ENHANCEMENT OF THE FORCE MEASUREMENT CAPABILITY AT IPT - MODERNIZATION OF A 5 MN HYDRAULIC FORCE STANDARD MACHINE

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Abstract: Accurate force measurements by universal testing machines and force transducers (e.g., load cells) are required in many business sectors: oil and gas, civil, railways, and so forth. The exploitation of the pre-salt layer oil has imposed technical challenges such as the integrity evaluation of chain cables used to anchor petroleum floating units. Large forces may be involved, which need to be conveniently evaluated. Some technical details and performance assessment related to the ongoing upgrading of a hydraulic standard machine for large forces are outlined and discussed in this paper. They include the machine reinstallation in a new laboratory, improvement in the calibration setup and preliminary results of the current infrastructure.

Key-words: large force metrology, traceability, calibration, hydraulic force standard machine, build-up system.

1. INTRODUCTION

The General Conference on Weights and Measures (CGPM) established in 1901 that force is derived from the basic units of mass, length, and time. In 1960, the CGPM adopted the newton as the unit of force in the International System of Units (SI), where one newton is the force required to accelerate a mass of one kilogram to one m/s^2, expressed in terms of SI base units as $kg \cdot m \cdot s^{-2}$ [1].

Even though force is a derived unit, the realization and dissemination of the unit is of primary concern in many application cases. In fact, reliable force measurements using force transducers, load cells and universal testing machines, are required in many business sectors, such as:

(a) The Oil and Gas Sector makes use of force transducers for weighing petroleum platform modules, for load proofing of cranes and towboats, for calibrating load cells attached to cranes, for calibrating testing devices devoted to cable and belt investigation.

(b) The Construction Sector claims for the metrological evaluation of hydraulic jacks and force measuring instruments applied to load test of structures (bridges, buildings, tunnels, anchoring) [2].

(c) The Aerospace Sector requires force measurement for aircraft weighing, as well as mounting parts of the turbine engines and landing gears; which are subjected to significant large force magnitudes during operation.

(d) The Port and Logistics Sector uses force transducers for load testing of cranes and towboats, for calibrating load cells attached to cranes.

(e) The Railways Sector demands metrological evaluation of load cells for weighing wagons and for measuring tensile strength.

Other business sectors demand force measurements to verify testing machines utilized to evaluate the strength of materials (e.g., plastics, metals, composites, textiles, woods, ceramics, foams, adhesives) and to assure quality control in production lines. Fig. 1 shows the force measuring range for several examples from industry.

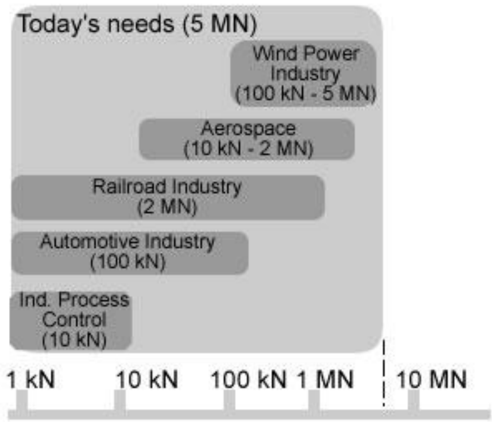

Fig. 1. Typical force measurement magnitudes for different business sectors - adapted from [3]

The exploitation of the pre-salt layer oil has faced many technical challenges. One of them is related to the integrity of chain cables, which are used to anchor floating units. Since they are subjected to very large forces, their integrity needs to be ensured in order to avoid hazard to the platform in the event of a breakage. For this reason, the metrological confirmation of platform anchoring elements for breakage load plays an important role in the whole process.

Significant efforts have been undertaken by the Institute for Technological Research of the State of São Paulo - IPT to enhance their capabilities in large force metrology. The target of IPT is to realize the force quantity with the relative uncertainty figures illustrated in Fig. 2. For the range up to 0.3 MN, load cells are calibrated by direct comparison with our deadweight machine of rated capacity 0.3 MN, which is calibrated by the Brazilian NMI; for forces above 0.3 MN, force transducers are calibrated using the build-up method. This paper outlines some technical and metrological details of the modernization of a hydraulic force standard machine with nominal loading range to 5 MN, which will contribute to the realization of force to 9 MN. The first experimental findings related to the already-implemented improvements are presented and discussed.

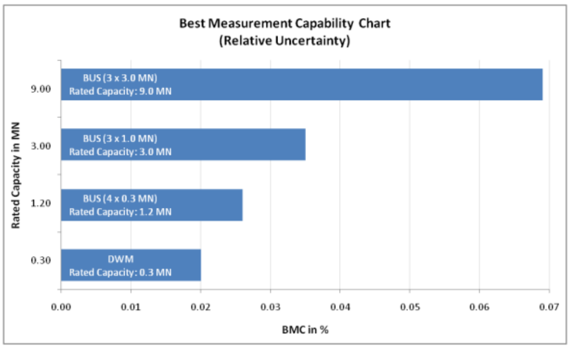

Fig. 2. Relative uncertainty for the corresponding measuring ranges (DWM: deadweight machine; BUS: build-up system)

2. TOPICS OF CONCERN

The modernization of the 5 MN hydraulic force standard machine shown in Fig. 3 in response to increasing demand for large force realization is the main object of this paper. The original machine structure consists of a fixed robust base frame with a four-column movable loading frame (non-controlled driver). The machine modernization plan includes the following macro activities:

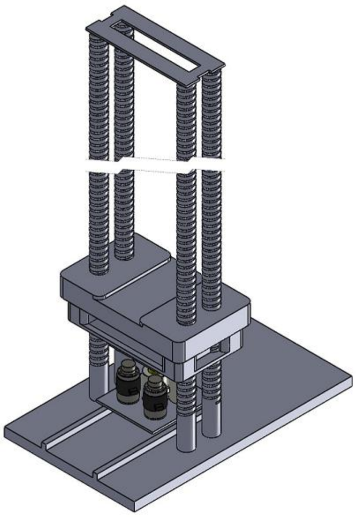

Fig. 3. Illustrative drawing of the hydraulic force standard machine with 5 MN nominal loading capacity

(a) Reengineering of mechanical and hydraulic parts of the measuring equipment: the original four-pillar structure and the material used in the hydraulic machine ensure an excellent mechanical stiffness and through changes in the hydraulic system the measurement capability can be significantly improved.

(b) Improvement of the environmental conditions in the measuring envelope: temperature variation may affect calibration results of force transducers. To diminish the measurement uncertainty, it is a must to maintain the measuring volume under controlled temperature.

(c) Introduction of closed-loop control system and data acquisition automation: one of the major issues of the current arrangement is the operational efficiency. To make the measuring equipment more appropriate for practical use, and reduce operator effects, automation solutions are needed.

(d) Metrological and operational validation of the renewed machine: the impact of the proposed solution is to be confirmed through performance tests and estimation of the measurement capability.

3. EXPECTED AND PRELIMINARY RESULTS

The machine upgrading project has been put into action since the beginning of this year, after transferring the entire machine to the new IPT laboratory for heavy structure tests. In parallel to the specification of all new machine parts and the basic project of the equipment enclosure, improvements have been already executed.

Basically they involved replacing the original indication pointer (mechanical and analogical) by a pressure transducer with digital display, thus enabling measurement automation, and enhancing the build-up technique as a whole. The build-up approach allows calibrating either load cells or hydraulic force machines of higher capacity by using three or more load cells of equal and lower nominal capacity arranged in parallel to each other [4-6].

One could then define three measurement states, which are explored in the remaining paragraphs. The results of the force machine calibration to the entire load range with the original structure as per ISO 7500-1 [7] are summarized in Table 1 (testing machine of class 1). Five load cells of 1 MN nominal range, all them calibrated in conformity with ISO 376 [8], were grouped in order to form a 5 MN build-up system. The largest relative deviations were observed in the lower-end of the range (accuracy to 1.0%). The same remark could be applied to the relative uncertainties (uncertainty to 0.8%).

Table 1. Summary of the calibration results for the original machine using five load cells of equal rated capacity in a build-up system

Machine Indication	Reference Value	Error		Uncertainty	
		Acc.	Repeat.		
(tf)	(tf)	(%)	(%)	(tf)	(%)
50	49.6	0.9	0.4	0.3	0.6
60	59.4	1.0	0.6	0.3	0.5
80	79.3	0.9	0.5	0.4	0.5
100	99.0	1.0	0.5	0.7	0.7
150	148.8	0.8	0.5	0.8	0.5
200	198.4	0.8	0.5	1.5	0.8
250	248.3	0.7	0.4	1.6	0.6
300	298.2	0.6	0.4	1.9	0.6
350	347.8	0.6	0.1	0.7	0.2
400	397.8	0.5	0.0	0.7	0.2
450	448.2	0.4	0.3	1.4	0.3
500	498.7	0.3	0.1	0.7	0.1

Considering only the measurement principle change, i.e., force values deriving from readings of a pressure transducer, calibration results have complied with testing machine class 0.5. By attaching a pressure transducer to the machine, one could also make profit of automatic data acquisition through a digital display communicating in real time to a computer. Table 2 points out the calibration results for the second case, in which the relative errors are significantly lower than those checked for the previous investigation. One could extend the same remark to the relative uncertainties.

Table 2. Summary of the calibration results for the changed machine using five load cells of equal nominal capacity in a build-up system

Machine Indication	Reference Value	Error		Uncertainty	
		Acc.	Repeat.		
(kN)	(kN)	(%)	(%)	(kN)	(%)
300	300.0	0.0	0.1	0.6	0.2
400	399.9	0.0	0.3	1.3	0.3
500	500.1	0.0	0.3	1.4	0.3
600	599.9	0.0	0.2	1.2	0.2
800	802.1	-0.3	0.3	2.9	0.4
1000	1003.0	-0.3	0.3	3.4	0.3
1500	1503.4	-0.2	0.3	4.1	0.3
2000	2002.9	-0.1	0.3	5.2	0.3
2500	2506.4	-0.3	0.3	6.9	0.3
3000	3008.9	-0.3	0.3	9.7	0.3
3500	3500.5	0.0	0.3	11.4	0.3
4000	4001.0	0.0	0.3	15.9	0.4
4500	4512.6	-0.3	0.3	14.3	0.3
5000	5007.2	-0.1	0.4	20.4	0.4

The build-up system for machine calibration up to 5 MN has been recently enhanced by replacing the five load cells of similar capacity in parallel by three load cells with rated capacity of 3 MN (in fact, the new build-up arrangement has a maximum nominal capacity of 9 MN). That has involved developing new parts for the build-up system, in particular pendulums and mounting bases.

In the third experimental case, the machine calibration was undertaken with a single force transducer for the range up to 3 MN, and with the build-up system for the upper-end measuring range. One could observe a valuable reduction of the relative error and relative uncertainty in comparison with the former situation.

Table 3. Summary of the calibration results for the changed machine using three load cells of equal nominal capacity in a build-up system

Machine Indication	Reference Value	Error		Uncertainty	
		Acc.	Repeat.		
(kN)	(kN)	(%)	(%)	(kN)	(%)
50	50.0	0.0	0.3	0.2	0.4
125	125.0	0.0	0.3	0.4	0.3
250	249.6	0.2	0.3	0.8	0.3
500	499.7	0.1	0.2	1.1	0.2
1000	1001.7	-0.2	0.2	2.1	0.2
1500	1503.4	-0.2	0.2	3.5	0.2
2000	2005.1	-0.3	0.2	5.1	0.3
2500	2570.0	-0.3	0.2	5.6	0.2
3000	3010.0	-0.3	0.2	5.8	0.2
3500	3511.8	-0.3	0.2	8.0	0.2
4000	4014.4	-0.4	0.2	9.1	0.2
4500	4518.8	-0.4	0.2	12.6	0.3
5000	5022.1	-0.4	0.2	10.4	0.2

For results showed in Table 1 and Table 2 the main setup difference was the use of a pressure transducer instead of the original mechanical pointer. That resulted in improving the uncertainty attributed to the machine display resolution by 25 times and hence enhancing machine accuracy.

For Table 3 the values are related to the calibration using a three-load-cell-based build-up system (illustrated in Fig. 4) in place of the five-load-cell-based build-up system used in the first two tests.

For all cases the following uncertainty contributors were regarded: (a) reference load cell(s) uncertainty stated in the calibration certificate; (b) calibration process repeatability; (c) reference standard display resolution; (d) machine-under-calibration display resolution; (e) thermal effect; (f) load cell stability over time; (g) machine hysteresis.

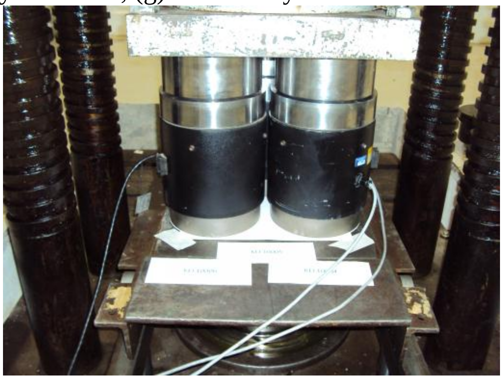

Fig. 4. Complete three-load-cell-based build-up system during force machine calibration

The graphs shown in Fig. 5 make clear the differences between machine errors found with the original machine (blue lines with diamond-type marker) and the machine outfitted with a pressure transducer (red lines with square-type marker). In addition to the uncertainty bar shortening caused by measuring variation reduction, the measurement bias was systematically smaller for the entire range.

Comparing the results of the five-load-cell-based build-up system with the three-load-cell-based build-up system, all values are compatible (uncertainty bar overlapping). The main advantage of the newer build-up arrangement (green lines with triangle-type marker in Fig. 5) over the previous setup is the reduction of the calibration uncertainty. The newer build-up setup also has produced more consistent outcomes, as relative uncertainties keep reasonably constant over the entire measuring range.

4. CONCLUDING REMARKS

Through the machine modernization one has expected to reduce calibration process lead time by 50% and increase confidence in the calibration results according to ISO 7500-1 and ISO 376. This could be attained by including a closed-loop control system and by improving the data collection process. In fact, thanks to the pressure transducer assembled directly to main piston-cylinder, data acquisition process has been already improved. Operator effect on the measurement result has been minimized and throughput increased. Due to increasing demand for calibration services over large magnitude forces, improving productivity is a factor that needs to be taken into account.

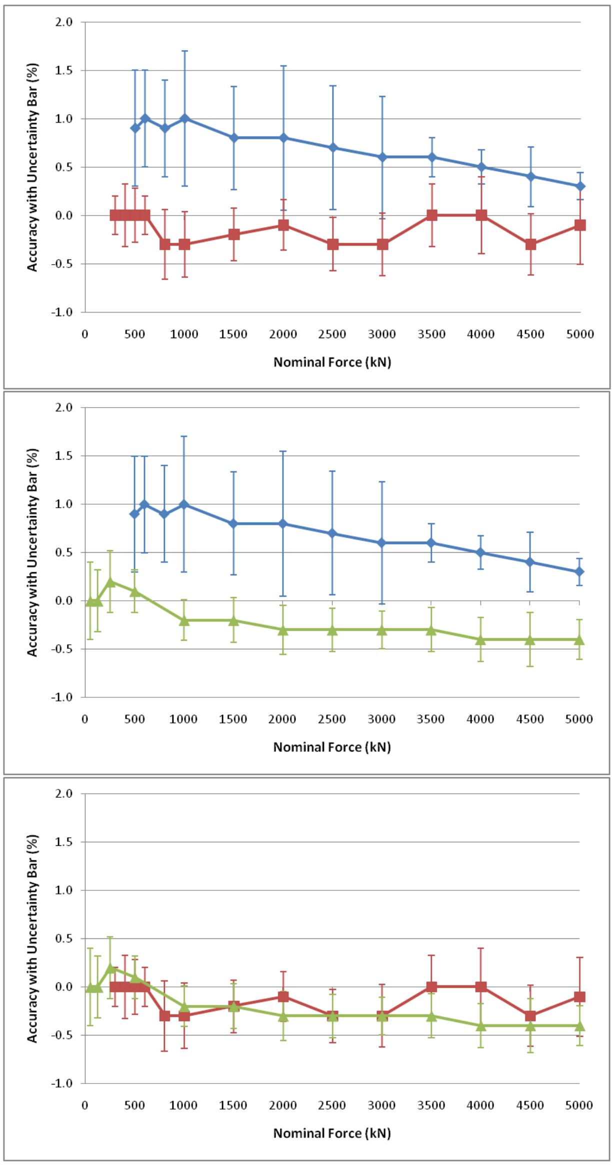

Fig. 5. Machine calibration results for three different scenarios: (a) original machine (blue lines, diamond-type marker); (b) improved machine (red lines, square-type marker); (c) new build-up system setup (green lines, triangle-type marker)

The insertion of closed-loop control system would allow speeding up the calibration procedure of load cells of higher loading capacity (limited to rated capacity of the hydraulic force machine used as comparator) with better uncertainty using lower capacity force transducers. Predefined working ranges could be also defined and a look-up table created to automatically correct systematic errors on each individual testing point.

In fact, the expected outcomes of the hydraulic force standard machine modernization are most driven by market needs. The petroleum exploitation in the pre-salt area is just one of the major business sectors demanding large force measurement solutions. To enhance the measurement and operation capability is highly necessary in a competitive market. More reliable products and processes in terms of performance, quality and safety would necessarily require more reliable force measurements.

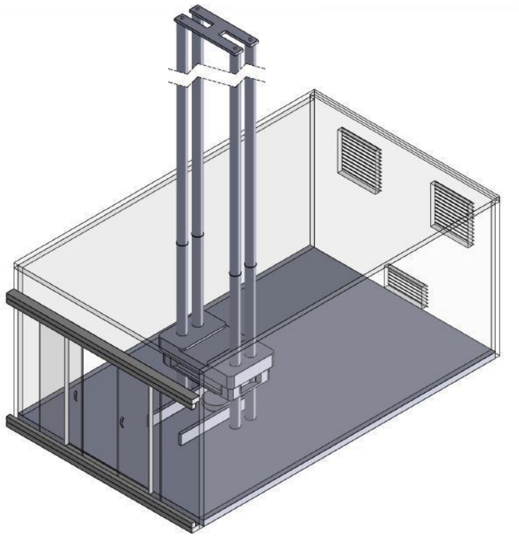

Fig. 6. Sketch of the temperature-controlled room for the hydraulic force standard machine in order to improve calibration confidence

More reliable calibration results also require redesigning and changing some parts and confining the test volume. Fig. 6 illustrates the sketch of the temperature-controlled room, where part of the machine column is not conditioned since it has no practical use in the calibration of force transducers. One has estimated to improve the best measuring capability by 20% for direct measurements. The results obtained thus far after replacing mechanical parts, measuring standards, and redesigning the build-up system are very convincing. From the application point of view, that means to be very promising the intent of extending our calibration service portfolio to some more critical cases.

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