Development of a test bench for calibration of load moment limiter used in mobile crane

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***Abstract*—The calibration and setting of mobile crane load moment limiters require a series of lifting tests. To shorten and improve these tests, a test bench strategy simulated the validation of the load limiters. Costs were also reduced regarding human resources, instrumentation and materials consumption. The prototype of the test bench simulator grew from postponing building site calibration to processing a numerical model to acquire a vast range of data on real cranes. The test bench simulations reliably replicate load limiter calibration in the laboratory and eliminate setting times on the building site.**

***Index Terms*—Load moment limiter; Lifting tests; Mobile crane; Test bench simulator; Stability.**

I. Introduction

Nowadays, the development of effective test benches to determine the limits of stability and of resistance to mechanical systems is increasingly used. Both for very small systems [1], [2], [3], which for large structures and industrial plants the use of test benches can provide valuable and useful information [4], [5]. Processing a numerical model to verify the stability of a mobile crane requires formulating the correlations between the load raised by the crane and the relative forces on the hydraulic jack [6], [7], [8]. By means of a load diagram and crane lift-capacity tables those correlations can be calculated [9], [10], [11].

Among mechanical systems simulation techniques [12], [13], [14], [15], [16], the test bench simulation strategy to the calibration and setting of the sensors and limiters [9] is the most effective and efficient.

The model should list the maximum loads the crane can lift safely in all its varying operational configurations relating to boom inclination and telescopic extension, any manual extensions (with main load block) and with various sized JIBs and considering if the crane operates with a raised boom or a winch.

Usually, the maximum loads at which the load moment limiter intervenes with a pre-alarm or alarm and subsequent shut-down are worked out from the lift capacity tables.

The test bench simulator is a scale-model of the cranes main orientations and so studying a numerical model to apply electronically to a test bench and load moment limiter makes it a requirement to know about the stability and any possible over-loading.

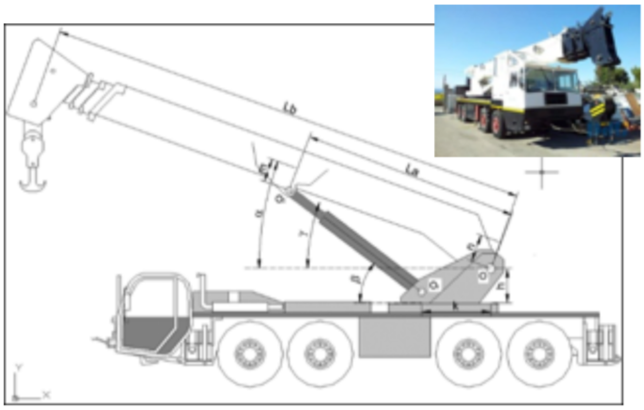

Fig. 1. G&C 45ATL mobile crane scheme.

Processing a numerical model which provides the security system with all the necessary data for calibration requires it to be referenced to an actual mobile crane, in this case a G&C 45 ATL. A preliminary on-site analysis was carried out to acquire the characteristics of the crane's geometry, its fixed and moving parts. Using a digital photogrammetry technique acquisition as described in [17], [18], [19], [20], [21] all 3D geometries were detected.

This data together with data from the cranes lift capacity tables helped define the numerical model to apply to the test bench and load moment limiter.

II. Processing a Numerical Model to Test Stability

To define the geometric parameters after the on-site measurements, we drew a 2-dimensional diagram of the crane from which, referring to the booms rotational axis, we obtained the hydraulic jack attachment distances, the boom lengths, the centre of gravity distances of each boom section with the boom closed, the characteristic angles of the raised boom and hydraulic jack, and the distances of the fifth wheel centre and the booms centre of gravity.

The model provides the correlations between the forces acting on the hydraulic jack lifting the arm, the hydraulic liquid pressure and the lifted load. To calculate the static equilibrium, the booms centre of gravity is needed as well

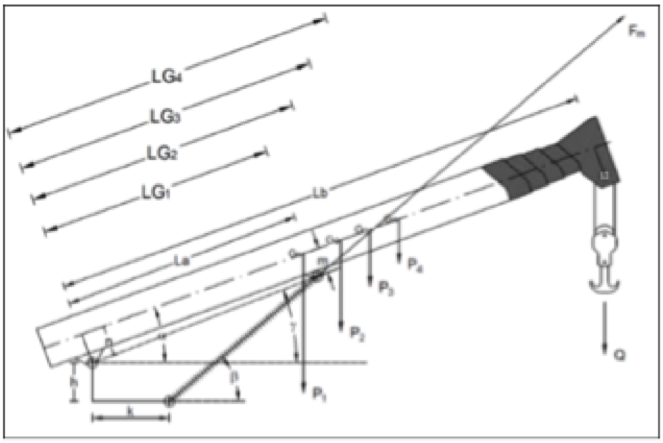

Fig. 2. Non-extended boom' configuration.

as those of the booms telescopic sections (G_1, G_2, G_3, G_4 in Fig. 2).

These help calculate the moments of force lifted (P_1, P_2, P_3 and P_4) by a single section rolled around the boom's hinge O. This is the 'non-extended boom' configuration.

The terms Lgn for nos. 1, 2, 3, and 4 are the distances of the centre of gravity G_n from hinge O of the un-extended boom (Fig. 2). P_g is the force hanging from the main load block including the weights of various accessories and Q is the cranes capacity.

Having studied the mobile crane's geometry, and considering the centre of gravity of the hanging weight, the equilibrium equation of the forces acting in the system and the distance R from the ground to the fifth wheel centre, a formula is obtained which expresses the restraining force F_m of the hydraulic jack in the 'non-extended boom' configuration.

$$F_m = \frac{(Q+P_g)R}{L_a(sin\beta cos\gamma - cos\beta sin\gamma)} + F_{m1}$$

where

$$F_{m1} = \frac{(P_1(L_{G1} - n\,tan\alpha) + P_2(L_{G2} - n\,tan\alpha)}{L_a(sin\beta cos\gamma - cos\beta sin\gamma)} + \\ + \frac{(P_3(L_{G3} - n\,tan\alpha) + P_4(L_{G4} - n\,tan\alpha))cos\alpha}{L_a(sin\beta cos\gamma - cos\beta sin\gamma)}$$

Similarly for the 'non-extended boom' configuration, we calculated the formulae to obtain F_m for the configurations of the booms 1st, 2nd and 3rd sections extended. Then, we report thee general formulae as functions of the crane's lifted loads and the extended boom's inclination:

$$F_m = \frac{(Q+P_g)R + \sum_1^4 \left|P_i \times (L^i_{Gb} - n\,tan\alpha)\right| cos\alpha}{L_a(sin\beta cos\gamma - cos\beta sin\gamma)}$$

We also included various JIB lengths. Taking into account JIB weight (PJIB) and the weight of the main load block with its various accessories (PgJIB) we arrived at the following:

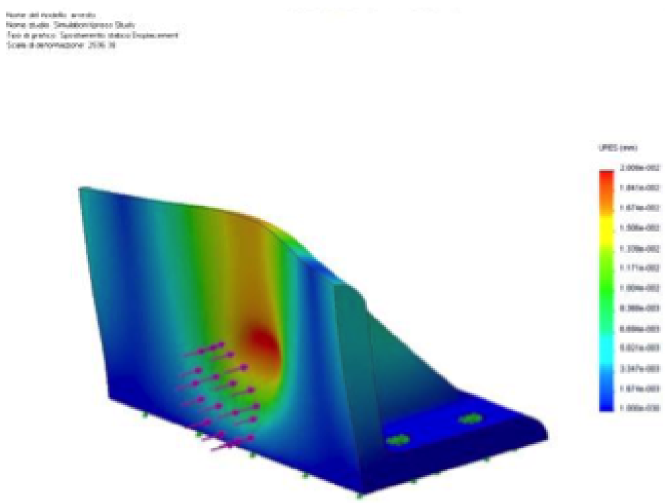

Fig. 3. Maximum strain on the resistant bracket.

$$F_m = \frac{(Q+P_{gJIB})R^{JIB}}{L_a(sin\beta cos\gamma - cos\beta sin\gamma)} + F_{m2}$$

where

$$F_{m2} = \frac{\sum_1^4 \lfloor P_i \times (L^i_{Gb} - n\,tan\alpha)cos\alpha}{L_a(sin\beta cos\gamma - cos\beta sin\gamma)} \dots \\ \dots \frac{+P_{JIB} \times \lfloor R^4 + (LG_{JIB} \times cos(\alpha - \theta_{JIB}) \rfloor}{L_a(sin\beta cos\gamma - cos\beta sin\gamma)}$$

By reading the hydraulic pressures of the jack with the boom extended, the force (F_m) is obtained and then by inverting the previous formulae we obtain the capacity values (Q) even with JIB configurations.

These formulae are then applied to a spreadsheet subdivided into two sheets: the first calculates the force of the extended boom (and consequently the jacks hydraulic pressure) knowing the geometric configuration and the lifted weight; the second calculates the inverted scenario: from the hydraulic pressure of the extended boom for a given geometric configuration we can obtain the lifted weight. Thus, we can compare and verify the results from the numerical model with the load capacity limits and the cranes security parameters in the load capacity tables and the load diagram.

III. Test Bench Project

The test bench was of a suitable size to accommodate all the components to simulate an operational crane. To do this, we calculated the operational stresses and strains considering the total vertical loads (lifted weights + boom + accessories), the horizontal tensile stress with a maximum force of 20 tons resulting from the stems force on the resistant bracket applied to two opposite nodes with respect to its centre line on the HEA girder; we also considered the moments applied to the HEA 240 support girder (at the above-mentioned nodes) as a result of the maximum weight applied to the resistant bracket

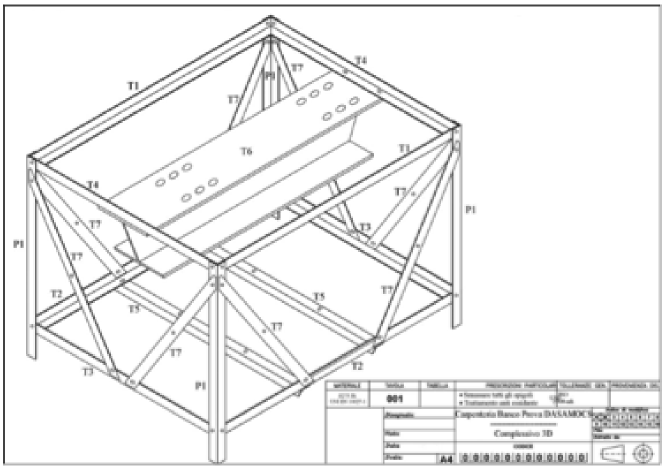

Fig. 4. 3D drawing of test bench

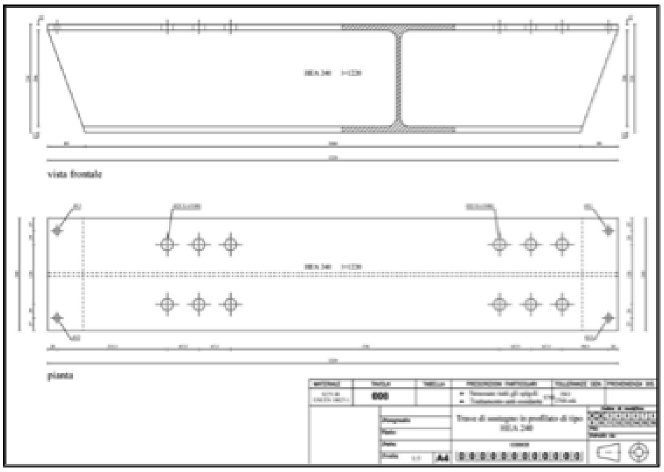

Fig. 6. HEA 240 support girder.

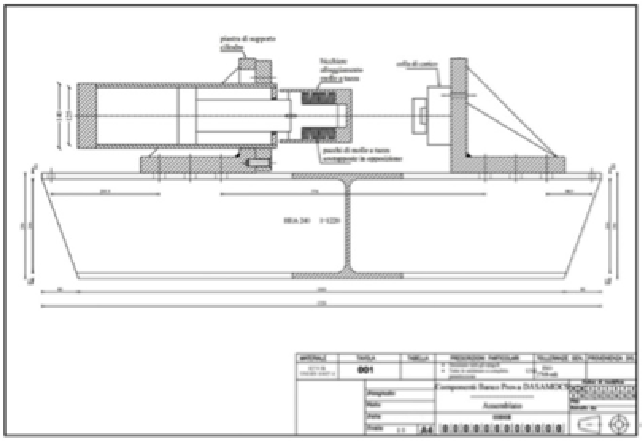

Fig. 5. Longitudinal section of assembled test bench.

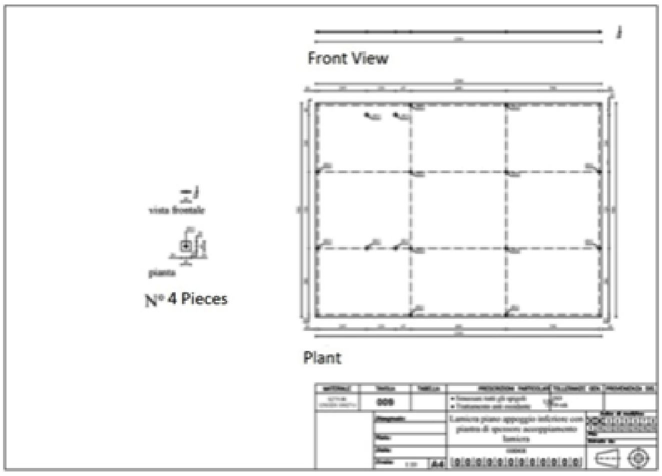

Fig. 7. Supporting steel panel.

with a 125 mm boom. As a function of the maximum force (20 ton) and the moments (2.5 ton/m), we then calculated the most suitable size for the resistant bracket (Fig. 3) (the forced load of 20 t is distributed on the impact area of the load cell mounted on the circuit).

Given the large forces on the resistant bracket, it was made with an L profile, stiffening beads and a thickness of 30 mm. Analytical verifications were performed also by means thermocamera (as described in [22]) to verify the small deformation ($< 0.1\,mm$). Then we sized up the threaded components required to attach the other plates to the HEA 240 support girder: M24 8.8 bolts. The HEA 240 steel section was measured as 12 mm thick at the accessory bolt holes.

Fig. 4 shows the test benchs metal structure including all the useful accessories mounted on the hydraulic cylinder like the L-bracket which supports the cylinder head and load transmission resulting from the cylinder stem on the resistant bracket.

Fig. 5 shows the HEA 240 support girders for the bracket.

To read the load applied to the load cell even as the cylinder stem of the test bench withdraws (when the boom lowers on the actual machine), we devised some cup-shaped elastic components opportunely wrapped according to the maximum loads anticipated for each test.

A 'cup' houses the 'cup-shaped springs' which are compressed by the stem of the hydraulic cylinder.

On the lower cross-members and the perimeter stays beneath the test bench a steel panel (Fig. 7) is bolted to which the other test bench components are fixed, the layout of which is described in Fig. 8.

A. Hydraulic Circuit

The design of the hydraulic circuit (Fig. 9) is crucial in simulating the hydraulic jack which lifts the crane's boom. It must replicate all the operational modes of boom lifting, stopping and lowering. It was sized up on the following values:

- maximum operating pressure: 200 bar
- maximum force: 20 tons

The force developed by the hydraulic cylinder stem is measured by an opposing compressible load cell. It works by replicating the force developed from lifting the load (raised

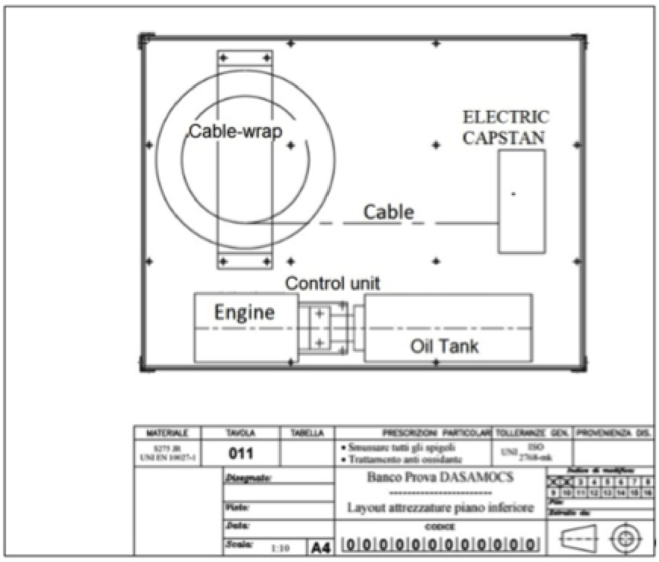

Fig. 8. Lower level component layout.

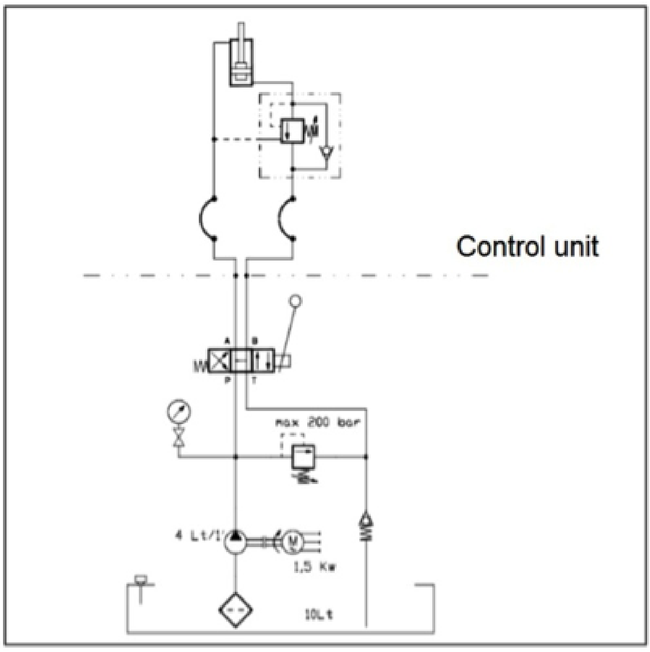

Fig. 9. Hydraulic circuit diagram.

boom). The resistance of piston movement into the cylinder was evaluated with a procedure similar at Sequenzia et al. [23].

B. Cable Wrap with Inclinometer and Electric Capstan

The extension and the inclination of the mechanical arm of the crane are simulated through an cable wrap endowed with an inclinometer. The first one is constituted by a drum with rubber band of call, on which an electric cable is wound resistant flexible to traction. The drum is endowed with a potentiometer that transforms the number of turns effected in electric signal allowing the measure of the length of cable developed through a system of data acquisition. On board some drum is present an inclinometer that produces in exit an electric signal that provide the inclination to which the same is submitted. Besides, an electric capstan simulates the maneuvers of it prolongs some arm dragging the electric cable ultraflexible of the cable wrap. Such device of lifting is positioned in such way by to assure the drag of the cable ultraflexible, climbed on with horizontal draught in position contrasted to the cable wrap.

C. Pressure Transducers

Climbed on in the rooms of exit and reentry of the hydraulic jack to double effect: they have the function to measure, turning her into electric signal, the pressures in the aforesaid rooms from which, known the dimensional characteristics of cylinder and stem of the hydraulic jack the strengths of lifting (such values of strength will be compared with the values measured from the cell of load, this is made necessary with the purpose to proceed to the calibration of the system of measure and with the purpose to have a continuous control on mottos values) can be drawn. The simulation with the hydraulic circuit of the crane happens to parity of pressure among bench and wrecker, therefore the transducers of pressure on the crane and on the bench read the same parity pressure of configuration operational tax to the crane.

IV. Control System in the Test Bench

The correct operation of the test bench is verified through a system of control, which introduces a series of sensors that allow to connect the limiter of load to the test bench in such way to be able to test the safety device during the cycles of operation actions to simulate the operations developed by a crane. The innovative part of the control system consists in the tools of evaluation of the functional parameters and in the implementation of the algorithms of control that happens through the creation of a dynamic 3D model of the system [24], [25]. The model is realized through the software SolidWorks. Such program allows, using LabVIEW and the form SoftMotion, to simulate the realistic movement of the crane keeping in mind of the inactivity and the attrition. Particularly information have cared of together of SolidWorks in LabVIEW environment and, through the creation of aces, with NI SoftMotion, a model of crane is created similar to that which the limiter of load is destined.

The exits of the sensors simulated in SolidWorks keep in mind of the mechanics, of the dynamics, of the inactivity, of the attrition of the real system. Such measures are made notes to control's algorithms developed in LabVIEW and the exits of such algorithms are again sent to the simulator and they allow to effect the mobile parts of the modeled crane verifying the execution of the desired behavior. This allows a notable advantage, both in terms of times devoted to the development, and in safety terms, in how much possible errors in the phase of development of the algorithms don't involve some material damage to the real system. Only after having been "debuggati" and made a will, the algorithms are

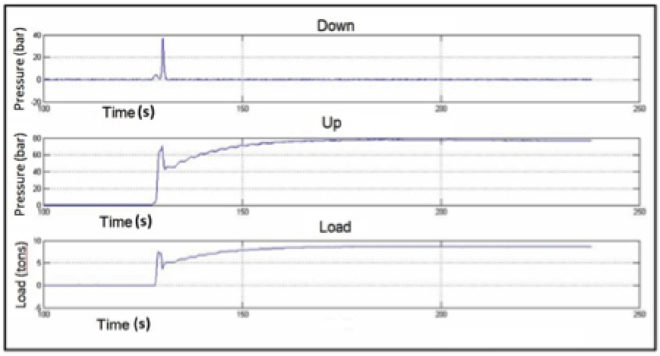

Fig. 10. Tests in the control system - load cell: 8.5 tons.

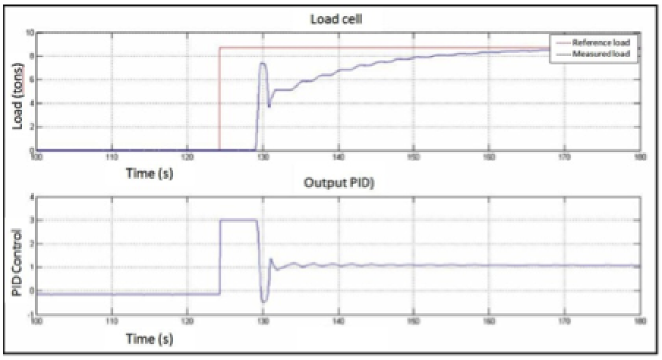

Fig. 11. Reported diagram in the cell of load of 8.5 tons.

implemented in fact on the card of real control connected to the bench of test. The system of control is implemented using the card of acquisition and elaboration of the data NI USB-6216 of the National Instruments. A great advantage offered by this device is the possibility to plan the configuration and to manage the acquisition or the generation of the data through a computer using the software LabVIEW (Laboratory Virtual Instrumen-tation Engineering Workbench), an environment of development for the visual planning developed by the National Instruments. Such software contains a bookstore of tools for the acquisition, the analysis, the visualization and the filing of the data.

In the visual planning a textual code doesn't exist, but there is a diagram that allows to plan the flow of the data in the program. The programs LabVIEW has called virtual tools because it imitate the physical tools as oscilloscope and millimeters. It is constituted from a frontal panel and from a scheme to blocks. The frontal panel is constituted in general by commands (handle grips, pulsating and other input devices) and indicators (graphic, LED and other display). After having built the frontal panel, the code is inserted in the scheme to blocks using graphic representations of functions to check the objects of the frontal panel.

Different tests were performed to the purpose to verify the operation of the single under-systems and the efficiency of the system of control. The tests of laboratory allow to verify the ability to get, with a suitable degree of precision, a geometric

TABLE I. SIMULATION TEST

N° Simulaz	Angle[deg]	Arm [m]	Radius [m]	Trans ratio	Load (tons)	Load admis (tons)	Pressure on cylinder (bar)	Force on load cell (kN)	Force on load cell (ton)	N° Springs	Load moment limiter
1	0	10	8,93	12^	0,75	0,75	41,67	45,41	4,63	4	REGOLARE
	36	10	7,02	12^	0,75	15,5	20,83	22,70	2,32	2	REGOLARE
	70	10	2,35	12^	0,75	50	7,81	8,51	0,87	2	REGOLARE
	70	10	2,35	12^	48	50	124,60	135,79	13,85	3	PRE-ALLARME
	70	10	2,35	12^	0,75	50	7,81	8,51	0,87	2	REGOLARE
	20	10	8,33	12^	0,75	0,75	27,15	29,59	3,02	2	REGOLARE
	0	10	8,93	12^	0,75	0,75	41,67	45,41	4,63	4	REGOLARE
2	0	10	8,93	4^	0,75	0,75	41,67	45,41	4,63	4	REGOLARE
	60	20	8,93	4^	0,75	11,3	25,74	28,05	2,86	2	REGOLARE
	60	27	12,43	4^	0,75	6,3	29,61	32,27	3,29	2	REGOLARE
	60	27	12,43	4^	6	6,3	77,77	84,75	8,64	1	PRE-ALLARME

configuration assigned of the crane. Following they turn back the results of the test effected with cell of load of 8.5 tons. In Fig. 10 are illustrated the graphs related to the in relief pressure on the low room, to the pressure of the tall room and the values to the exit of the cell of load following the answer of the system to a reference of 8.5 tons on the load cell.

In Fig. 11 bring him in the superior part the reference to the course (8.5 tons) in red and the answer of the cell of load: it results evident as the desired value is quickly reached. In the inferior part of the figure the exit of the regulator PID is represented in the loop of control of the cell of load instead: it is possible to observe in the graph the glut of the action of the PID.

The gotten answers allow to verify the goodness of the system of acquisition and control and the goodness of the loop of control implemented for the control of the position of the piston. Analogous tests are finished on the loops of control of the inclinometer and the cable wrap, with results as many satisfactory.

V. VERIFICATION OF THE LIMITER: TEST IN THE LABORATORY

The tests of simulation on the test bench are conducted under the operational conditions of normal activity of the instrument of lifting and in those more serious than operation of the same. In the choice of the set of test of possible errors of formulation of the limiter is kept in mind from the operator verifying the goodness of the intervention of the same in to signal conditions of alarm and prealarm.

The purpose of the activity of laboratory is to avoid useless wastes of resources for the activities on the field [26], [27], for which it is necessary to face in the laboratory a series of test very deepened and well articulated so that to only proceed to the experimentation on the field when the results gotten damage unequivocal confirmation on the goodness of operation of the prototype in all the predictable operational configurations granted for the instrument of lifting.

In the Tab. I are suitable the number of simulations: activity is composed of three sessions of tests, every session is constituted by seven tests that differentiate him for the type of configuration of the telescopic arm simulated of the car "Type" (angle of lifting of the telescopic arm, length of the arm, ray to center earth ralla, draught) and for the value of the load sustained by the wrecker that he/she is wanted to simulate.

The tests for the verification of the limiter of load make reference: for the value of the load lifted by the crane to the load table related to the model G&C 45 ATL; for the values of pressure in the rooms of the hydraulic jack the values are considered in staircase of the bench of test calculated in the spreadsheet in which the values are inserted gotten by the formulas of the numerical model and inserted in the software of the safety device in phase of simulation. The evaluations done on the prototype bench it tries on the possible results of the tests, related to the present configurations in this series of simulations, they are brought in the column Condition Limiter Attended of the load table. The comparison among the attended conditions and the results gotten by the software of the limiter of load results positive for every single test of this session.

VI. Conclusions

In the present work the realization and the employment of a test bench for the validation of load moment limiter is described. The test bench allows to effect a fast and effective setting of the load moment limiter.

Tests effected on the G&C 45 ATL allow to find a good correspondence in comparison to the picked data to the bench with the program of simulation implemented in various configurations of job and with different loads.

The test bench allowed to foresee with notable precision the condition of alarm. The system it goes off when a value is reached equal to the maximum admissible value individualized by the load diagram. The condition of prealarm instead, as agreed upon, it goes off when a value is reached equal to the 85% of the admissible maximum value individualized by the load diagram.

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