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Flow Measurement Turn Down Analysis for DP Flow Meter using Multiple Multivariable Transmitters

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Abstract

We conducted differential pressure (DP) flow meter calibration at CEESI and observed that the combined linearity of VERIS Accelabar® flow primary element and Yokogawa EJX910 multivariable transmitter DP measurement indicated excellent performance. The observation result was that linearity with reference flow rate was 0.5% with 15:1 turndown for the EJX910 H range with the 4" VERIS Accelabar® during the 800 psia air test. EJX910 has also L range and we show that adding L range, flow measurement turndown will be increased beyond 15:1 until 20:1. Firstly we show flow rate equation and uncertainty of the combined flow meter. We assume that VERIS Accelabar® flow uncertainty contribution is 0.5% with 20:1 turndown derived by previous experiments. Also, we assume the density contribution as 0.1%. Then, EJX910 L range DP uncertainty at 20:1 turndown point is analysed. With assumption of using L range data tested at the factory, DP measurement uncertainty including reference accuracy and static pressure (SP) span effects is assumed as 0.24%. Flow uncertainty is calculated as 0.52%, which is almost 0.5%. EJX910 is designed with multi-sensing capabilities using built-in silicon resonant sensor technology. EJX910 dynamically & continuously minimizes the effect of SP fluctuation with two resonators incorporated into one sensor tip and provides precise DP measurement. This shows that EJX910 has an advantage of low DP measurement under high SP condition. This indicates the latest progress of DP flow meter technology and the DP flow meter has still big potential for use in industry widely.

1. Introduction

We conducted differential pressure (DP) flow meter calibration at CEESI located at Nunn, Colorado, USA in 2015 and observed that the combined linearity of VERIS Accelabar® flow primary element and Yokogawa EJX910 multivariable transmitter DP measurement indicated excellent performance [1] (See Figure 1 to 3). The VERIS Accelabar® is a flow primary element which combines a unique toroidal nozzle design with the VERIS Verabar® averaging pitot tube [2]. The Yokogawa EJX910 is a multivariable transmitter based on pressure transmitter, which is designed with multi-sensing capabilities using built-in silicon resonant sensor technology [3].

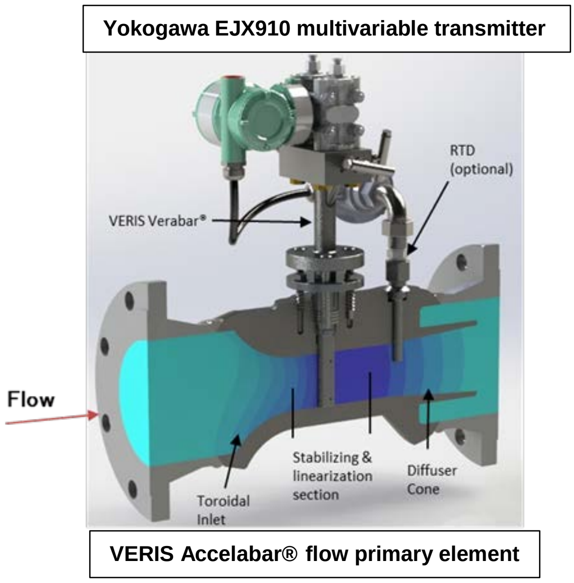

Figure 1: Combined DP flow meter VERIS Accelabar® and Yokogawa EJX910

The observation result was that linearity with reference flow rate was 0.5% with 15:1 turndown for the EJX910 H range (DP: 2000inH2O) with the 4" VERIS Accelabar® during the SP: 800 psia air test. CEESI flow facility reference flow uncertainty was 0.3%-0.46% during the flow range.

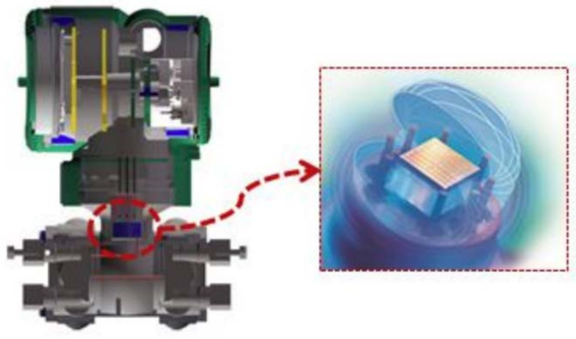

Figure 2: EJX910 multivariable transmitter with silicon resonant sensor

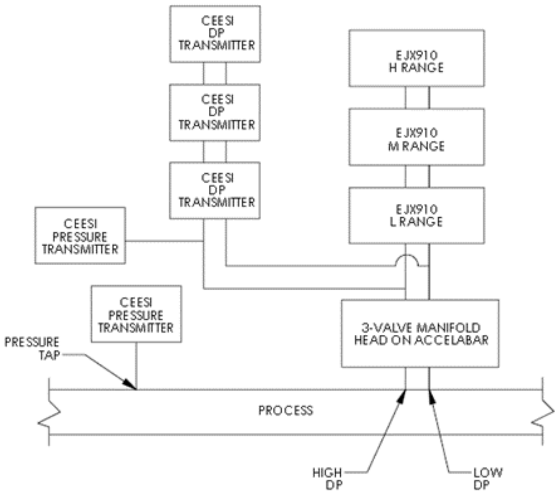

Figure 3: Instrument connections at CEESI calibration

EJX910 has also L range (DP: 40inH2O) transmitter and capability of using for low flow rate measurement. In this paper, we show that adding L range transmitter with H range transmitter, flow measurement turndown will be increased beyond 15:1 until 20:1. Also we show that EJX910 has an advantage of low DP measurement under high static pressure (SP) condition.

2. Flow calibration result at CEESI

2.1 Result using single multivariable transmitter

The combined linearity of VERIS Accelabar® flow primary element and Yokogawa EJX910 DP measurement was 0.5% with 15:1 turndown. The result was obtained using single EJX910 H range (2000inH2O). The result is shown in Figure 4 [1].

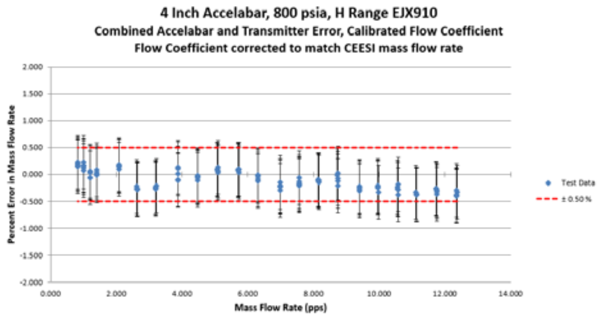

Figure 4: Flow measurement result using single multivariable transmitter (0.50% Accuracy, 15:1 Turndown).

2.2 Flow rate equation at the CEESI test

We show flow rate equation of the combined flow meter EJX910 and VERIS Accelabar® [4].

$$q_m = \frac{\pi}{4} K \varepsilon D^2 \sqrt{2 \Delta P \rho_f} \quad (1)$$

Where

K stands for flow coefficient

ε stands for expansibility

D stands for diameter of the conduit

ΔP stands for DP

ρ_f stands for density

The maximum flow rate at the test is around 12.4 lb/sec where DP is around 890inH2O. Minimum flow rate is around 0.82 lb/sec where DP is around 3.9inH2O. The flow turndown is calculated as below.

$$\text{Flow turn down} = \frac{12.4\ lb/sec}{0.82\ lb/sec} = 15.1 \quad (2)$$

The flow turndown 20:1 flow rate from the maximum flow point 12.4 lb/sec is as below.

$$\text{20:1 flow point} = \frac{12.4\ lb/sec}{20} = 0.62\ lb/sec \quad (3)$$

Corresponding DP $\Delta P_{20:1}$ is as below, assuming K and ε difference is small around 15:1 flow rate $q_{m(15:1)}$ and 20:1 flow rate $q_{m(20:1)}$.

$$q_{m(15:1)} = \frac{\pi}{4} K \varepsilon D^2 \sqrt{2 \Delta P_{15:1} \rho_f} \quad (4)$$

$$q_{m(20:1)} = \frac{\pi}{4} K \varepsilon D^2 \sqrt{2 \Delta P_{20:1} \rho_f} \quad (5)$$

$$\Delta P_{20:1} = \frac{{q_{m(20:1)}}^2}{{q_{m(15:1)}}^2} \times \Delta P_{15:1} = \frac{0.62^2}{0.82^2} \times 3.9 = 2.2\ inH2O \quad (6)$$

We will analyse 20:1 flow point uncertainty and confirm if flow measurement turndown will be increased beyond 0.5% 15:1 until 20:1 in case of adding L range transmitter.

3. Combined flow uncertainty

We show general equation of combined flow uncertainty of the flow meter [4].

$$\frac{\delta q_m}{q_m} = \sqrt{\left(\frac{\partial K}{K}\right)^2 + \left(\frac{\partial \varepsilon}{\varepsilon}\right)^2 + \left(\frac{2\partial D}{D}\right)^2 + \left(\frac{\partial \Delta P}{2\Delta P}\right)^2 + \left(\frac{\partial \rho}{2\rho}\right)^2} \quad (7)$$

The uncertainty contribution of VERIS Accelabar® $Uncert_{pe}$ is as below.

$$Uncert_{pe} = \left(\frac{\partial K}{K}\right)^2 + \left(\frac{\partial \varepsilon}{\varepsilon}\right)^2 + \left(\frac{2\partial D}{D}\right)^2 \quad (8)$$

In this paper, we assume that VERIS Accelabar® flow uncertainty contribution is 0.5% with 20:1 turndown derived by previous experiments [5].

$$\sqrt{\left(\frac{\partial K}{K}\right)^2 + \left(\frac{\partial \varepsilon}{\varepsilon}\right)^2 + \left(\frac{2\partial D}{D}\right)^2} = 0.5\% \quad (9)$$

Using the assumption, below is calculated.

$$Uncert_{pe\_as} = \left(\frac{\partial K}{K}\right)^2 + \left(\frac{\partial \varepsilon}{\varepsilon}\right)^2 + \left(\frac{2\partial D}{D}\right)^2 = (0.5\%)^2 \quad (10)$$

The uncertainty contribution of the density $Uncert_{\rho}$ is as below.

$$Uncert_{\rho} = \left(\frac{\partial \rho}{2\rho}\right)^2 \quad (11)$$

We assume below equation by current EJX910 specification [6].

$$\left(\frac{\partial \rho}{\rho}\right) = 0.1\% \quad (12)$$

Using the assumption, below is calculated.

$$Uncert_{\rho\_as} = \left(\frac{\partial \rho}{2\rho}\right)^2 = (0.05\%)^2 \quad (13)$$

After next section, we will show 0.5% turn down 20:1 is achieved by analysing EJX910 DP uncertainty under above assumption.

4. DP measurement uncertainty

The uncertainty contribution of the EJX910 $Uncert_{dp}$ is as below.

$$Uncert_{dp} = \left(\frac{\partial \Delta P}{2\Delta P}\right)^2 \quad (14)$$

EJX910 flow uncertainty contribution are DP uncertainty which consists of reference accuracy, ambient temperature effects, and SP effects. EJX910 L rage uncertainty is described as below [6].

a) Reference accuracy is defined as ±0.04% of span. In this case, we assume span is configured as 40inH2O same as maximum range value.
b) Ambient temperature effect per 28°C (50°F) change is defined as ±(0.055% Span + 0.09% URL). In this test, the temperature is kept in room temperature and this effect can be ignored.
c) SP effects consist of span effects and effects on zero. SP span effects per 6.9 MPa (1000 psi) change is defined as ±0.075% of span. SP effect on zero per 6.9 MPa (1000 psi) change is defined as ±0.05% URL. In this test, DP zero adjustment is conducted at 800 psia condition. So, zero effect can be ignored.

5. L range DP comparison with CEESI master meter

We also used EJX910 L range transmitter when we conducted DP flow meter calibration at CEESI (See Figure 3). In the ISFFM paper, we only showed DP comparison between EJX910 H range and CEESI master meter [1]. Here we show L range and H range combined data in Figure 5 below 200inH2O. L range data is available below 40inH2O.

The minimum data point is around 3.9 inH2O where flow turndown is 15:1. The EJX910 L range data difference between the EJX910 H range and CEESI master meter at the point is around 2%. The EJX910 uncertainty calculated by general specification is around 1%. The CEESI master mater uncertainty is 0.8%. The uncertainty of EJX910 and the reference CEESI master meter at the point is relatively bigger than the difference. It is not possible to obtain DP uncertainty value below 3.9 inH2O point from Figure 5. In the next section, we will calculate DP uncertainty at 2.2 inH2O point corresponding to 20:1 flow point.

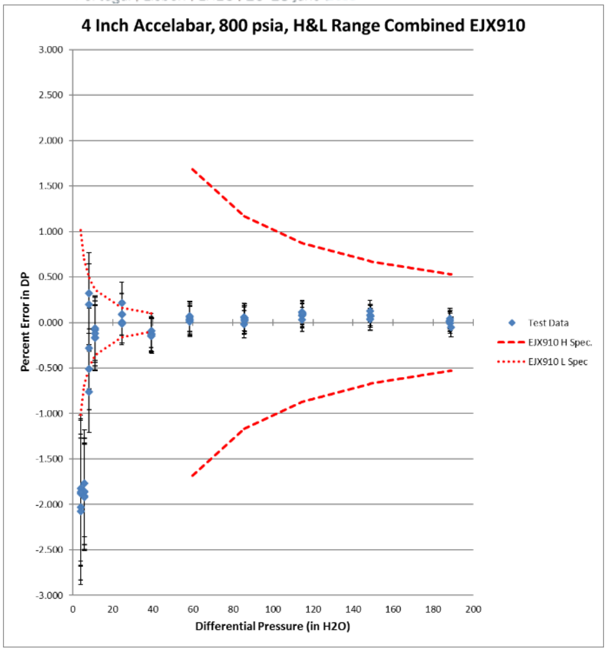

Figure 5: DP difference between EJX910 and CEESI master meter.

6. L range DP uncertainty analysis under CEESI calibration condition

EJX910 L rage DP uncertainty assumption at 2.2 inH2O point under CEESI calibration condition is shown.

6.1 Reference accuracy

Reference accuracy is defined as $\pm$0.04% of span. From this defined accuracy, uncertainty at 2.2 inH2O point $\left(\frac{\partial \Delta P}{\Delta P}\right)_{ref}$ is as below.

$$\left(\frac{\partial \Delta P}{\Delta P}\right)_{ref} = 0.04\% \times \frac{40\ inH2O}{2.2\ inH2O} = 0.7\% \qquad (15)$$

On the contrary, L range EJX910 used at the CEESI test is tested at the factory. The result at 10 inH2O point is 0.005% of span. Also, the result at 0 inH2O point is 0.003% of span. If we assume the actual reference accuracy at 2.2 InH2O is 0.005% of span. Then, assumed uncertainty at 2.2 inH2O point $\left(\frac{\partial \Delta P}{\Delta P}\right)_{ref\_as}$ is as below.

$$\left(\frac{\partial \Delta P}{\Delta P}\right)_{ref\_as} = 0.005\% \times \frac{40\ inH2O}{2.2\ inH2O} = 0.09\% \qquad (16)$$

6.2 SP span effects

SP span effects per 6.9 MPa (1000 psi) change is defined as $\pm$0.075% of span. From this defined accuracy, uncertainty at 2.2 inH2O point $\left(\frac{\partial \Delta P}{\Delta P}\right)_{span}$ is as below.

$$\left(\frac{\partial \Delta P}{\Delta P}\right)_{span} = 0.075\% \times \frac{800\ psia}{1000\ psia} \times \frac{40\ inH2O}{2.2\ inH2O} = 1.1\% \qquad (17)$$

If we assume the actual span effects at 2.2 InH2O is 0.01% of span from the data tested at the factory, then, assumed uncertainty at 2.2 inH2O point $\left(\frac{\partial \Delta P}{\Delta P}\right)_{span\_as}$ is as below.

$$\left(\frac{\partial \Delta P}{\Delta P}\right)_{span\_as} = 0.01\% \times \frac{800\ psia}{1000\ psia} \times \frac{40\ inH2O}{2.2\ inH2O} = 0.15\% \qquad (18)$$

6.3 DP measurement uncertainty

From Equation (16) and (18), assumed uncertainty at 2.2 inH2O point $\left(\frac{\partial \Delta P}{\Delta P}\right)_{as}$ is as below.

$$\left(\frac{\partial \Delta P}{\Delta P}\right)_{as} = \left(\frac{\partial \Delta P}{\Delta P}\right)_{ref\_as} + \left(\frac{\partial \Delta P}{\Delta P}\right)_{span\_as} = 0.09\% + 0.15\% = 0.24\% \qquad (19)$$

Then, from Equation (14) and (19),

$$Uncert_{dp\_as} = \left\{\left(\frac{\partial \Delta P}{2\Delta P}\right)^2\right\}_{as} = \left(\frac{1}{2} \times \left(\frac{\partial \Delta P}{\Delta P}\right)_{as}\right)^2 = \left(\frac{1}{2} \times 0.24\%\right)^2 = (0.12\%)^2 \qquad (20)$$

7. Extending flow turn down to 20:1

From Equation (7), (8), (10), (11), (13), (14), and (20).

$$\left(\frac{\delta q_m}{q_m}\right)_{as} = \sqrt{\left(Uncert_{pe\_as} + Uncert_{\rho\_as} + Uncert_{dp\_as}\right)} = \sqrt{\left((0.5\%)^2 + (0.05\%)^2 + (0.12\%)^2\right)} = \sqrt{(0.25\% + 0.0025\% + 0.0144\%)} = \sqrt{0.2669} = 0.52\% \qquad (21)$$

If we assume condition (9), (12), and (19), L range uncertainty 2.2 inH2O point which corresponds to 20:1 flow turn down point is 0.52%, which is almost 0.5%. Then flow turn down 20:1 will be achieved using L range transmitter in addition to H range under CEESI test condition.

8. DP measurement contribution for flow measurement

EJX910 is designed with multi-sensing capabilities using built-in silicon resonant sensor technology [7] (See Figure 3). The pressure sensor based on advanced silicon resonant sensor structure contributes to the flow measurement performance which realizes uncertainty 0.5% turn down 20:1 by multiple multivariable transmitters.

8.1 Pressure sensor structure

Left drawing in Figure 6 shows two resonators which are incorporated into one sensor tip inside EJX910 using MEMS technology at the location of the silicon diaphragms. Two resonators are located where tensile strain and compressive strain occur. One of the specific characteristics of EJX910 sensor structure is that the SP is simultaneously measured along with the DP by this one sensor tip.

For typical flow application, SP is measured on high-side and DP is measured between high- and low- side. The pressure applied to the high-side diaphragm is conveyed to the front side of the sensor tip and the pressure applied to the low-side diaphragm is conveyed to another side of the sensor tip.

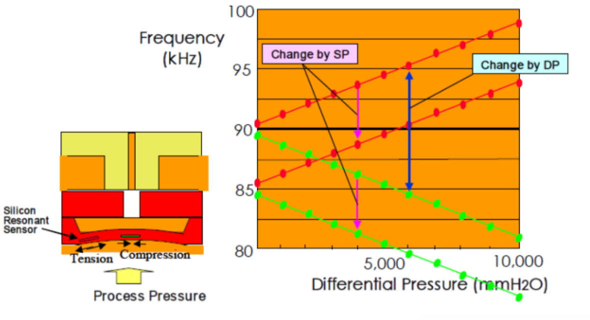

Figure 6: EJX910 pressure sensor structure and signal

8.2 Pressure sensor signal

The DP and SP signals can be calculated by making differential computations and summation computations of the two resonators respectively. Changes (Δf^2) in resonance frequencies f_1 and f_2 of the two resonators due to pressure are simply given as below [7].

$$\Delta {f_1}^2 = \Delta {f_{01}}^2 \cdot G_{f1}(+\varepsilon_{dp1} + \varepsilon_{sp1}) \qquad (22)$$
$$\Delta {f_2}^2 = \Delta {f_{02}}^2 \cdot G_{f2}(-\varepsilon_{dp2} + \varepsilon_{sp2}) \qquad (23)$$

where

f_0 stands for the resonance frequency when the tensile force is zero

G_f stands for the squared sensitivity of the resonator (=0.2366・(1/h)^2)

h stands for thickness of the resonator

ε_{dp} stands for change in the tensile force due to DP

ε_{sp} stands for change in the tensile force due to SP

DP and SP change is calculated as below.

$$\Delta \mathrm{DP} = \Delta {f_1}^2 - a \cdot \Delta {f_2}^2 \qquad (24)$$
$$\Delta \mathrm{SP} = \Delta {f_1}^2 + b \cdot \Delta {f_2}^2 \qquad (25)$$

where

Δ DP stands for DP change

Δ SP stands for SP change

Equation (24) eliminates the term ε_{sp1} in (22) and ε_{sp2} in (23) related to SP and provides a DP signal. Equation (25) eliminates the term ε_{dp1} in (22) and ε_{dp2} in (23) related to DP and provides a SP signal. By previously determining each coefficient from actual measured appropriate data, DP and SP signals can be calculated. This indicates that DP and SP signals are both generated using two resonator's frequency signals inside one sensor tip.

EJX910 dynamically & continuously minimize the effect of SP fluctuation inside the transmitter based on above feature. It provides precise DP measurement under real conditions which is explained in Equation (15) to (18).

8.3 Pressure sensor characteristics

EJX910 pressure sensor has advanced characteristics indicated as below.

a) EJX910 silicon resonant sensor is made of single crystal which is tetrahedral structure with strong bonding. It reacts ideal elastic deformation from outside force.
b) EJX910 pressure whole range measurement is conducted under elastic deformation state. The deformation is proportional and uniform and the hysteresis is small. The two resonators deformation precisely match the theoretical Equation (22) and (23).
c) Two resonators are incorporated into one sensor tip and the compensations (24) and (25) are achieved precisely.
d) The silicon resonant sensor is inside the vacuum cavity and the resonance is robust from outside disturbance.

8.4 Low DP measurement under high SP condition
Right drawing in Figure 6 indicates the two resonators signals influenced by the DP and the SP. The resonators frequency shifts according to the DP and the SP changes keeping two resonators frequency relation.

The changes are proportional and uniform and the hysteresis is small. SP compensations of DP signal for whole ranges are achieved precisely. This indicates that the uncertainty of the DP is small even at the condition of low DP under high SP. This shows that EJX910 has an advantage of low DP measurement under high SP condition.

9. Conclusion

In this paper, combined DP flow meter VERIS Accelabar® flow primary element and Yokogawa EJX910 multivariable transmitter is analysed. It indicates that adding EJX910 L range transmitter with H range transmitter, combined flow measurement turndown will be increased beyond 15:1 until 20:1 under 0.5% linearity with reference flow rate.

EJX910 is designed with multi-sensing capabilities using built-in silicon resonant sensor technology. EJX910 dynamically & continuously minimizes the effect of SP fluctuation with two resonators incorporated into one sensor tip and provides precise DP measurement under real conditions.

EJX910 has an advantage of low DP measurement under high SP condition with built-in silicon resonant sensor technology. This indicates the latest progress of DP flow meter technology and the DP flow meter has still big potential for use in industry widely.

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