Linearity Improvement and Synchronous Measurement Technology for Developing the MT300 Digital Manometer

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Yokogawa's MT series digital manometers equipped with a silicon resonant sensor have excellent long-term stability and are widely used in various industries for manufacturing, research and development, and calibration. An MT series digital manometer was selected by national metrology institutes as a transfer standard for the international comparison of national pressure standards. However, there is still room for improving linearity. Yokogawa thus developed a new adjustment method through collaborative research with the National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology (NMIJ/AIST) and incorporated it into the new MT300 digital manometer. This paper describes this adjustment method, evaluation results obtained from NMIJ/AIST, and a synchronous measurement technology used in this method.

INTRODUCTION

Digital manometers are lightweight, portable, and easy to use, and thus more convenient than pressure balances (dead-weight piston gauges) that are conventionally used as pressure standards. The accuracy of digital manometers has been improving to handle increasingly sophisticated target instruments, and they are now used as pressure standards in a wide range of industries(1). As target instruments become more sophisticated and automation of systems progresses, digital manometers are expected to be used more widely and so their accuracy and usability need to be improved.

In September 2019, Yokogawa Test & Measurement Corporation released the MT300 series digital manometers (gauge pressure model: 4 ranges, absolute pressure model: 1 range, differential pressure model: 4 ranges) as successors to the MT210/220. In April 2020, the company added two high-pressure ranges to the gauge pressure model and absolute pressure model, respectively. Figure 1 shows the external view of the MT300. Its silicon resonant sensor (2) has the same excellent long-term stability as the previous models while offering higher accuracy and functionality.

Figure 1 MT300 digital manometer
Left: 1 kPa range differential pressure model
Right: 200 kPa range gauge pressure model (24 V DC output, with DCV/DCA measurement option)

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DEVELOPMENT POLICY OF MT300

The main users of the MT series are calibration institutions, manufacturers of pressure instruments (pressure sensors, manometers, pressure controllers, and so on), and consumer electronics manufacturers. In addition to the main usage for laboratories, the MT300 is in demand in the IA maintenance market because of its battery operation and loop current measurement capability. To satisfy these applications, the specifications and functions of digital manometers are becoming more demanding in addition to higher accuracy.

- More ranges (to measure higher pressures)
- Wider range (to measure pressures exceeding the rating of target instruments)
- Newer communication interface (to respond to automation of systems)
- Longer calibration cycle (to reduce running costs)
- Higher display resolution (to reduce uncertainty in calibration)
- Less susceptible to disturbances such as fluctuations of atmospheric pressure (for multi-point and low-pressure measurements)

To meet these requirements, two ranges of 16 MPa and 70 MPa were added to the gauge pressure model and 700 kPa and 3500 kPa to the absolute pressure model. In the gauge pressure model, the ranges of 130, 700, and 3000 kPa were extended to 200, 1000, and 3500 kPa, respectively.

In response to the increasing automation of systems including PCs, the communication interfaces of the MT300 include GPIB, USB, and Ethernet as standard, enabling add-on applications to systems.

While inheriting the long-term stability of the previous models, the accuracy guarantee period of the MT300 has been doubled from 6 months to 12 months based on the accumulated data of the previous models, the performance evaluation during the development process, and the aging evaluation in collaborative research with the National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology (NMIJ/AIST).

In response to the increasing market demand for calibration based on ISO/IEC17025 such as Japan Calibration Service System (JCSS), we added the option of high display resolution to reduce uncertainty.

In addition, the synchronous measurement function[3], which is effective for multi-point and low-pressure measurements, has been added. This function is also used in adjustment technology and is indispensable for automating manufacturing processes.

The following sections introduce the improvement of linearity for higher accuracy and the details of the synchronous measurement function.

IMPROVEMENT OF LINEARITY

Characteristics of Previous Models

Figure 2 shows the calibration results of the MT210 (differential pressure range: 10 kPa) over the two years from October 2014 to November 2016. The maximum variation was 0.06 Pa, showing excellent long-term stability. However, nonlinearity became apparent above 4 kPa, and the deviation from the standard was −0.8 Pa at 8 kPa. The same characteristics were reported with the MT210 owned by NMIJ/AIST[4].

Suppose a digital manometer with a calibration curve as shown in Figure 2. When a low-order interpolation formula is calculated from the calibration values and is used to correct the indications of the manometer, the difference between the actual and calculated values is so large that the uncertainty is not improved. For a high-order interpolation formula, measurements must be repeated to optimize the calibration points and the number of calibration points. The improvement of linearity solves these problems and thus is beneficial to users.

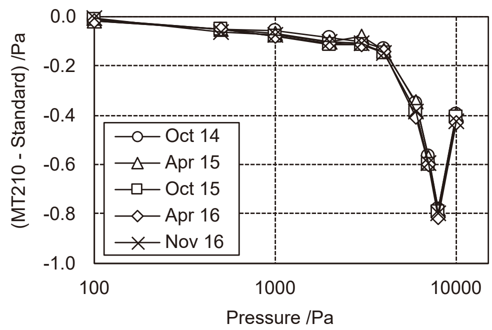

Figure 2 Calibration results and long-term stability of the MT210 (differential pressure range: 10 kPa)

Although the structure of the silicon resonant sensor greatly affects the long-term stability and hysteresis of pressure sensors, the linearity can be adjusted by optimizing the correction coefficient. Therefore, in collaborative research with NMIJ/AIST for developing transfer standards, we revised a method for calculating correction coefficients in the adjustment process and prototyped a pressure sensor. The calibration performed by NMIJ/AIST showed good characteristics. The contents of this collaborative research and the characteristics of the pressure sensor are described below.

Collaborative Research with NMIJ/AIST

There are compact digital manometers without a display and operation keys, specialized for pressure measurement. We call such manometers “pressure sensors” and distinguish them from other digital manometers such as the MT300. Our previous model, the 265381/Z, is a kind of such pressure sensors, manufactured for national metrology institutes such as the National Institute of Standards and Technology (NIST). The 265381/Z was used as a transfer standard for international comparisons of national pressure standards[5][6], and we still receive requests for its re-release. Thus, we started a collaborative research project with NMIJ/AIST in 2016, to develop a pressure sensor that can be supplied continuously as a transfer standard for international comparisons. We adjusted the pressure sensors and NMIJ/AIST evaluated them against its own pressure standards[7].

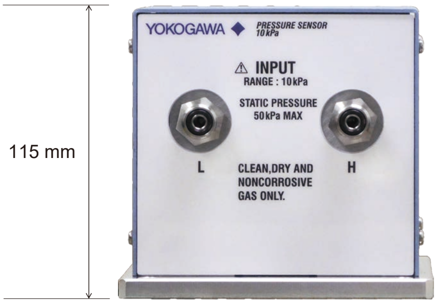

Figure 3 External view of the prototype pressure sensor (differential pressure range: 10 kPa)

Figure 3 shows an external view of the prototype developed for the collaborative research. Designed based on the 265381/Z, this pressure sensor is equipped with input ports on the front and a USB port on the back for communication with a PC and for power supply. Various settings and pressure value acquisition are performed on the PC. Just like previous models, the sensor has two main parts: one is an assembly of a sensor capsule and two flanges, and the other is a board for signal processing and communication. A silicon resonant sensor is mounted in the sensor capsule. To improve the characteristics, sensor capsules come with different diaphragm sizes for each range, except for some models.

How to Adjust Pressure Sensors

We set two requirements for the adjustment method: automatic and simultaneous adjustment of multiple pressure sensors and applicability to the MT300.

To determine pressure values, the pressure sensor uses an expression that is a function of the oscillator frequency of the silicon resonant sensor. The correction coefficient is another element of the expression and reflects the characteristics of the pressure sensor. In the adjustment process, pressure is applied to the target pressure sensor, the value of the oscillator frequency is substituted in the expression, and the correction coefficient is determined so that the resulting value of the expression matches the value of the applied pressure. In the previous adjustment method, the correction coefficient was calculated using a standard with nonlinear characteristics, resulting in nonlinear characteristics of the target sensor. In the collaborative research, we used the standard calibrated by NMIJ/AIST or Yokogawa, corrected the measurement value by its calibration value, and determined the correction coefficient. We expected that this method would deliver excellent linearity with less deviation from the NMIJ/AIST pressure standard.

In the adjustment process, multiple pressure sensors were placed in a thermostatic chamber, different pressures were applied simultaneously from the pressure controller while changing the temperature, and the oscillator frequencies of the pressure sensors were measured. The applied pressure was measured by a standard placed outside the thermostatic chamber. The measurements corrected with the calibration value of the standard were used to determine the correction coefficient of the pressure sensors.

Minor fluctuations of the applied pressure are inevitable, but greatly affect the adjustment of sensors when the data are acquired sequentially (i.e., not simultaneously) from the standard, sensor 1, sensor 2, and so on. To solve this problem, we adopted synchronous measurement, which is explained later.

The linearity is also affected by the combination of pressure points used to determine the correction coefficient. Therefore, we set multiple conditions with different combinations of pressure points, calculated correction coefficients and pressure values, repeated simulations for each case, and determined the combination with the best linearity. The result was also used to adjust the sensor of the MT300.

Characteristics of the Prototype Pressure Sensor

This section describes the results of calibration performed by NMIJ/AIST on pressure sensors. Figures 4 to 6 show the results of comparing pressure sensors with the pressure standards owned by NMIJ/AIST. The error bars in the graphs indicate the expanded uncertainty of the calibration (k = 2).

Figure 4 shows the calibration results of two pressure sensors (differential pressure range: 10 kPa). The maximum deviation from the NMIJ/AIST pressure standard was 0.07 Pa. A comparison of this result with the calibration result of the MT210, which was used as the adjustment standard for this pressure sensor (see Figure 2), showed that the linearity was greatly improved. Furthermore, the maximum difference between the calibration results of the two units was 0.03 Pa. In the 10 kPa range, the adjustment method described in the section "How to Adjust Pressure Sensors" effectively improved the linearity, achieving very low differences among individual units.

We applied this adjustment method to other pressure ranges. Figure 5 shows the results of calibration performed by NMIJ/AIST on two pressure sensors (absolute pressure range: 130 kPa), which had been adjusted by different methods. Pressure sensor A had been adjusted using the MT210 (absolute pressure range: 130 kPa) owned by Yokogawa as a reference (with no correction). Pressure sensor B was adjusted using pressure sensor A as a reference after sensor A was corrected with the calibration results shown in Figure 5. Comparing the calibration curves of both sensors showed that the linearity of sensor B improved just like the pressure sensor (differential pressure range: 10 kPa), confirming that this adjustment method is effective for improving the linearity in other ranges.

Improved linearity allows a larger margin for the accuracy specification, and the accuracy guarantee period can be extended when changes over time are small. To confirm the long-term stability of a pressure sensor (differential pressure range: 10 kPa), we compared the calibration results in March 2017 and January 2018. Figure 6 shows the results. Even after 10 months, the difference remained within 0.04 Pa. This satisfies the accuracy specification of the MT300, which has the same sensor capsule as the prototype pressure sensor. The excellent long-term stability of the silicon resonant sensor can also be confirmed from the calibration results of the conventional MT210 described in the section "Characteristics of Previous Models." Based on these results, the accuracy guarantee period of the MT300 was extended to one year.

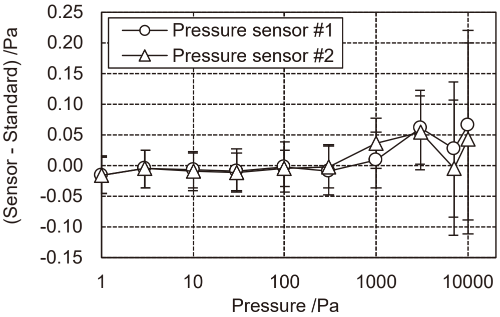

Figure 4 Calibration results of pressure sensors (differential pressure range: 10 kPa)

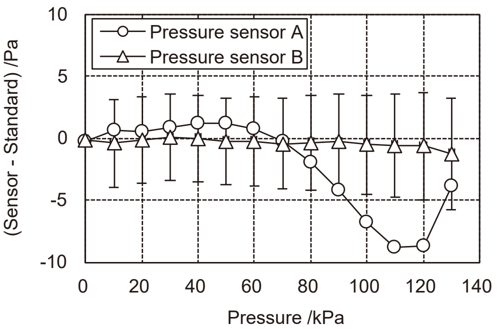

Figure 5 Calibration results of pressure sensors (absolute pressure range: 130 kPa)

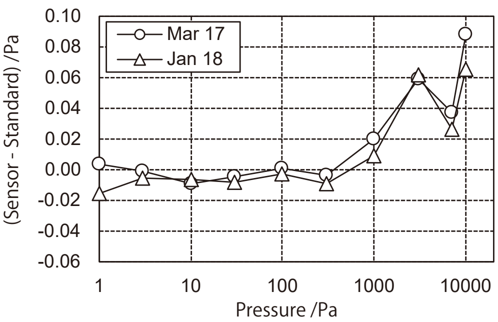

Figure 6 Long-term stability of a pressure sensor (differential pressure range: 10 kPa)

Characteristics of the MT300

We manufactured nine pressure sensors with different pressure ranges as standards for adjusting and inspecting the MT300. These sensors cover all the pressure ranges of the MT300 series. All sensors were adjusted by the method described above, and their characteristics were confirmed by calibration at NMIJ/AIST. We manufactured MT300 prototypes using a facility equipped with these pressure sensors. The following are the results of evaluating the accuracy of the prototype MT300.

Figures 7 and 8 show the evaluation results of the MT300s (differential pressure range: 10 kPa and absolute pressure range: 130 kPa). Pressure was applied from the pressure controller simultaneously to the MT300 and the standard. Pressure was increased and then decreased three times, and the difference between the indications of the MT300 and the standard was determined. The standard for this evaluation was the pressure sensor adjusted by the method described in the section "How to Adjust Pressure Sensors."

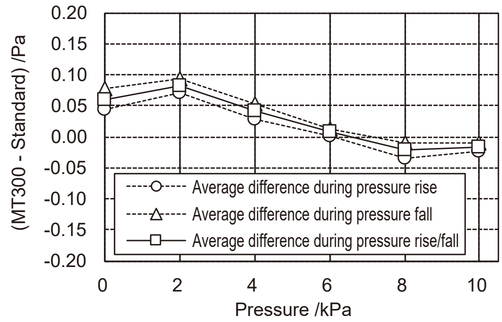

Figure 7 Evaluation results of the accuracy of the MT300 (differential pressure range: 10 kPa)

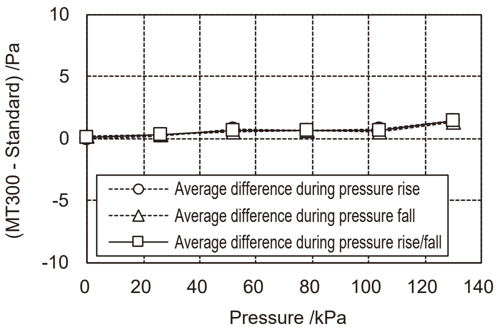

Figure 8 Evaluation results of the accuracy of the MT300 (absolute pressure range: 130 kPa)

The MT300 (Figures 7 and 8) did not show nonlinearity like the MT210 (Figure 2) and pressure sensor A (Figure 5) show. Its characteristics were similar to those of the prototype pressure sensor introduced in the section "Characteristics of the Prototype Pressure Sensor," indicating that the linearity of the MT300 has been improved compared to previous models. The adjustment and inspection process of the MT300 is automated with an instrument that combines a pressure controller and a standard (in this case, a pressure sensor). This instrument can adjust four sensor capsules simultaneously, making it possible to efficiently manufacture digital manometers having excellent linearity. The next section explains the synchronous measurement function, which is incorporated in the adjustment and inspection process of the MT300 and contributes greatly to automating the process, especially for the low-pressure range.

SYNCHRONOUS MEASUREMENT FUNCTION

Pressure measurement applications include multi-point measurement, low pressure measurement, and calibration using a standard. In these measurements, a handy pressure controller is often used to apply pressure, but its fluctuations can spoil high-precision measurements. Particularly in low pressure measurement, it is difficult to stabilize the control pressure. In addition, the signal-to-noise ratio is very small. Therefore, fluctuations in the control pressure as well as in the atmospheric pressure affect the measurement results more greatly.

Figure 9 shows a system for inspecting (or calibrating) pressure measuring instruments. Figure 10 shows differences in indications. When the reference manometer and devices under test (DUT) measure the fluctuating input pressure at different timings (indicated by arrows), the resulting measured values differ from each other.

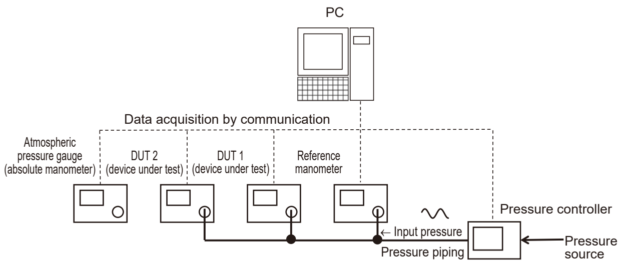

Figure 9 A system for inspecting or calibrating pressure measuring instruments

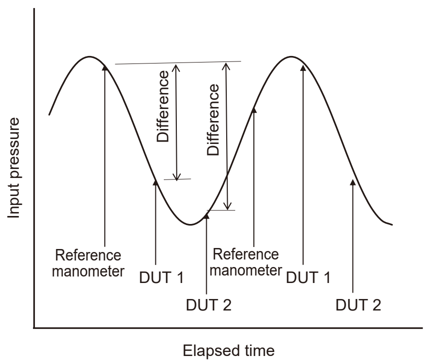

Figure 10 Differences caused by different measurement timings

The MT210/220 series had a 1 kPa range model for low pressure measurement. In its adjustment and inspection process, two pressure balances were used to generate differential pressure instead of a pressure controller because it was difficult to obtain a pressure controller that can stably generate 1 kPa of pressure. However, it was not easy to generate low pressure by manually operating pressure balances. Therefore, this process was extremely time-consuming.

The MT300, on the other hand, uses a pressure controller as the pressure source for adjustment and inspection in the 1 kPa range, and also uses a synchronous measurement function to cancel fluctuations in control pressure and atmospheric pressure. These features enable the adjustment and inspection process to be automated. Figure 11 shows the connection diagram of a system for adjusting the MT300.

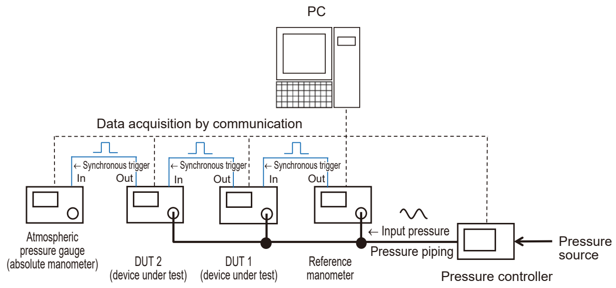

Figure 11 Connection diagram of a system for adjusting the MT300

The synchronous measurement function gives a source trigger and a trigger input function to pressure measuring instruments, synchronizes the measurement timings of multiple items, and eliminates differences in measurement values caused by fluctuations in the input pressure. The trigger signal generated by the reference manometer is transmitted to DUT1 when the reference manometer performs measurement. This means that DUT1 measures the pressure in synchronization with the reference manometer. DUT1 also transmits the trigger signal to DUT2, which thus performs measurements at the same timing as DUT1, achieving synchronous measurement between the reference manometer and DUTs.

To verify this function, we connected three MT300s (MT1 to MT3 in Figure 12), performed synchronous and asynchronous measurements 20 times each, and compared the data. Figure 13 shows fluctuations when 1 kPa of pressure was input from the pressure controller, Figure 14 shows the difference between the reference manometer and the DUT during asynchronous measurement, and Figure 15 shows the difference during synchronous measurement. These results show that under the condition where the control pressure fluctuates as shown in Figure 13, differences of up to 3.63 Pa are caused by asynchronous measurements in P-P. In the case of synchronous measurement, differences were almost constant and very low (up to 0.17 Pa) in the same period. These results confirm that the measurement value of the MT300 was almost the same as that of the reference manometer.

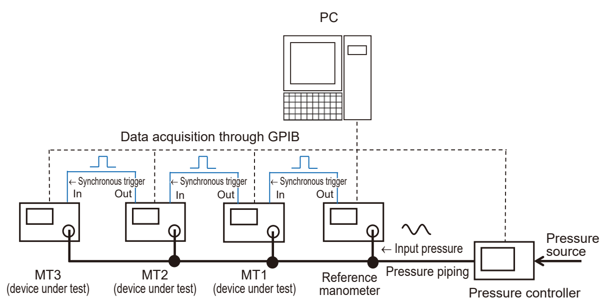

Figure 12 Connection diagram of a system for verifying the synchronous measurement function

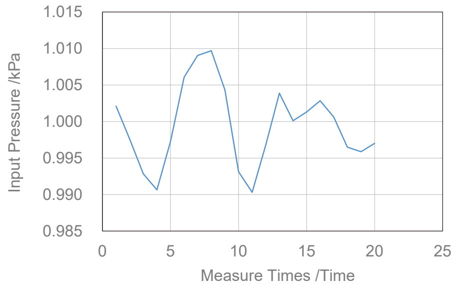

Figure 13 Fluctuations of input pressure (1 kPa)

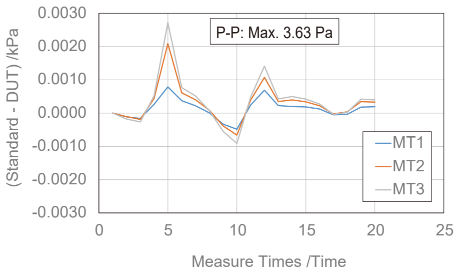

Figure 14 Differences during asynchronous measurement

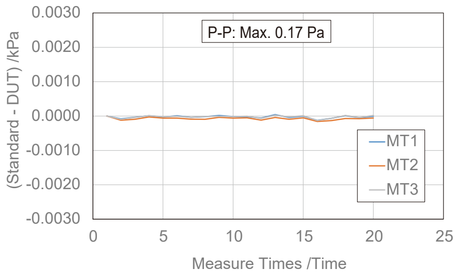

Figure 15 Differences during synchronous measurement

The synchronous measurement function implemented in the MT300 can be used in various applications. To determine the suction power of a vacuum cleaner, for example, it is necessary to measure negative pressure in a pressure equalizing chamber and air flow in a pitot tube as shown in Figure 16. Although the target pressure keeps fluctuating, the synchronous measurement function can eliminate the effect of differences in the measurement timing and thus the negative pressure and air volume can be determined with high accuracy.

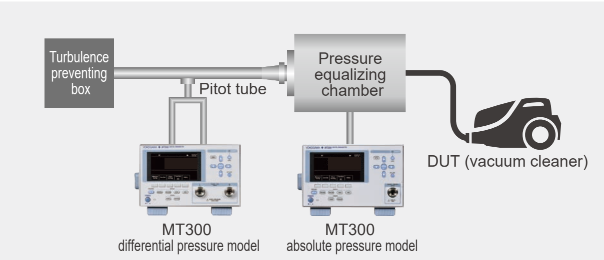

Figure 16 Measurement of suction power of a vacuum cleaner

CONCLUSION

This paper introduced an adjustment method for improving the linearity of digital manometers and the synchronous measurement function of the MT300. In addition to the standard models, custom-made models are to be released for medical equipment manufacturers and laboratories. In accordance with the Measurement Act, these models can be used with units specific for medical and healthcare fields, such as mmHg and cmH_2O, for in vivo pressure measurement applications. Regarding pressure measurement in these fields, there is high demand for improving medical devices (ventilators, blood pressure monitors, etc.) and increasing their production, due to COVID-19 and many other factors. The MT300 custom-made models are expected to satisfy these needs.

We will continue to develop a variety of pressure measuring instruments including pressure controllers to boost Yokogawa's pressure business and contribute to society.

ACKNOWLEDGMENTS

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