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FEEDBACK CONTROLLED DEADWEIGHT MACHINE

***G. Barbato* [1], *S. Desogus* [2], *A. Germak* [2] *and M. Vattasso* [3]**
[1] DSPEA, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy
[2] Istituto di Metrologia "G. Colonnetti", Strada delle cacce 73, 10135, Torino, Italy
[3] TMT, Via S. Francesco d'Assisi 8, 10040 Rivalta, Torino, Italy

Abstract: deadweight machines have followed an evolution from the traditional fixed-sequence machine to modern automatic machines that with a small number of masses can generate a large number of load increments. The new machine made by T.M.T. is based on the substitution principle, but every group of masses has a specific actuator, allowing independent substitution. The change of force from one step to the subsequent step follows closely a given time function without overloading due to dynamic effects. The mass management system does not need, therefore, to maintain the force constant using the loading frame, and this helps the simplicity of the design and of its realisation. Thanks to that, this loading system can be used as the loading part in other types of standard machines (e.g. torque machines, hardness machines and automatic calibration systems) as a totally independent mass management system that provide required forces. This paper describes the new deadweight machine, the feedback method used for moving the masses during the force changes, the different force-time functions tested and the results obtained.
Keyword: dead-weight machine, force, torque

1 INTRODUCTION

Force measurement has certainly followed an evolution from measurement based on weighing instruments to spring dynamometers and finally to modern force transducers and load cells. That evolution has, in the same time, modified the working limits and evidenced the necessity of evaluating the main characteristic of force measuring devices certainly with higher accuracy and also with increasing consideration about accessory characteristics as time response. This last characteristic is of principal interest in case of dynamic measurements, but even with force transducers and load cells designed for working only in static conditions at least the time response to a single load step form zero to the maximum capacity is required by standard specifications both for force transducers (ISO 376:1999) and for load cells (OIML R60).

That evolution of the force measuring devices has involved a parallel evolution of force standard machines that is evident specifically as refers to time response and to its evaluation. In fact, even if the working principle of a modern deadweight standard machine is equal to that of the deadweight loading device designed by Leonardo da Vinci in the XV century for testing the strength of materials [1], the dynamic is much changed. On the side of the possibility of evaluating time responses much is changed from old machines working with the pilgrim step method [2], to modern automatic machines. The evolution in four stages is evident. Pilgrim's step machines are based on a series of masses that shall be loaded and unloaded one after the other, always unloading the device under test at each loading step. Sequential machines can load continuously a fixed series of masses; the sequence remains rigid but the necessity to pass through the zero at every step is avoided. Multiple scale pan machines have two or three series of masses that can be loaded independently, allowing so a more flexible loading sequence, but requiring the time necessary to pass through each load step of the sequence to reach the device capacity. Modern machines, finally, generally based on binary sequence of loads [3, 4, 5, 6], keep the load nearly constant with automatic systems while interchanging the masses for producing the subsequent required load in an extremely flexible way (any load in the range of the machine that is a multiple of the minimum load is available), and giving the possibility of reaching directly and immediately each of the possible loads.

Indeed the advantages of the modern automatic machines are not limited to the possibility of checking the time response of the devices under test, but even the accuracy can be improved. In fact, beside the main advantages of the large number of load increments that can be generated with a small number of masses, with the relevant advantage of lower costs for mass production and calibration, the possibility of self-calibration is also important. Self calibration consists in the internal mutual comparison of the forces generated by the different masses. Beside the great practical advantage of avoiding the separation of the masses from the machine for calibration, It produces a great metrological advantage. It has been noticed during international comparisons of deadweight machines [7] that the theoretical uncertainty of the forces generated by masses at their centre of gravity does not cover the differences observed. One reason of that could be due to the transfer of forces from the mass centre of gravity to the force transducer used for the comparison. The transfer of a vector quantity as force is sensitive to deformations and distortions of loading frames [8]. The metrological advantage of self calibration consists in the fact that forces produced by different groups of masses are compared directly at their point of application to the force transducer. It takes, therefore, into account eventual systematic effects due to the force transfer and cancels them.

Even with this last type of machines two drawbacks remain to overcome.

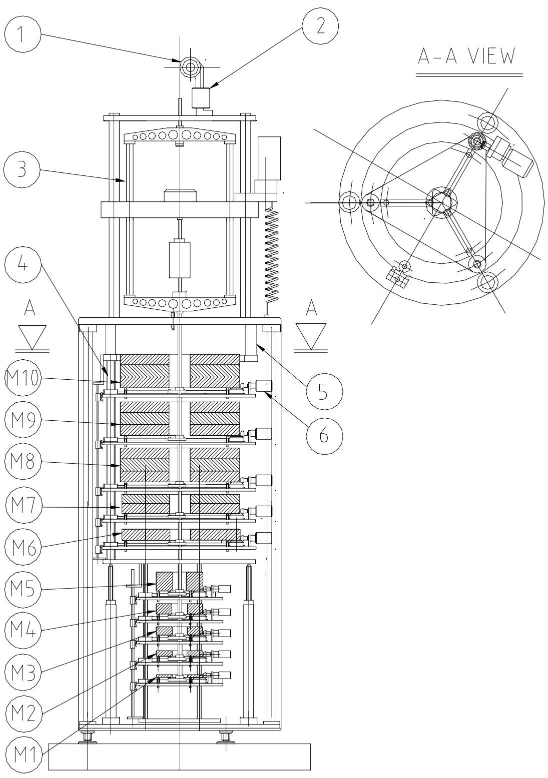
On the one side, even if the loading time (that is the time necessary to pass between the two levels of the load step) is very rapid, the machine requires a much longer time while preparing the masses for the successive load, because the preparation requires to lift all the masses, to switch and to load the new selection. The time characteristic after a rapid loading can be observed, but at any load step there is a “blind interval” during which the load is given by the elastic force and, therefore, is not accurate at the level of deadweight.

On the second side the elastic force requires a rigid frame. This is not a problem for a force deadweight machine, that must have such a frame for loading the device under test, but do not allow other types of applications, that is to produce the force for a deadweight torque machine or for an hardness machine.

For these reasons a further evolution has been studied, and a new machine (Fig. 1) has been designed and constructed by T.M.T., a Centre of the Italian Calibration Service (SIT), in cooperation with IMGC.

2 DESCRIPTION AND NEW WORKING METHOD

The base of the study of this new machine is directed to avoid the presence of the frame, necessary for keeping the load constant with an elastic force, and, at the same time, to shorter the loading cycle.



1 air bearing pulley
2 balancing weight
3 loading frame
4 lifting screws
5 force sensors
6 motor driving
M1 mass 1 ≈ 1 kg
M2 mass 2 ≈ 2 kg
M3 mass 3 ≈ 4 kg
M4 mass 4 ≈ 8 kg
M5 mass 5 ≈ 16 kg
M6 mass 6 ≈ 32 kg
M7 mass 7 ≈ 64 kg
M8 mass 8 ≈ 128 kg
M9 mass 9 ≈ 128 kg
M10 mass 10 ≈ 128 kg

Figure 1. Drawing of the new deadweight machine. The mass management part and the loading frames are completely independent, so that the mass management part can be used for generating very accurate forces for different uses (force machines, torque machines, hardness machines multicomponent test rigs).

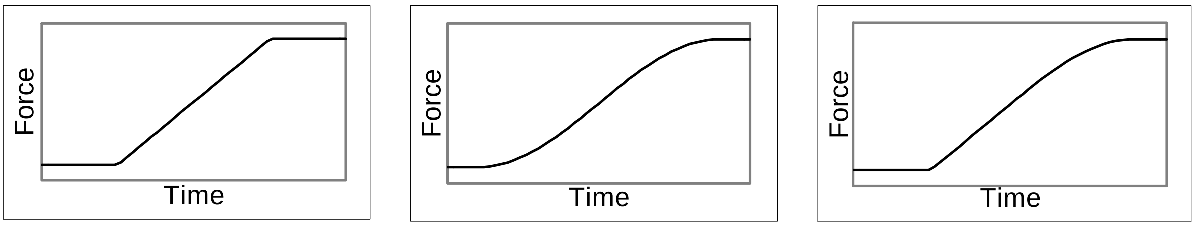
The machine is described in fig. 1. The masses are subdivided in some independent groups (M1 to M10), each one moved by a motor driving three lifting screws.

The new machine made by T.M.T. is based on the substitution principle, but every group of masses has a specific actuator, so that every group of masses can be moved independently, in the same time, for passing from the initial to the end force of each loading step.

The way chosen for having a regular force path between the two forces of a loading step was to control the movement speed of the groups of masses involved in such a way to produce a continuous and regular force variation.

Three force sensors of the machine monitor the force applied to the force transducer under calibration, and the signal obtained is used as feedback signal for controlling the movement of the masses. For every possible load change an adequate strategy of movement of the necessary number of groups of masses in the same time is used. Moving, therefore, with different velocities some groups down, to increase the load, other groups up, to decrease the load, allows as combined effect to obtain a continuous increasing or decreasing of the force as required. The force path from one step to the subsequent step is planned to follow a given time function. Some drive functions are provided, to allow a rapid change of forces and, in the same time, to avoid, in any case, overloading by dynamic effect. In fact, even if force transducers and load cells are sufficiently robust against overloading having very small mobility errors, nevertheless, being the loading system envisaged for most general uses, great care has been given to avoid overloading. To do so not only the last part of loading steps is monitored and controlled, but also the whole loading change is defined by a loading model.

Three loading models are available: linear function, sinusoidal function and a combined linear-sinusoidal function (fig.2).



a) linear b) sinusoidal c) combined linear-sinusoidal

Figure 2. The three different loading models available in the new feedback controlled deadweight machine to achieve the next force level: a) linear, b) sinusoidal, c) combined linear-sinusoidal.

The relative advantages of the different functions are the following:

- the first model describe the loading change as a linear function of the force vs. time. It is the easier method, but it presents at the beginning and at the end of the mass changing a point of discontinuity of the function, when the masses are collected or released;
- the second model describe the loading change as a sinusoidal function that connect smoothly the two different force levels. This method can be considered the best one for a smoothly force exchange, but it turns out to be slower compared with the linear model, if the same maximum gradient of force exchange is used;
- the third model combine the first with the second one. In fact a combined linear-sinusoidal loading model can associate a faster loading change with a good guarantee of absence of overloading. Possible force irregularities at the beginning of loading change are, usually, acceptable.

The mass changing automatic system, therefore, does not need to use the loading frame to maintain the force constant, and this helps the simplicity of the design and its realisation.

3 PERFORMANCE EVALUATION

A complete evaluation of the metrological characteristics has been done. First of all the force evolution during the substitution phase has been monitored, then the general performances of the loading system of the machine has been examined.

For the mass management system the point is the way any force step is reached. The main load strategies have been monitored, recording their Force vs. time path for checking the working conditions. No significant irregularities can be seen, being the force path of the type given in figure 3, that shows one of the most critical load steps, being at the lower part of the force scale.

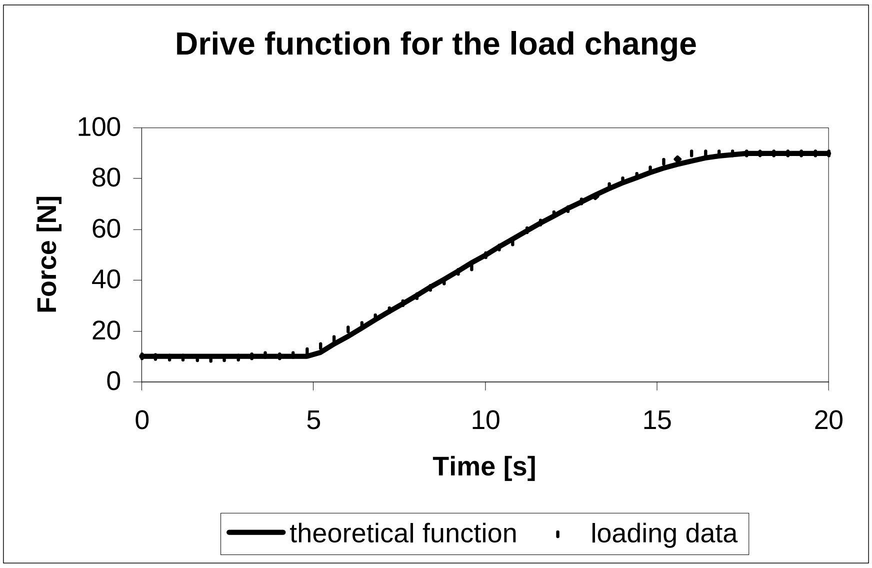


Figure 3. Example of a changing of force following a theoretically given linear-sinusoidal time function. Different drive functions (sinusoidal, linear, etc.) are provided to allow a rapid change of forces and, in the same time, to avoid, in any case, overloading.

The mass management system has demonstrated good performances, giving at the same time regular force vs. time path and rapid load changes.

The second part of the evaluation is specific for the present application to a force deadweight machine, within which it is, of course, necessary to use a loading frame. Taking into account the specific vectorial characteristic of the quantity Force [9], and the advantages of wide extension of the loading field, two antithetic necessities arise:

- to drive correctly the vector force from the center of gravity of the mass to the device under calibration it is necessary to have a rigid frame
- to avoid a first load step, produced by the frame itself, too high, it is necessary to have a loading frame as light as possible.

A method for having in the same time a good stiffness of the loading frame and a first load step very small consists in balancing the weight of the loading frame. The usual way consists in using a balance arm [10], but this produces two types of drawbacks: a limited field of movement and a small change of the balancing force with different inclination of the lever.

For these reasons the adopted balancing device is an air bearing pulley. As it is well known, air bearing are widely used in Coordinate Measuring Machines, to obtain frictionless movements together with a good stiffness. At a price of a few tenths of micrometer displacement one get a nearly non-measurable friction. The case of the air bearing pulley is even more advantageous, as the resultant force and the relevant displacement are orthogonal to the direction of unwonted displacement of the rotation center. The main expected effects of balancing force variation are, therefore, due to geometrical errors of the pulley itself and to the non-uniformity of elasticity and hysteresis of the steel strip used to connect the loading frame with the counterweight. The geometrical effect is expected to be lower than 10^{-4} of the weight of the loading frame over a complete revolution of the pulley. Therefore, with the displacement of few tenths of millimeter normally involved for the flexion of the device under test, the balancing force variation is expected to be lower than $2 \cdot 10^{-5}$ of the weight of the loading frame.

The effect of possible friction or of the hysteresis of the steel strip cannot be evaluated theoretically, therefore it ha been measured checking the mobility threshold and mobility error. The test was done with a load of about 0.5 N (obtained with a weight of 50 g), then adding masses of 10 mg (about 0,1 mN), 20 mg, 20 mg, 50 mg and 100 mg and finally subtracting 150 mg to evaluate the mobility error. The results are given in table 1. The effect of 0,1 mN is in the range of the noise, when the force is measured with a 100 N force transducer, nevertheless, adding to the filter of the indicator a mean over 100 samples, one can see the effect of even a load change of 0,1 mN. The mobility threshold is, therefore, lower than 0,1 mN.

With reference to the results attained at about 500,5 N with increasing load and decreasing load, one can say that also the mobility error is lower than 0,1 mN.

Table 1. Results obtained with the mobility test

Load/mN	Output/(µV/V)
500,0	0,000
500,1	-0,004
500,3	-0,014
500,5	-0,024
501,0	-0,044
502,0	-0,079
500,5	-0,024

At present the calibration of the machine has been done in the classical way, that is weighing accurately each mass and the results are shown on fig. 4. In fact the capacity of the machine is such that the masses are small and easy to be handled, and, again for the low capacity and, in addition, for the stiffness of the loading frame and for its geometrical accuracy, modification of the vector Force is not expected. In any case a self calibration activity for comparison with the results of the classical calibration is planned presently.

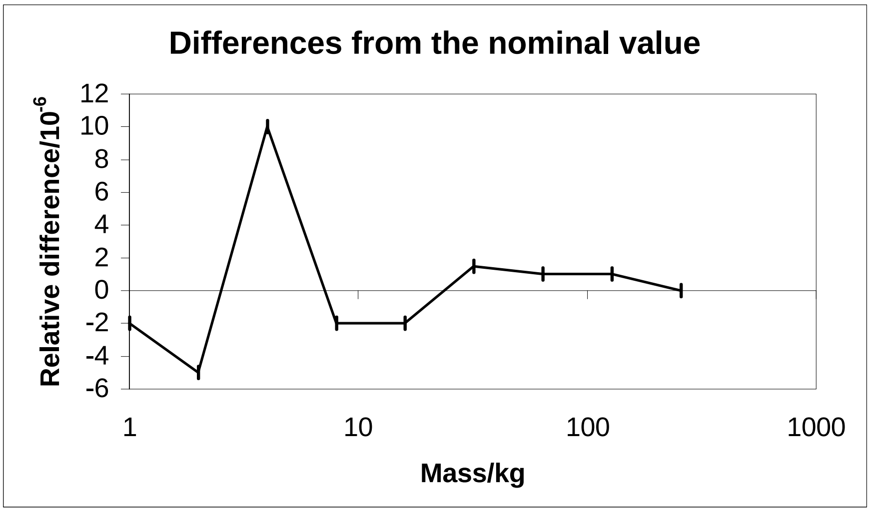


Figure 4. Results of the masses calibration. The relative error shown in the figure is the cumulated error of the masses that compose the reported levels of force.

4 CONCLUSIONS

The new mass changing automatic system ha been developed and tested to check its main characteristics specifically connected with the capability of switching the proper mass application to obtain anyone of the possible forces in a regular way, that is without shocks, vibrations and overloading. Thanks to the independently mass changing automatic system, this loading system can be used as very accurate force generator in various types of deadweight machines (e.g. force standard machines, torque standard machines, hardness standard machines and automatic multicomponent calibration systems) as a totally independent mass management system that provides required forces. A complete set of tests has been performed for the case of a Force standard machine, showing both the good working characteristics of the mass changing automatic system, together with the performances of the air bearing adopted.

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AUTHORS: Univ. Prof. Dr. Ing. Giulio BARBATO, DSPEA, Polytechnic of Turin, C.so Duca degli Abruzzi 24, Torino, I-10129 Torino, Italy, Phone Int. +39.011.5647285, Fax Int. +39.011.5647299
E-mail: barbato@athena.polito.it
Alessandro GERMAK, Istituto di Metrologia “G. Colonnetti”, Strada delle cacce 73, Torino, I-10135 Torino, Italy, Phone Int. +39.011.3977.367, Fax Int. +39.011.3977.426
E-mail: A.Germak@imgc.to.cnr.it