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THEORETICAL STUDIES AND EXPERIMENTAL DETERMINATIONS FOCUSED ON THE INCREASE OF THE GANTRY CRANE'S WORK SAFETY
PART II – EXPERIMENTAL DETERMINATIONS, CONCLUSIONS AND RECOMMENDATIONS CONCERNING THE INCREASE OF THE WORK SAFETY

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Abstract: *From the analysis of the current stage concerning the strength and stability studies for the gantry crane, taking into account the actual valid standards, the content of the calculation, based on the experts actual recommendations and on the prescripts presently used at the design and calculus of the gantry crane, the authors emphasize an important conclusion for the ensuring of the crane's work safety: the current standards do not approach issues regarding the vibratory state; certainly one states that the first signs regarding a bad working and changes in the evolutions of the technical state, respectively, appear in the "vibratory mark" of the structure.*
Keywords: *gantry crane, deflection, oscillations, modal analysis.*

1. SUMMARY DESCRIPTION OF THE TECHNICAL MATERIAL

SPIDER 8 is an electronic system for the numerical measurement of the analogical data. It is specialized on recording mechanical quantities: forces, mechanical stresses, pressures, accelerations, velocities, displacements, temperatures and also on the measurements of the electric voltage analog signals (it shows a generalization in the measurement field).

THE SIGNAL CONDITIONER is required in order to increase the magnitude of the low electric sign which comes from the accelerometer and to transform the high output of the accelerometer into a lower one (this way, the electric voltage signal can be measured with the usual equipment – voltmeters, oscilloscopes, recording systems). One used the signal conditioner NEXUS 2692 – A – O14 (Bruel & Kjare), a four channel conditioner, designed for the working with force transducers and for the measuring of vibrations, noises and forces.

THE PIEZOELECTRIC ACCELEROMETER is an electromechanical transducer which provides at the output an electrical signal direct proportional to the accelerometer to which it is subjected.

IMPACT HAMMER works on the same principles like the accelerometer.

INDUCTIVE TRANSDUCER FOR LINEAR STROKE - its working is based on the appearance of an electromotive electric voltage in the coil's circuit in changing magnetic field:

$$E = L\frac{d\phi}{dt},$$

where:

E – the electromotive electric voltage at the coil's terminal;

L – inductance of the coil;

ϕ - changing magnetic flux in the coil's area.

RESISTIVE TRANSDUCERS FOR LINEAR STROKES MEASURING

ELECTROTENSOMETRIC TRANSDUCERS (ETT) are based on the change of the wire's resistance, whose resistivity is ρ, subjected to an elongation $\delta\ell$. The central element of the electrotensometric transducer is represented by the strain gauge. The very low relative variations of the transducer's resistance lead to the requirement of a Wheatstone bridge. This one ensures both the transducer excitation and the amplification of the

electrical signal from the transducers and also the bridge protection against the changes of the electrical voltage caused by modifications of the working conditions. Depending on the requirements one may conceive different types of transducers to which one adapts fitting with one, two or four active gauges.
For the processing and the experimental data, the program "DINAMICA MACARA.TST", under Test Point software was achieved [3].
Further on present some of the experimental researches achieved by the authors. The researches were settled on three main directions, regarded as highly significant for increase of the work safety at gantry cranes:

- one studied the answer of the structure acted by dynamical forces in windbracings [Fig. 3];
- one studied the behavior of the main beam under static and dynamic load {deformations);
- one considered the behavior of the whole structure (gantry crane) in dynamic regime (the failure of the driving cable of the lifted loads)

2. STRESSES AND INTERNAL FORCES IN THE FRACTURE AREA

Figure 4 presents the assembling required for the determination of the stresses in the failure susceptible elements; Figure 5 contains recordings of the stresses and internal axial traction compression forces in windbracings (the external load relative to points P3). Table 2 contains recordings.
Relative to the loads applied in points P1, P2, …, P7. (Figure 1)

Fig. 4

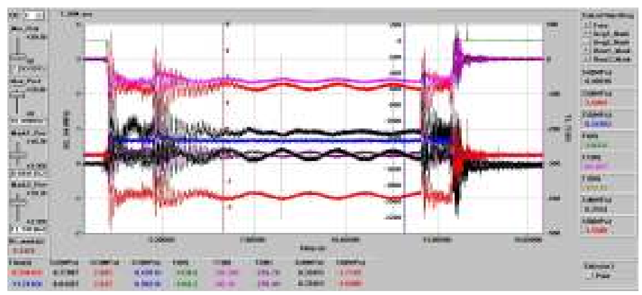

Fig. 5

Table 2

Application point	Number of weights	Ft (N)	Si1 (MPa)	Si2 (MPa)	Si3 (MPa)	Si4 (MPa)	Si5 (MPa)
P1	4	583.3328	-0.28681	-0.08416	-0.37049	-0.70892	1.086433
P1	6	868.7676	-0.3959	-0.09174	-0.47035	-1.06058	1.680689
P1	8	1158.472	-0.49697	-0.06315	-0.57373	-1.3924	2.266022
P1	10	1444.092	-0.56341	-0.07319	-0.65974	-1.94479	2.61358
P2	4	583.3328	0.891048	0.147195	0.401483	-1.09387	-0.0185
P2	6	868.7676	1.271963	0.212301	0.570935	-1.63531	0.010073
P2	8	1158.472	1.439609	0.283946	0.778276	-2.12466	-0.02303
P2	10	1444.092	1.897573	0.310765	1.055137	-2.57573	-0.12012
P3	4	583.3328	0.234848	0.461476	1.084563	0.11005	-0.62083
P3	6	868.7676	0.338495	0.676804	1.624871	0.163816	-0.95031
P3	8	1158.472	0.428675	0.774307	2.100624	0.228413	-1.24899
P3	10	1444.092	0.541017	0.88938	2.606904	0.253396	-1.55888
P4	4	583.3328	0.11045	0.165878	0.969304	0.505078	-0.72989
P4	6	868.7676	0.186542	0.195233	1.444216	0.752605	-1.08383
P4	8	1158.472	0.245665	0.217381	1.883697	0.985493	-1.43623
P4	10	1444.092	0.29417	0.196337	2.31269	1.236637	-1.8138
P5	4	583.3328	0.047676	-0.1286	0.658351	0.564331	-0.61751
P5	6	868.7676	0.064812	-0.20624	0.925532	0.827994	-0.90176
P5	8	1158.472	0.095057	-0.29158	1.236273	1.100154	-1.21218

P5	10	1444.092	0.109774	-0.40445	1.510528	1.365756	-1.52015
P6	4	583.3328	-0.011	-0.06181	0.1154	0.145073	-0.0945
P6	6	868.7676	-0.01383	-0.10795	0.206517	0.28476	-0.1519
P6	8	1158.472	-0.01616	-0.1658	0.276117	0.357984	-0.21576
P6	10	1444.092	-0.02572	-0.22585	0.337007	0.449007	-0.30353
P7	4	583.3328	-0.05259	-0.17848	0.064437	0.341755	-0.13712
P7	6	868.7676	-0.07396	-0.25509	0.116943	0.520546	-0.21624
P7	8	1158.472	-0.09182	-0.33864	0.166251	0.694758	-0.2772
P7	10	1444.092	-0.13577	-0.42991	0.173065	0.882781	-0.37164

Table 3 Internal forces in windbracings

Application point	Number of weights	Ft (N)	T1 (N)	T2 (N)	T3 (N)	T4 (N)
1	4	583.3328	-366.777	-249.698	2.099316	17.15721
1	6	868.7676	-541.094	-364.537	2.507816	27.88273
1	8	1158.472	-714.217	-480.649	2.820725	33.96707
1	10	1444.092	-829.093	-555.193	2.986383	42.43365
2	4	583.0404	-77.3679	-67.1541	-7.38523	5.350258
2	6	869.5302	-117.347	-98.8672	-15.1543	11.85774
2	8	1156.937	-152.968	-131.48	-18.0383	13.2324
2	10	1442.996	-176.812	-162.686	-23.7392	16.35647
3	4	586.1524	-25.8232	-116.621	-64.9434	9.851587
3	6	869.6965	-37.9071	-172.027	-92.7282	14.71909
3	8	1157.135	-50.0482	-223.275	-125.907	18.33355
3	10	1443.607	-62.0366	-273.147	-154.673	23.25374
4	4	585.5376	-3.49574	-99.2354	-100.327	-3.56565
4	6	869.9202	-4.62819	-147.313	-148.786	-4.62819
4	8	1156.203	-7.04137	-192.145	-190.245	-6.97096
4	10	1444.921	-7.64758	-235.352	-237.941	-7.72406
5	4	592.2682	9.73477	-64.2368	-116.621	-25.8232
5	6	871.0108	14.54455	-91.7193	-172.027	-37.9071
5	8	1156.942	18.11616	-124.537	-223.275	-50.0482
5	10	1443.583	22.978	-152.99	-273.147	-62.0366
6	4	584.56	5.297285	-7.27609	-67.1541	-77.3679
6	6	872.357	13.16064	-14.9304	-98.8672	-117.347
6	8	1156.113	13.10138	-17.7717	-131.48	-152.968
6	10	1444.369	16.19452	-23.3884	-162.686	-176.812
7	4	584.2636	16.90365	2.078531	-249.698	-366.777
7	6	869.5993	27.47067	2.482986	-364.537	-541.094
7	8	1155.5	33.46509	2.792797	-480.649	-714.217
7	10	1444.887	41.80655	2.956815	-585.193	-859.093

3. THE MAIN BEAM - EXPERIMENTAL DETERMINATIONS

The crane's carriage was successively positioned in points P1, P2, P3, …, P7, Fig. 6. The load's magnitude is 1444 N and it was attached to the crane's hook through the force transduces U2B 10 [kN].

Fig. 6 Mounting scheme for deflections measuring

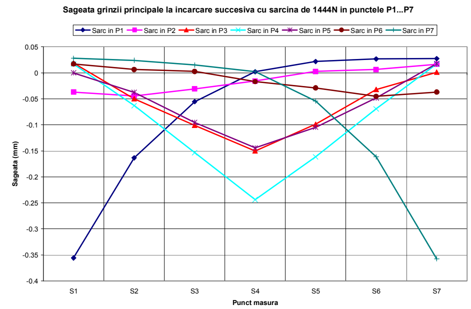

Fig. 7 1444 N load in points P1 … P7. Deflections

In order to ensure a proper interaction between the crane's main beam P1 – P7 and the fixed body of the inductive transducers of the linear stroke, a metallic frame was achieved, as shown in Figure 6. Inductive transducers were mounted on the metallic frame and their moving roads (of negligible mass) were stiffy attached to the main beam of the crane.

For each position of the carriage in points P1 … P7 one achieved the following succession:

- start the recording system SPIDER 8;
- lifting of the road at an approximately 400 mm height;
- stopping and waiting about 5 seconds;
- load descent and waiting about 5 seconds;
- stopping of the recording system.

Table 4 Main beam's deflections

Application point	F (N)	S1 (mm)	S2 (mm)	S3 (mm)	S4 (mm)	S5 (mm)	S6 (mm)	S7 (mm)
P1	1449.65	-0.35594	-0.16332	-0.05543	0.001866	0.021758	0.026528	0.027321
P2	1454.38	-0.03704	-0.04429	-0.03078	-0.01579	0.00259	0.006151	0.016375
P3	1446.58	0.01875	-0.04976	-0.10099	-0.1501	-0.09885	-0.0319	0.001305
P4	1447.94	0.016905	-0.06318	-0.15366	-0.2438	-0.16171	-0.0693	0.016751
P5	1450.09	5.36E-05	-0.03769	-0.09547	-0.14441	-0.10467	-0.04819	1.75E-02
P6	1452.2	0.017142	0.006282	0.002603	-0.01692	-0.02915	-0.04522	-0.03711
P7	1440.2	0.027938	0.02394	0.014999	0.001842	-0.05413	-0.16155	-0.35734

4. THE BEHAVIOR OF THE WHOLE STRUCTURE UNDER LOAD. CRANE'S DYNAMICS

One achieved a software relative to the graphs of the crane's dynamics, when the external load are applied successively in points P1 … P7. Figure 8 shows the position of the measuring points on the crane's structure.

Fig. 8 Position of the measuring points on the crane's structure

Table 5 Eigenfrequencies of the traction force and deflection of the main beam

Analyzed parameter	Time for lifting (*s*)	Height load (*mm*)	Acting point load	The traction force frequency (*Hz*)	Arrow frequency (*Hz*)
Săgeţi	0.67	166	P1	8.88	8.88
Săgeţi	0.72	179	P3	8.79	7.85
Săgeţi	0.66	166	P4	8.79	7.96
Săgeţi	0.77	191	P5	8.93	7.91
Săgeţi	1.04	266	P7	10.6	10.6

IMPORTANT ISSUES: From the achieved researches, based on the above complex experimental determinations, one specifies the following conclusions:

- the eigenfrequency of the force in the driving cable varies in the field 7.8 Hz … 10,6 Hz (depending on the magnitude of the suspended mass and on the driving cable's length);
- the usual working loads of the crane lead to forced vibrations in the structure of the main beam;
- the eigenfrequencies of the crane's mechanical structure are excited, too;
- a favorable working of the crane suppose the eigenfrequencies of the mechanical structure to be outside the frequency field of the exciting forces;
- an accurate knowing of the dynamics of the main beam's deflections under changing load is required; that means the identification of the eigenfrequencies of the whole mechanical structure and also of the oscillations eigenforms;
- analyzing the crane's behavior in dynamic operating mode, the most detrimental position of the carriage (of the load) is specified.

FAILURE OF THE DRIVING CABLE: Tests relative to the determination of the crane's dynamic answer at changing strains, due to the driving cable failure during the load's lifting, are achieved. One mentions that at the uplifting from the bottom of the 1444 N weight the force in the driving cable increases with the force of inertia, due to the acceleration of the lifted road; the real force in cable reaches approximately 1700 N. In order to simulate the cable's fracture between the force transducer and the crane's hook a steel wire, 3 mm diameter, is inserted; the wire fails under a force of about 1700 N. The force transducer was joint connected to the lifted road. Some determinations were achieved. One established that the failure phenomenon is reproducible.

IMPORTANT ISSUES: Analyzing the frequency answer of the accelerations in points P1 … P7 at the cables failure, when the load is in P4, one ascertained that the main beam's oscillations are large band vibrations; the frequencies field of the vibratory answer extends in the 0 … 400 Hz range.

5. CONCLUSIONS

All the achieved researches stand on the base of the knowledge and determination of the gantry crane's operational safety degree. The conclusions can be extended to other cranes types.

The experimental tests schedule was a complex one, the conclusions being a great usefulness for the increase of the cranes operational safety.

One emphasizes some of the main conclusions of the achieved researches:

- the functions of the frequencies answer provide a highly efficient valuation method, through experimental and theoretical techniques (relative to the dynamic answer of a mechanical system subjected to external forces in a single or more points of the structure);
- through theoretical studies and experimental check one achieves a well optimization of the structure;
- in order to achieve the analytical answer of the structure at imposed excitations, the experimental determination of the functions matrix of the frequencies answer is required;
- the studied structure is brought to a controlled vibratory state , one performs measurements and the mathematical model of the structure is finally achieved;
- the so called composite mathematical models, theory and test, lead to accurate results;
- the mechanical system is in well-known conditions excited; one achieves the development laws of the oscillations and the vibratory answer; one achieves the functions of the frequencies answer which describes the vibration modes of the structure; the eigenpulsations and the oscillation forms in eigenvibration modes are specified;
- the frequencies answer functions are uniquely related to the real system and allow the theoretical valuation of the structure's answer to different exciting conditions applied in distinct points of the structure;

- the location of some structural resonance in the exciting frequencies fields lead to the dangerous amplifications of the vibratory answer; for this reason, the identification of the eigenpulsations is extremely important;
- most of the time, the experimental structural analysis is applied together with the theoretical method FEM; FEM must use a mathematical model similar to that one yielded from tests;
- depending on the applied software (FEM) and on the users skills results which can describe adequately the behavior of the real structure;
- any finite elements structural model must be certified through experimental determinations (tests) in order to avoid major errors which might occur due to an inexactly knowing of the geometrical and material specific features.

Besides the above presented issues, one suggests also researches concerning the applications of the modal experimental analysis relative to the valuation of the technical state of the cranes. This method aims to complete the actual procedure and to lead to the increase of the gantry crane's operational safety.

The experimental modal analysis (EMA) is the procedure used to develop the mathematical model of the structure, on basis of experimental data yielded by tests. These are performed on a controlled vibratory state of the structure. One mainly follows the below sequences:

- the structure is stimulated in the known conditions;
- one achieves the development laws of the stimulation (excitation);
- recording of the vibratory answer;
- one registers a number of parameters relative to the vibrations eigenmodes: eigenpulsations, damping constants, modal forms;
- establishment of the modal model which joints uniquely to the real system;
- achievement of the theoretical valuation of the structure's answer to various exciting conditions (uplift to the load, carriage motion, longitudinal swing).

One states that the modal pattern allows the achievement of changes to the real structure and the valuation of the theoretical answer of the changed system. Thus, one achieves visual changes by attainment of a system with a desired vibratory answer.

Analyzing the modal patterns, one emphasizes the weakness and the failure areas of the structure. One identifies those frequencies which are dangerous for the tested mechanical structure.

The experimental modal analysis benefits of the high speed recording techniques and a large work and storage capacity. This method may be highly efficient. It completes usefully the actual testing methods of the gantry cranes achieving a significant increase of the work safety.

One achieved a comparison of the results yielded by FEM and by tests – the level of the deformations in the seven points of the main beam was emphasized.

The study results (in tabular or graphical form) show that more outstanding values must be eliminated. The tests were achieved with adequate equipment, of high accuracy, recognized in the field of mechanical engineering.

The achieved research allows a systematization of the yielded results in a new methodology which allows a periodical check of the vibratory answer to the crane's operational load.

All the achieved researches stand at the base of knowledge and determination of any crane's operational safety and especially of gantry cranes.

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