

# THE DESIGN OF 30 MN HYDRAULIC AMPLIFICATION FORCE STANDARD MACHINE AT SHANDONG INSTITUTE OF METROLOGY

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## Abstract:

This paper describes the design and construction of the hydraulic amplification force standard machine of 30 MN (so-called Pascal-type), which will be the biggest force standard machine by hydraulic amplification in the world. The main elements and the most critical components of the machine were expounded, including the hydrostatic support cylinder and the dead-weights groups, which directly affect the system accuracy, and determine the measurement range. The performance of the machine maximises the use value for the user. This machine will play a very important role in promoting the development of high-precision large force metrology technology.

**Keywords:** Pascal force standard machine; pure hydrostatic support; large range and high precision; wide measurement range

## 1. INTRODUCTION

With the rapid development of aviation, aerospace, shipbuilding, bridge building, high-speed railway, construction, and other industries, the measurement of 10 MN is emerging one after another, and the measurement of 100 MN is also emerging. If the measurement problem cannot be solved, it cannot guarantee the safety, accuracy, long-term reliability, and stability of these industries. After more than 5 years of planning, we believe that it is of great significance to build a large-scale and high-precision force standard machine. Because the only way to build a force standard machine above 10 MN is to reproduce the force through deadweights, because the accuracy of a single piece of deadweights can currently be better than 0.001 %, which can meet the requirements of the force standard machine. However, if several thousand tonnes of deadweights are used to achieve this, the cost of the equipment and the space of the site are very expensive, and the equipment is also very large, which is not conducive to the use and maintenance of the equipment. After research, the

most reasonable solution is to use large and small cylinders for hydraulic amplification, such as 500 times or 250 times, then the response of the weight at the small cylinder end is reduced by 1/500 or 1/250. For such a design based on the principle of Pascal connector, the key technology is the design of the oil cylinder. For a force standard machine with a design accuracy of 0.01 %, the influence of various frictional factors of the oil cylinder must be less than 0.01 %, that is, it must be repeatedly verified through experiments. The design and processing of the oil cylinder is a very big challenge, so this article will focus on the design of this aspect. To make the equipment better serve more customers, we specially designed the measurement range of the equipment with a wide range design, which can freely achieve any integer multiple measurement points between 1 % and 100 % of the full scale, without the need to exchange deadweights, which can ensure that the influence of various precisions caused by the return and return travel is eliminated during high-precision measurement.

## 2. OVERALL DESIGN AND CONSTRUCTION

The small hydrostatic support cylinder floats the weight of a certain force level and reaches equilibrium at a certain position in the vertical height. In this state, the pressure of the small hydrostatic support cylinder is used as the standard pressure of a force level of the system. It is known from the Pascal connector principle that the pressure at the bottom of the large hydrostatic support cylinder connected to the small hydrostatic support cylinder through the connector is also the standard pressure of the force level, and the area of the large hydrostatic support cylinder is the same as that of the small hydrostatic support cylinder. Several multiples, such as 500 times or 250 times, can achieve a standard force level with a corresponding magnification on the large hydrostatic support cylinder.

According to the user's demand, the machine is designed in two directions: tension and compression. The measuring range of compression is from 0.25 MN to 30 MN, and the measuring range of tension is from 0.25 MN to 15 MN. The accuracy of the machine is better than 0.03 % (the whole range except 0.25 MN), and the design accuracy of the machine is better than 0.01 %.

To ensure the accuracy of the system and the convenience of operation, the structure used is that the oil cylinder is placed on top, and the deadweights and tension and compression test areas are directly below the oil cylinder. The main structure consists of loading host, deadweights system, hydraulic system, control circuit and the software system consist of the loading main frame (upper beam, lower beam, column, pressure pad, worm gear lifting system), large hydrostatic support cylinder with steel ball, main frame (upper base, lower base, four supports column, pull-down head) composition (as shown in Figure 1).

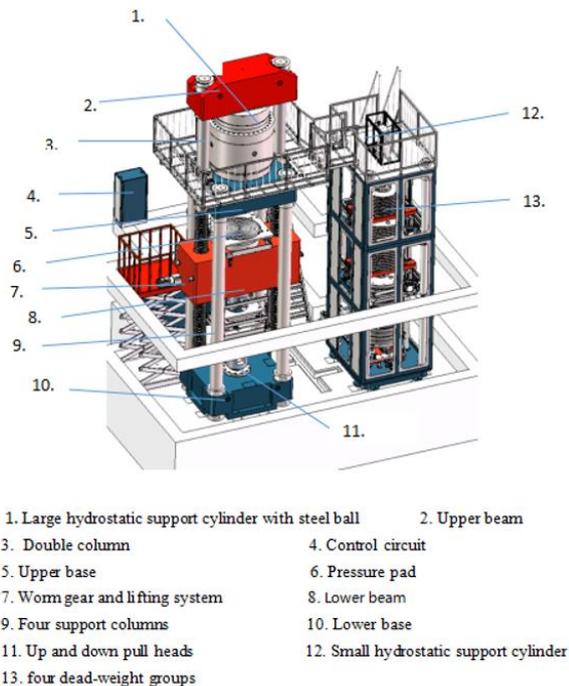


Figure 1: The 30 MN hydraulic amplification machine

The upper beam of the reaction force frame is supported directly above the large hydrostatic support cylinder through a special steel ball. The lower beam of the reaction force frame can be kept in a horizontal state, and the test space can be adjusted by moving up and down electrically. Just above the lower beam is the test area for compression. The space below the lower beam is the area for tensile test. The heat-treated compress pad and tension joint are fixed on the lower beam. The main frame adopts a four-column structure, which is convenient for installation and disassembling the test pieces at ordinary times, and some auxiliary

loading and unloading mechanisms can be added. The upper surface of the upper base of the main frame is fixed with a loading oil cylinder, and the lower surface of the upper base is fixed with a compress pad, and both are designed with a centre indicating position. The lower base of the main frame is fixed with a pull-down joint for tensile test. Columns, beams, and bases have passed finite element analysis and must meet sufficient rigidity.

The deadweight part is the mechanism that generates the standard pressure. The small static pressure support cylinder lifts the weight of a certain force level and suspends it at a certain height. To ensure that the loading speed meets the relevant standard requirements, we divide the weight into four groups for independent loading. To ensure the stability of loading deadweights, we use ball screws and servo motors to achieve high-speed lifting, and fast automatic switching between low-speed smooth contact lifting.

### 3. THE DESIGN OF THE HYDROSTATIC SUPPORT CYLINDER

The design and processing of the cylinder are the key points for the success of the hydraulic amplifying force standard machine. Rubbing, even a few percent of the friction force, can be solved by rotating the oil cylinder or the piston and the sensor to only measure the output force, etc. It is difficult to reach the standard machine level, and there are very few specially designed for the force standard machine. The oil cylinder introduced in this paper is a non-rotating hydrostatic support cylinder, and it is the first time that pure hydrostatic hydraulic support technology is used in the field of metrology.

The hydrostatic cylinder is mostly supported by a multiple of 4. As shown in Figure 2, take  $4 \times 2 = 8$  symmetrical cavities numbered a1, a2, b1, b2, c1, c2, d1, d2 as an example (the actual cavity of the large oil cylinder in this case is  $4 \times 8 = 32$ ). The theoretical state is that the pressure  $P_{a1}$ , the area  $S_{a1}$ , the gap  $\delta_{a1}$  between the piston and the cylinder of these 8 cavities must be exactly equal to the symmetrical  $P_{a2}$ ,  $S_{a2}$ , and  $\delta_{a2}$ , respectively, and the piston will exist in the cylinder. The red line position, (as shown in Figure 2, the schematic diagram of hydrostatic support cylinder, and Figure 3), in this case, the precision of the system is very high and can meet the requirements of the standard machine. The test proves that the sensitivity of the machine can reach 0.001 %; if  $F_1 = P_{a1} \times S_{a1} > F_2 = P_{a2} \times S_{a2}$ , the piston may exist in the blue dotted line position in the cylinder (as shown in Figure 2), which will inevitably cause the cylinder to have hard friction at the a2 position, and so on for other cavities. The hard friction between the equipment, the sensitivity, fluctuation,

repeatability, and other performance indicators of the equipment cannot meet the requirements of the standard machine.

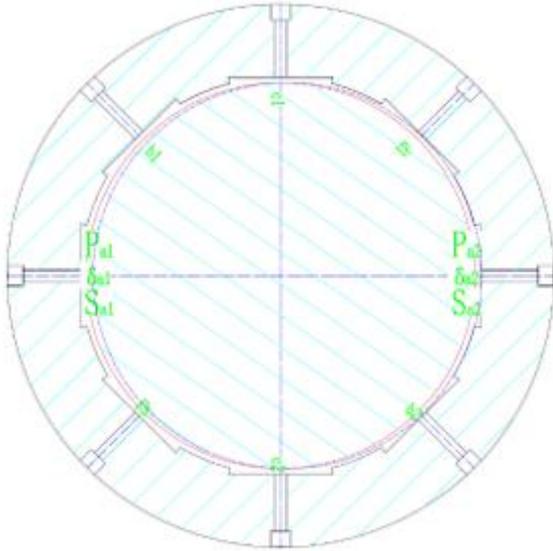


Figure 2: The design schematic diagram of hydrostatic support cylinder

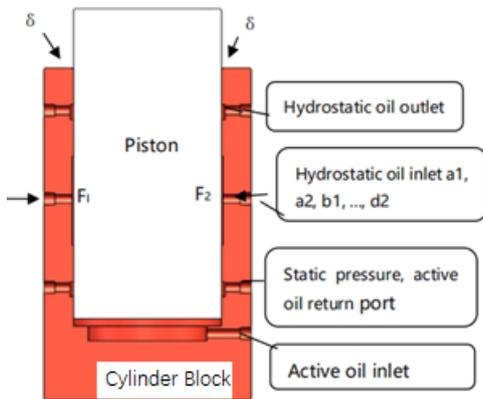


Figure 3: The hydrostatic support cylinder

Because in the actual processing process, the area  $S_{a1} \neq S_{a2}$  is fixed, and if we give the pressure  $P$  of the two a position equal,  $F_1 = P \times S_{a1} \neq F_2 = P \times S_{a2}$ , the piston will move to the area which the force is small, there will be undesired results. In order to correct the possible influence of processing, a pressure flow device must be designed so that  $F_1 = P_{a1} \times S_{a1} = F_2 = P_{a2} \times S_{a2}$ , and the flow rate on the side with a large area is reduced. Keep the pressure low and make  $P_{a1} = P_{a2} \times S_{a2} / S_{a1}$  reach the balance of force, so as to realise the long-term stability of the equipment during use.

Once the thrust of the piston under static pressure is equal to the clearance  $\delta$  around the lower part, it is equal to the cylinder barrel.

When there is no friction, the piston is completely supported in the cylinder by the surrounding static pressure. At this time, the oil

entering from the active oil inlet will float the piston of the large.

Hydrostatic support cylinder under the standard pressure provided by the small hydrostatic support cylinder generates an amplified force level.

During the test, add a tiny weight of 0.01 % or 0.001 % at the position where the weight can be added manually. The standard force sensor set on the moving beam compress pad of the machine host will have a visible and repeatable one. The indication value changes, which is the sensitive area in the usual sense. Under the condition that the sensitivity can be detected, the smaller the weight, the better. It proves that the system friction force of the device is smaller, the uncertainty brought by the system is smaller, and the performance of the device is better.

In terms of software control, we adopt the secondary development of LabVIEW professional industrial measurement and control software from NI in the United States to control the position of the small cylinder suspended in space through the closed loop of pressure and displacement and control the pressure of each static pressure chamber through servo valves and motors. Properly control the flow of the hydraulic system. After setting the test points to be verified, the software automatically completes the test tasks according to the test requirements.

#### 4. DESIGN OF MEASURING POINTS AND WIDE RAGNGE

The real value of the standard machine is not only to solve the problems of measurement accuracy and measurement upper and lower limits, but also to be able to achieve more measurement points, to maximise the utilisation rate and use range of the machine.

After fully study, the dead-weight combination can provide coverage (0.25 ~ 30) MN of standard force at as many measurement points (force steps) as possible without deadweights exchange. The force steps of each nominal force are shown in the list, which can be seen in Table 1.

To avoid the counter-force phenomenon in the process of loading and unloading, the dead-weights cannot be exchanged during the whole process. To meet the wide range design requirements in the above table, finally 4 groups of 42 deadweights are used to achieve 102 force points (steps). Any force step in increments or decrements in multiples of one. Control the running direction and speed of each dead-weight during loading and unloading. When applying the force step that needs to exchange the deadweights, control the loading and unloading deadweights at different speeds according to the size of the load to ensure that when loading and

unloading, can precisely control the loading and unloading deadweights to leave the hanging time, to eliminate the measurement error caused by the reverse load.

Table 1: The list of the force steps

Nominal force	Force step in MN									
	0.5	0.75	1	1.25	1.5	1.75	2			
2MN	0.5	0.75	1	1.25	1.5	1.75	2			
2.5MN	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	
3MN	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	3
3.5MN	0.5	0.75	1	1.5	1.75	2	2.25	2.75	3.25	3.5
5MN	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
5.5MN	0.5	1	1.5	2.25	2.75	3.25	3.75	4.5	5	5.5
6MN	0.75	1.25	1.75	2.5	3	3.5	4	4.75	5.5	6
6.5MN	0.75	1.25	2	2.5	3.25	4	4.5	5.25	5.75	6.5
7MN	0.75	1.5	2	2.75	3.5	4.25	5	5.5	6.25	7
7.5MN	0.75	1.5	2.25	3	3.75	4.5	5.25	6	6.75	7.5
8MN	0.75	1.5	2.5	3.25	4	4.75	5.5	6.5	7.25	8
8.5MN	1	1.75	2.5	3.5	4.25	5	6	6.75	7.75	8.5
9MN	1	1.75	2.75	3.5	4.5	5.5	6.25	7.25	8	9
9.5MN	1	2	2.75	3.75	4.75	5.75	6.75	7.5	8.5	9.5
10MN	1	2	3	4	5	6	7	8	9	10
12MN	1.25	2.5	3.5	4.75	6	7.25	8.5	9.5	10.75	12
15MN	1.5	3	4.5	6	7.5	9	10.5	12	13.5	15
18MN	2	3.5	5.5	7.2	9	10.75	12.5	14.5	16.25	18
20MN	2	4	6	8	10	12	14	16	18	20
25MN	2.5	5	7.5	10	12.5	15	17.5	20	22.5	25
30MN	3	6	9	12	15	18	21	24	27	30

Remarks: the other nominal force :11MN, 13MN, 14MN, 16MN, 17MN, 19MN, 21MN, 22MN,23MN, 24MN, 26MN, 27MN, 28MN and 29MN can be referenced to 12MN or 18MN

## 5. SUMMARY AND OUTLOOK

In the process of designing the 30 MN Pascal-type force standard machine, technologies such as pure hydrostatic support, pure static pressure balance automatic control and multiple sets of independent loading deadweights are comprehensively used, which can realise automatic

process control and accurate reproduction of large force. The machine can perform calibration on the transducers according to both standards: ISO 376 [1] and JJG 144 [2].

Targets achieved by design are:

- Measuring range: compressive direction: (0.25 ~ 30) MN; tensile direction: (0.25 ~ 15) MN
- Accuracy class: 0.05 (the actual measurement data is better than 0.03, even up to 0.01)
- Repeatability: better than 0.03 %
- Reproducibility: better than 0.05 %
- Force threshold: 0.005 %
- Force rate of loading and unloading: each step  $\leq 35$  s
- Time of force approach:  $\leq 25$  s
- Fluctuation of force:  $\leq 0.01$  %
- Holding time of force step:  $\geq 360$  s

In the world there are several large force standard machines with Pascal-type: 20 MN at NIM China, 20 MN in Japan and 16.5 MN at PTB. It makes sense to do comparison tests among them to promote the large force metrology lever.

## 6. REFERENCES

- [1] ISO 376, "Metallic materials - Calibration of force proving instruments used for the verification of uniaxial testing machines", 2011.
- [2] JJG 144, "Verifications of standard dynamometers", 2007.