08$ Hz, $T_1 = 13$ s). The other two components have higher frequencies – one for the corner bars depending on the bending elasticity of the mast ($f_2 = 0.69$ Hz, $T_2 = 1.45$ s), and the other one for the lattice bars depending on the torsional elasticity of the same mast ($f_3 = 0.46$ Hz, $T_3 = 2.2$ s).

4. With respect to varying of stresses it can be stated that for the corner bars the *pulsation of compressing stresses*, and for the lattice bars the *alternation of stresses* are characteristic. These circumstances are to be taken into consideration in checking the mast structure for the static strength and for the fatigue life, too.

Comparison of simulated and measured results is made on the basis of data in *Table 1* and *Table 2*.

Table 1.

The loading components	Units	Simulated values (S)	Measured values (M)	$\delta = \frac{M-T}{T}100$ (%)
$\Delta\mathbf{F}_x$	N	2117	1727	−18.4
$\Delta\mathbf{F}_y$	N	3778	3785	0.18
$\Delta\mathbf{F}_z$	kN	−387.5	−32.0	−17.4
$\Delta\mathbf{M}_x$	kNm	94.6	108.6	14.8
$\Delta\mathbf{M}_y$	kNm	118.6	128.4	8.3
$\Delta\mathbf{M}_z$	kNm	98.0	105.0	7.14

Table 2.

The loading	The eigenfrequencies (Hz)		$\delta = \frac{M-S}{S}100$ (%)
components	Simulated (S)	Measured (M)	
$\Delta\mathbf{F}_x$	0.727	0.746	2.6
$\Delta\mathbf{F}_y$	0.441	0.417	−5.4
	1.073	0.977	8.9
$\Delta\mathbf{F}_z$	1.980	1.800	9.1
$\Delta\mathbf{M}_x$	0.438	0.417	−4.8
	1.073	0.977	−8.9
$\Delta\mathbf{M}_y$	0.732	0.708	−3.3
$\Delta\mathbf{M}_z$	0.074	0.134	81.1
	0.438	0.422	−3.7

In *Table 1* and *Table 2* are quoted the simulated (S) and measured (M) quantities of components of the cross-section vector $\mathbf{F}$, namely:

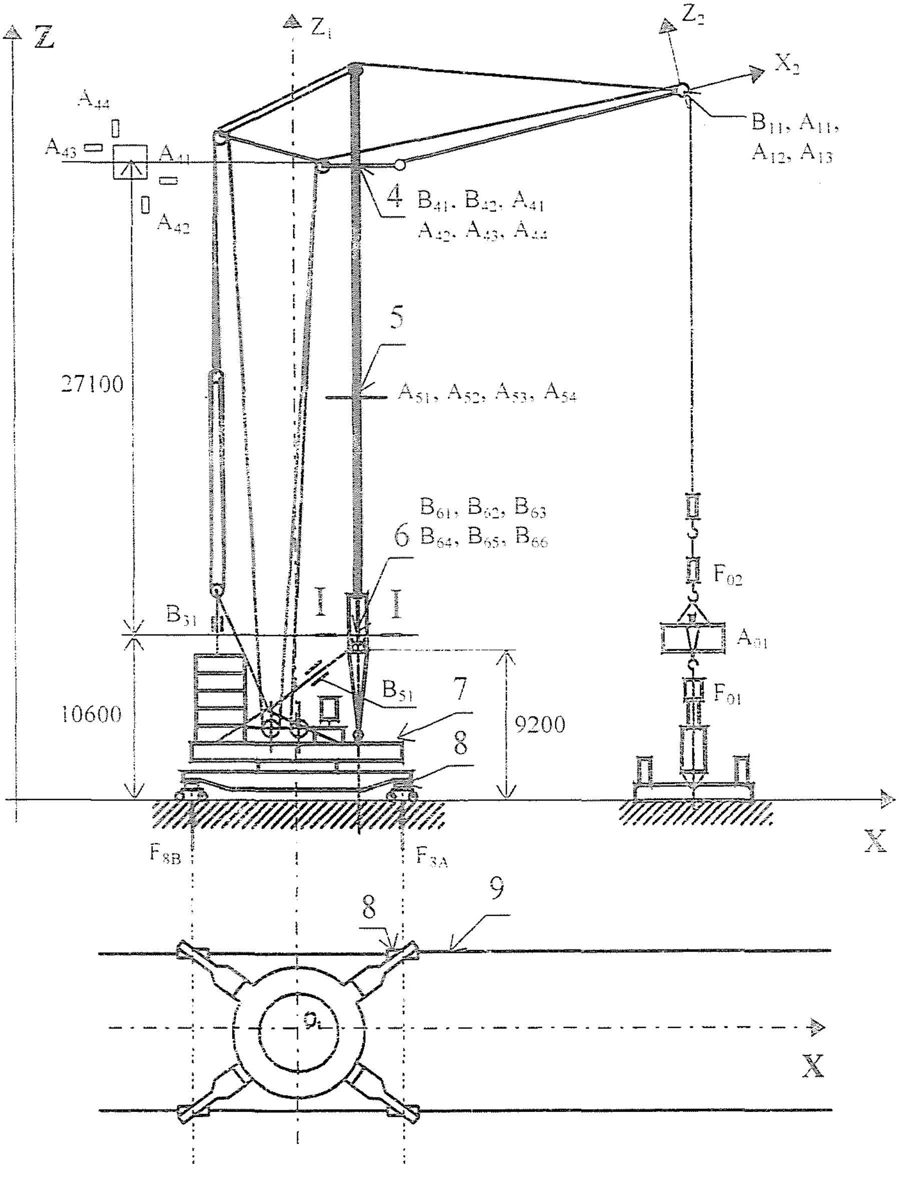

Fig. 4. Experimental crane model

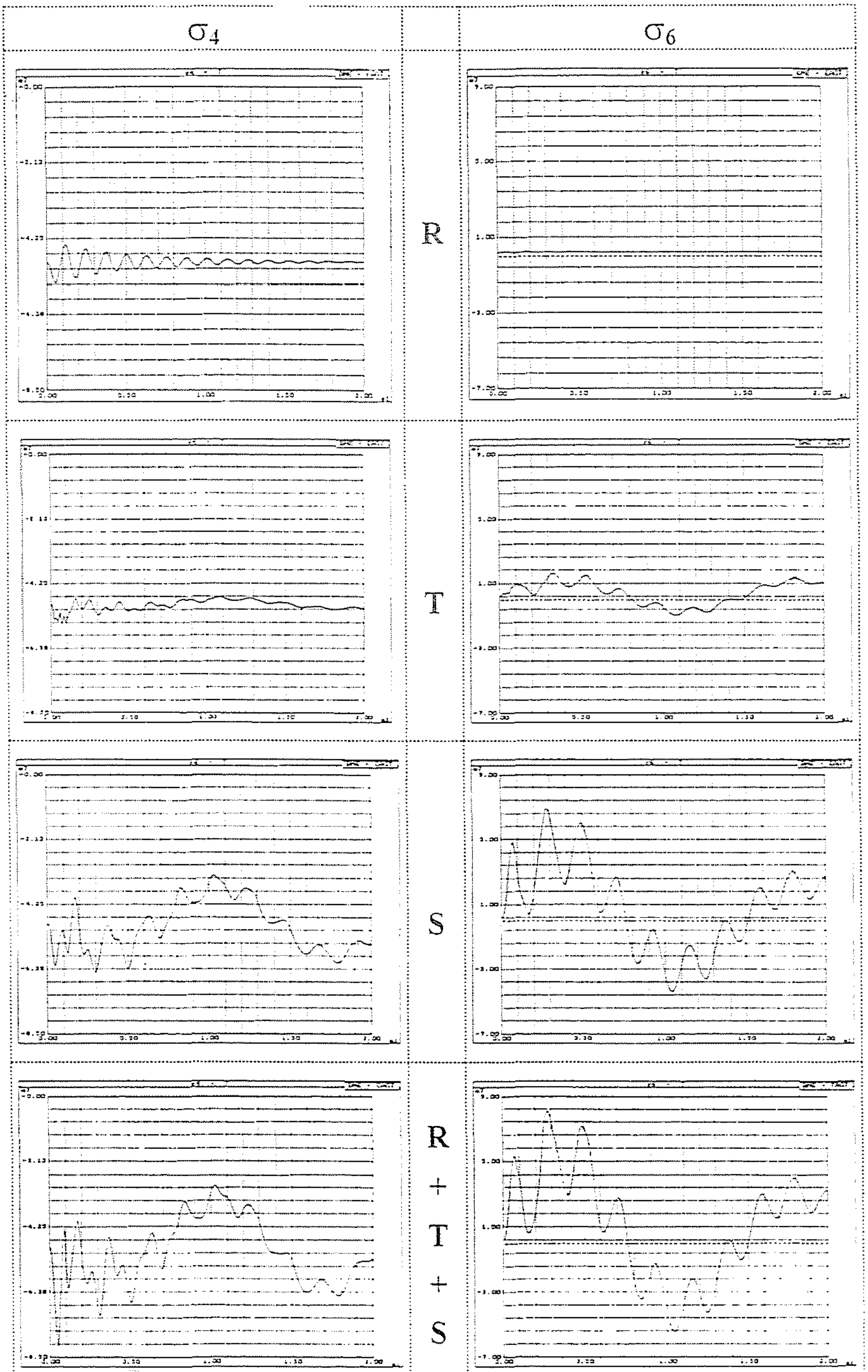

Fig. 5. Simulated stress-time histories

- in *Table 1* – the differences of static quantities ($\Delta\mathbf{F}_x$, $\Delta\mathbf{F}_y$, etc.), which are developed in the structure due to the action of inclined prestressing rope force and after releasing of it,
- in *Table 2* – the characteristic frequencies of free oscillations developed in the structure after sudden release of that prestressing force, which were simulated or measured on the same components of cross-section vector $\mathbf{F}$.

The prestressing rope forces in both simulations and measurements correspond to the static action of the rated load.

The comparison of these data seems to be convincing on the quality and acceptability of the models and simulation software developed and presented here for the dynamic analysis of the lattice type mast of a tower crane with rotating tower.

4. Conclusions

The dynamic model discussed and the simulation software developed at the Department of Building and Materials Handling Machines of T.U.B. is suitable for revealing the loading and stresses in the mast structure of the tower cranes more precisely than ever before, xand the possibility of creation of simulated stress-time-histories opens the way of checking the crane mast structure for fatigue life time.

Furthermore, the dynamic simulation, by giving the displacements, velocities, accelerations and loads of the structure as the functions of time, provides a better understanding and more accurate describing of tasks that are directed to the effective damping of oscillations and to the development of automated driving and braking systems.

The experiences obtained can be transplanted without any difficulties to loading and stress analysis of frame structures of the tower cranes with non-rotating tower or of the portal cranes, too.

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