Automation and Upgrade of the NIST 27.1 kN (6.1 klbf) Dead Weight Force Machine

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Abstract. This paper focuses on the automation and upgrades performed on the 27.1 kN (6.1 klbf) dead weight force machine located at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD. Of the six dead weight force machines maintained at NIST, this was the only machine that was not automated under the original automation program performed in the 1980s. The new automation approach, which incorporates the latest available technology, is detailed and compared to the original automation systems used on the other five dead weight force machines.

1. Introduction

The National Institute of Standards and Technology (NIST) in Gaithersburg, MD maintains six dead weight force machines ranging from 2.2 kN (505 lbf) to 4.448 MN (1000 klbf) which act as primary force standards for calibrating elastic force-measuring devices and standards, such as load cells and proving rings. [1] The machines were built in the early 1960s and were designed for manual control by an operator who would oversee the movements and functions necessary to perform dead weight force calibration procedures. However, in the mid 1980s, five of the six dead weight force machines were automated to perform a large portion of the calibration procedure without an operator present. [2] Unfortunately, the 27.1 kN (6.1 klbf) machine was not automated at that time, partly because the machine would require the most complex automation system of the six dead weight force machines due to the large number of weights and calibration configurations involved.

This paper discusses the automation process of the 27.1 kN machine and how the new approach utilizes numerous current technologies that overcome several pitfalls encountered on the original machine automations completed nearly 20 years ago. Section 2 provides operating details and pictures of the machine and explains how the force is applied to a force measuring device. Section 3 details the current approach used to automate the 27.1 kN dead weight force machine and the subsystems that were upgraded and/or added to the machine. This section also highlights the improvements over the original automation systems. Section 4 concludes with recommendations on using the new automation system model for upgrading and improving the automation systems of the other five dead weight force machines.

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2. Description and Overview of the 27.1 kN Dead Weight Force Machine

The 27.1 kN dead weight force machine consists of fifteen stainless steel weights. Their masses were adjusted to produce nominal force values for a given local acceleration of gravity and relative densities of air and stainless steel. One set of larger weights produces nominal forces in pounds-force (lbf). The other set contains smaller compensating weights which, when added in conjunction with the larger weights, produce an overall nominal force in kilogram-force (kgf). The weights can be individually loaded or unloaded from the load frame by closing switches which control solenoid-operated valves that cause hydraulic cylinders to either raise or lower the weight onto the weight shaft. After the necessary weights are chosen, the force transducer under test (or the unit under test – UUT) is raised using two screw jacks, causing the calibrated weights to be applied to the force transducer. The load frame height (as it is raised or lowered by movement of the two jack screws) is sensed using an optical sensor which will be discussed in more detail in Section 4. The force applied to the force transducer under test is equal to the sum of the weights selected (or loaded) plus the weight of the loading frame and weight shaft (which is 889.64 N (200 lbf) in this machine). Figures 1 and 2 illustrate the design of this type of machine.

One limitation of the 27.1 kN machine is that the weight frame was designed to be lowered to an unloaded state before a different combination of weights could be chosen and then reloaded onto the force transducer for additional measurements. Therefore, as originally designed, data normally taken to characterize the hysteresis behavior of a force transducer could not be acquired with this machine. Methods were eventually developed to allow some hysteresis data to be taken in the machine. However, it required tedious intervention from the operator and was not an ideal weight-changing process. As part of the automation project, this limitation has been overcome and is discussed in Section 3.

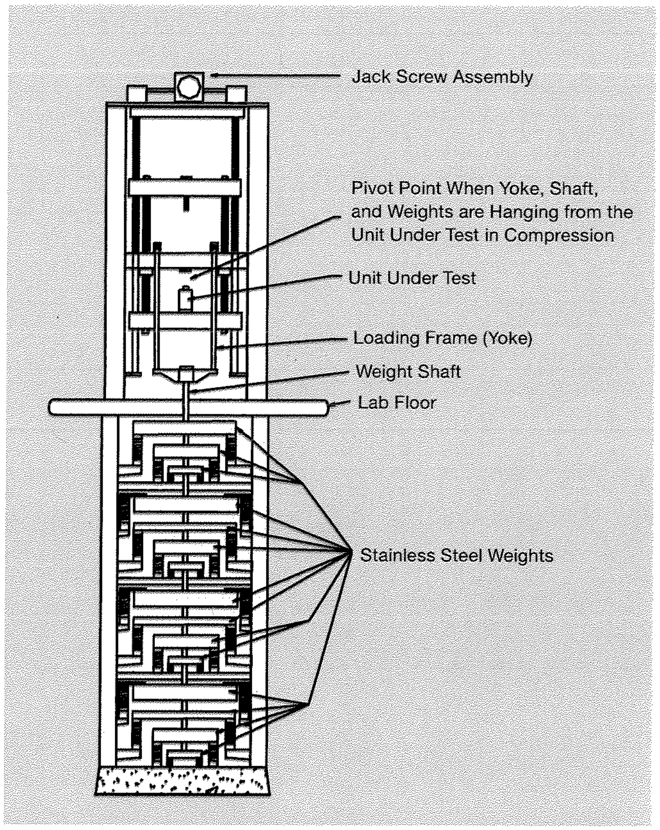

Figure 1. Computer-Aided Design (CAD) model of the 27.1 kN (6.1 klbf) dead weight force machine.

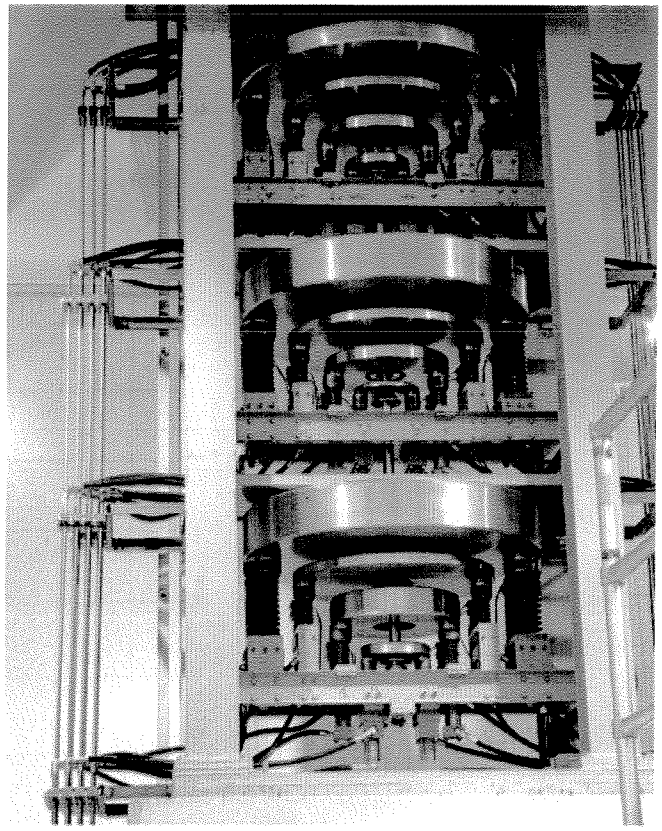

Figure 2. Photograph showing most of the main weight stack of the 27.1 kN dead weight force machine.

3. New Approach Used to Automate the 27.1 kN Dead Weight Force Machine

While the newly automated 27.1 kN machine incorporated some of the approach and operational details of the machines automated nearly twenty years ago [2], there are significant changes and improvements in the newly automated machine.

First, the DAC system chosen simplifies the connection and interaction between the PC computer and the instrumentation board by using a single USB connection in place of the IEEE-488 bus hardware. [3] The USB interface/controller board is significantly smaller and more compact, allowing it to fit inside the existing control panel of the deadweight machine. The solid state relays and digital inputs are contained on three small boards (also located in the existing console) that allow for quick plug-in and simple customized configuration (digital input or digital output) of each channel being used. See Fig. 3 for a photograph of the final board assembly.

The second major improvement is the capability to obtain hysteresis data in an automated fashion. As part of the earlier effort to automate the 112.5 kN dead weight force machine, a method was devised to allow for hysteresis data to be taken using air pistons to stabilize the shaft during weight changes while the weight frame remained in a loaded condition. Unfortunately, as reported in the paper "Redesign of the 112.5 kN Dead Weight Machine Snubber System" [4], the system was not optimal and needed to be improved. The original snubber was successful at stabilizing the shaft during a weight change but often failed to release the shaft in such a manner that ensured a stable measurement environment (meaning no swinging of the weight stack) without manual intervention by the operator. As a fix to the problem in the 112.5 kN machine and a precursor to the automation of the 27.1 kN machine, a new system was designed that used air bags to hold the shaft motionless and in the proper position while weights are being changed and subsequently releases them in a manner that ensures a stable environ-

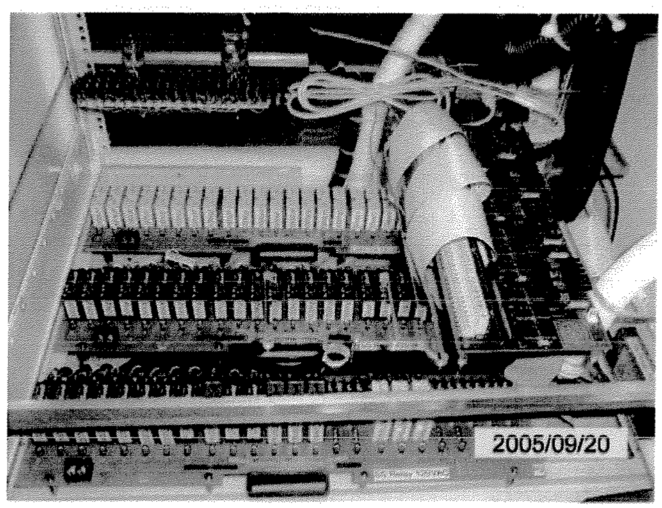

Figure 3. Photograph of the inside of the console showing the USB interface/control board (right) and the three relay boards (left).

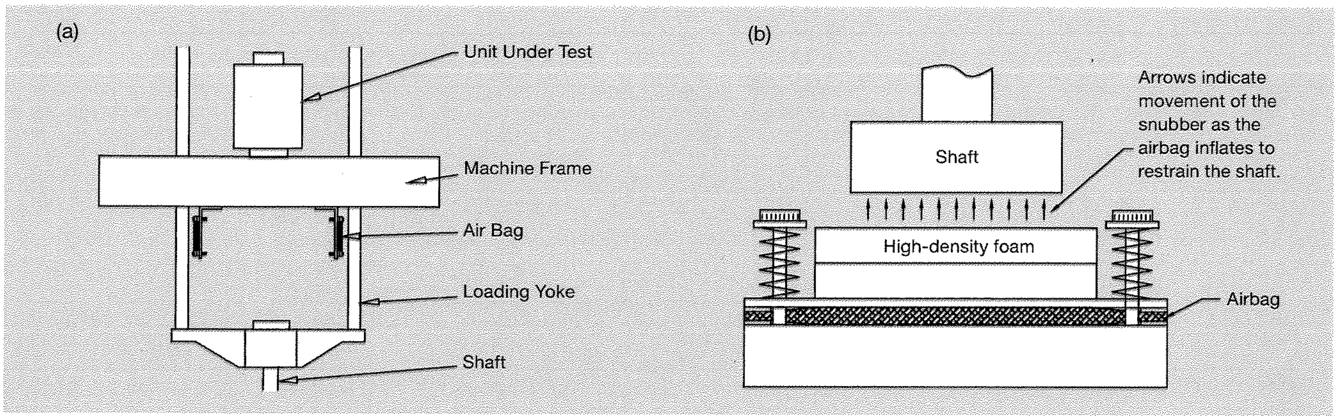

Figure 4. CAD model of the air bag snubber used (a) on the loading frame and (b) at the base of the machine.

ment without operator intervention . The air bag concept was built, tested, and implemented as part of the existing automation system on the 112.5 kN machine. Reference [4] presents extensive detail regarding hysteresis measurements, the original piston snubber system, and the subsequent improvements made using the air bag snubber system. The success of the air bag snubber system design led to the recommendation to apply a similar design to the 27.1 kN machine automation. The design was modified slightly (mostly due to space restrictions) and installed as part of this automation project. The airbags (3 total) operate using compressed air at a pressure between 68.9 kPa (10 psi) and 137.9 kPa (20 psi) and are inflated or deflated using two solenoid-operated air valves. Figures 4a and 4b show CAD models of the airbag snubbers and where they are located.

The third improvement to the system is mostly attributed to advances in software and programming over the past few decades: the use of LabVIEW[1] control software. [5] LabVIEW graphical programming software was chosen for user interface and automation control because of its intuitive processes in programming, ease of use in interfacing with various devices of different types, and the longevity and support of the software. The NIST 1.33 MN dead weight force machine was the test bed for evaluating the software and learning techniques needed to ensure that custom programs could be written to interface and run the older automation hardware as well as any new equipment or interfaces. LabVIEW allows for a gradual changeover of our older systems to the newer ones, because it can be used efficiently with both systems, allowing them to co-exist if necessary during transition/verification. The new automation system for the 27.1 kN machine runs solely under LabVIEW.

The fourth improvement involves the process of determining the height of the loading frame as it is loaded or unloaded. The old system used an optical sensor to indicate one of four frame positions: (1) zero load; (2) below target position; (3) target position (loaded); and (4) above target position. One approach is to modify the older pointer assembly that visually indicated the frame position to the operator, by adding a metal bracket that strategically blocks the sensor's infrared light to correlate one of the four frame positions. Since the pointer assembly is part of the calibrated mass of the loading frame, one drawback to modifying the pointer assembly is having to perform a new mass calibration on the modified pieces. A requirement of the new system was to maintain the same mass of the new pointer assembly compared to the original pointer assembly. In order to avoid this issue, a different method was chosen for determining the height of the loading frame.

A machine vision laser measurement sensor capable of projecting a laser beam onto the weight frame and using the principle of triangulation on the reflected beam is capable of differentiating frame movement to within 1.0 mm. The laser sensor was selected as the best solution since it does not contact the system and therefore requires no modification or reweighing of the pointer assembly. The sensor has an analog output that can be read by a low accuracy DVM, which in this case is a USB-interfaced module piggybacked to the USB interface/controller board. The output from the DVM is correlated to the frame position and is used as input to the control programs that raise or lower the weight frame.

Another advantage in using the laser sensor comes from the fact that the weight frame on the 27.1 kN machine can be "split" and serve as two loads. If the frame is loaded with all the weights and no other weights are added, the applied force is 889.6 N (200lbf). However, if the two removable spacers on which the weight frame normally rests are taken out (one of which can be seen in Fig. 5), the top half of the loading frame (the yolk) then can be loaded separately resulting in an applied force of 444.82 N (100 lbf). From this point, the frame can then continue to be raised and subsequently pick up the lower half of the shaft for normal operation using the full frame. The laser sensor has a range sufficient to automate this entire range of motion. See Fig. 5 for more detail on the split frame and laser sensor installation. Although the 112.5 kN dead weight force machine frame also has the same split frame capability, it is limited in the fact that the optical sensor is not flexible enough to work over that entire range of motion. Therefore, splitting the frame in the 112.5 kN machine to take advantage of the

[1] Certain commercial equipment, instruments, software, or materials are identified in this paper. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

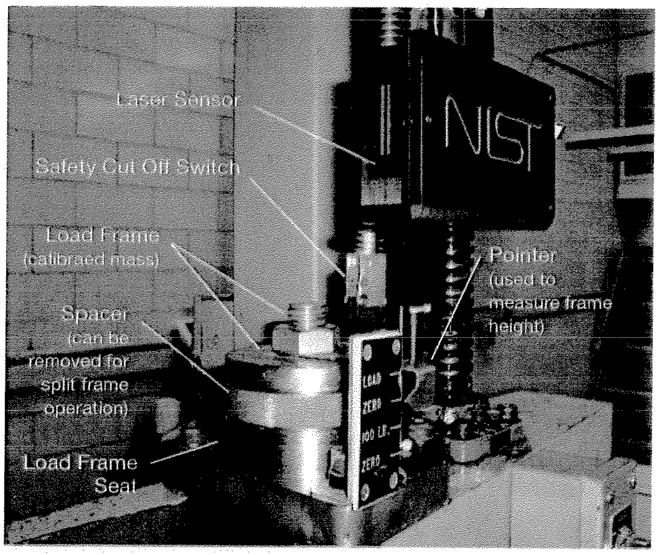

Figure 5. Photograph of the laser sensor, pointer, spacer, and the top portion of the load frame.

lower applied force needed in many calibrations is a process that is not currently automated.

Additional improvements to the 27.1 kN machine include safety features that have been implemented to protect the dead weight force machine itself and/or customer devices. One involves the electrical lockout of the frame up/down buttons on the console when the snubbers are activated. This lockout protects the airbags and the machine frame from damage that could occur during manual control of the machine if the frame were set in motion while the snubbers are in contact with the loading frame. A double-pole, double-throw (DPDT) mechanical relay is used to provide a mechanical break in the electrical circuit of the frame up/down buttons while the snubbers are activated. Also, a frame limit switch was installed to add protection to a customer device. A runaway, which means that the frame would continue to run in its current direction because it never received the command to stop, could be caused by a power bump, component failure, or any other unexpected departure from normal operating procedures. This miniature limit switch is installed directly above the upper frame collar and functions to cut off power to the screw jack motor and ensure that the frame stops before it picks up additional weights and potentially overloads a customer device. This switch is supplemental to existing limit switches that protect the dead weight force machine, but could ultimately allow the entire weight stack to be loaded onto the device under test before it stops frame movement. Therefore, it provides an additional layer of protection to the dead weight force machine and is supplemented even further with software timeouts that limit the amount of frame travel.

Another improvement is the incorporation of the "red light" circuit, which has been incorporated in the other deadweight machines within the NIST Force Laboratory. The "red light" circuit is used to ensure that the weights or weight frame are not touching anything while they are suspended from a unit under test. If the weights are touching, or grounded, the "red light" circuit is completed, thereby lighting a red LED on the console, indicating a potential problem to the operator. In the automated setup, the "red light" circuit is monitored using a digital input on the relay board that updates a Graphical User Interface (GUI) summarizing if any "red light" conditions existed during the calibration run.

The final improvement involved replacing the motor/starter control for the electric motor that turns the screw jack assembly for raising and lowering the weight frame. The motor/starter control was 40 years old and far exceeded the expected lifetime of the components. The upgraded motor/starter uses newer "soft switching" technology which results in noticeably quieter and efficient operation, as well as improved control characteristics. The motor speed is still controlled from the console via a potentiometer dial which varies the frequency of the voltage input to the motor. The new motor/starter assembly also has the advantage of increased feedback/troubleshooting information in case of a problem with the screw jack assembly.

4. Conclusions and Recommendations

Improvements to data acquisition and control hardware and software have dramatically improved in capability and smaller packaging since the 27.1 kN dead weight force machine was built. The new system used to automate this machine takes advantage of these features and improvements. Considering the age and availability of the current control hardware used on the older automation systems, the same technology advancement procedures and system will be used to eventually update all of the NIST dead weight force machine automation systems. Although none of the machines are designed completely alike, each machine will benefit greatly from the software enhancements and the simplified and streamlined DAC equipment that was incorporated into the 27.1 kN machine. The laser sensor and snubber system specifically will be used on the machines that are of similar design.

5. References

[1] T.W. Bartel, S.L. Yaniv, and R.L. Seifarth, "Force Measurement Services at NIST: Equipment, Procedures, and Uncertainty," *1997 NCSL International Workshop and Symposium*, pp. 421–431, 1997.

[2] Kenneth W. Yee, "Automation of Strain-Gauge Load-Cell Force Calibration," *NISTIR 4823*, NIST, Gaithersburg, MD, April 1992.

[3] Richard Norcross and Roger Bostelman of the NIST Intelligent Systems Division consulted on technology advancement systems and made recommendations based on their experiences using similar systems in other automation projects.

[4] Kevin L. Chesnutwood, "Redesign of the 112.5 kN Dead Weight Machine Snubber System," *NISTIR 7164*, NIST, Gaithersburg, MD, March 2005.

[5] *LabVIEW*, National Instruments Corporation, Austin, TX; website: www.ni.com