TECHNICAL PAPER:

FlowTracker2 Depth Measurements with Compensation for Dynamic Pressure Effects

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SonTek a xylem brand

I. INTRODUCTION

In November 2016, SonTek released an enhanced FlowTracker2 Acoustic Doppler Velocimeter (ADV) probe with a built-in pressure sensor. During a discharge measurement, a typical user will read the water depth from wading rod markings. With a pressure sensor, water depth can be measured automatically, reducing human error in the field and providing increased accuracy. Furthermore, when setting the probe depth during a measurement, the pressure sensor accurately determines the proper measurement depth (0.6, 0.2, 0.8, etc.) and guides the user to the correct measurement depth in real-time. In measurement locations where it is difficult or impractical to get an accurate depth reading from a top setting rod (from a high bridge, inside a manhole or pipe, etc.), the pressure sensor will be critical to provide an accurate water depth reading.

Adding a pressure sensor to the existing FlowTracker2 may sound simple in concept, but many factors had to be considered during development to obtain a proper water depth measurement. This technical note serves to explain the implementation of the pressure sensor hardware, as well as to outline the various patent-pending pressure corrections performed to obtain the most reliable and accurate automatic water depth measurement.

II. FLOWTRACKER2 PRESSURE SENSOR IMPLEMENTATION

The pressure sensor itself is embedded into the base of the FlowTracker2's acoustic sensor head. Small vent holes on the bottom and sides of the probe are visible in Figure 1, and allow for the sensor to read the water pressure effectively. The sensor is physically located about 1cm above the bottom of the probe, and this offset is measured at the SonTek factory and incorporated into the calculations during the calibration process.

Instead of the conventional vented pressure sensor, a non-vented pressure sensor is used. A non-vented pressure sensor is more durable and is less susceptible to moisture ingress. The user will be required to take a measurement of the atmospheric pressure in air to "calibrate" the sensor before starting a measurement. This process is described in detail in the Handheld software and in the FlowTracker2 Manual.

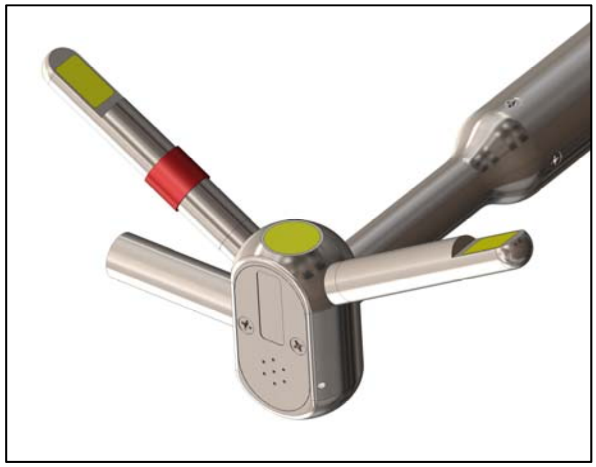

Figure 1. The SonTek FlowTracker2 probe head showing vent holes to the pressure sensor.

III. PATENT-PENDING DYNAMIC PRESSURE CORRECTION

When a pressure sensor is placed in flowing water, the measured pressure is affected by the Bernoulli principle, and results in a velocity-dependent offset. Lack of a proper correction for this effect has plagued other instrumentation solutions users may have encountered in the past. The FlowTracker2's patent-pending correction to properly compensate for the Bernoulli Effect is explained below.

A. Dynamic Pressure and the Bernoulli Principle

The Bernoulli Principle is a standard concept in fluid dynamics, and is applied widely in aviation, hydraulics, and thermodynamics fields. For fluids, it is derived from the general equations of motion, and can be generalized by

[1] $$\frac{\rho v^2}{2} + \rho g h + P = Constant,$$

where ρ is the fluid density, v is the fluid speed, g is the gravitational acceleration, h is the vertical coordinate along a streamline with respect to a chosen datum, and P is the measured pressure at a certain point. The first term represents the Dynamic Pressure, and can be thought of as the kinetic energy of the fluid in motion. The second term is the Hydrostatic Pressure, and can be thought of as the potential energy of the fluid at rest. The third term is simply the pressure measured by the sensor. The Bernoulli principle dictates that in a closed system, the sum of the Dynamic, Hydrostatic, and measured pressures must remain constant. This implies that an increase in fluid speed must correspond to a decrease in measured pressure, given a constant water depth (or Hydrostatic Pressure).

Figure 2 shows the Bernoulli Effect on the pressure measurement for a FlowTracker2 probe being towed at set speeds in a tow tank.

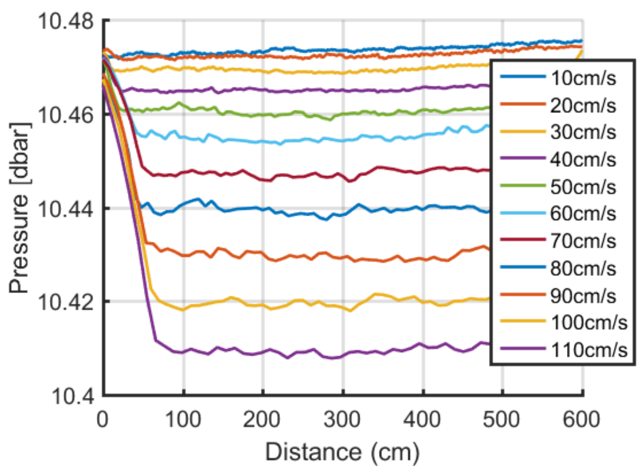

Figure 2. Pressure data from FlowTracker2 probe while being towed at various velocities.

The probe itself was fixed at a constant depth throughout all the velocity runs. As predicted by Equation 1, increasing the flow speed produces a decreased measured pressure. At a speed of 1m/s, the measured pressure reads about 0.05dbar lower than when there is no flow, producing an equivalent water depth offset of about 5cm. This offset is speed-dependent and must be compensated to measure the water depth accurately. The FlowTracker2 is uniquely poised to apply the compensation due to its highly accurate velocity measurement.

B. Pressure Correction Coefficient Derivation

The measured pressure, P_m, must be corrected to P_c, the corrected pressure. Assuming P_m includes the Hydrostatic Pressure term in Equation 1, we can write the corrected pressure P_c as

[2] $$P_c = P_m + b\rho v^2,$$

where b is the pressure correction coefficient to account for the Bernoulli Effect.

C. Density Compensation for Temperature, Salinity, and Altitude

The last term in Equation 2 represents the dynamic pressure correction, which is dependent on the fluid density, ρ. Typically, fluid density depends on temperature and salinity. Temperature measurements from the FlowTracker2 probe's built-in temperature sensor are used to calculate ρ, unless a user-input temperature is given. Likewise, if a salinity is input by the user, this value will be included in the density calculation. Otherwise, the default salinity is 0 (freshwater). The density of a fluid in the field also varies with the gravitational variation of the geoid at a specific geographic location; using the FlowTracker2's GPS function, if a GPS location is recorded, the final density value will compensate for the latitude and altitude where the measurement is taken. In this way, the FlowTracker2 calculates an accurate density value which is necessary for calculating b, and also is required to determine the speed of sound during an actual measurement in the field.

D. Calculating b from Tow Tank Data

To obtain b from Equation 2, we take an empirical approach using data collected from towing tanks which have a known reference speed to fit a correction coefficient specific to the probe head geometry. P_c from Equation 2 is the value of measured pressure when the probe is not moving, and $P_m$is the measured pressure recorded by the probe when it is being towed. We expect that the pressure correction will vary with the shape of the probe, so the formulation of b into a lumped correction coefficient takes this aspect into account. Different probe heads (2D or 3D) will have a different b value associated with them.

Measurements for the determination of b were made at towing tanks both at the SonTek factory as well as at the USGS Hydrological Instrumentation Facility (HIF). For more details on the HIF towing tank facility, please see the FlowTracker2 Tow Tank Verification Report (contact SonTek for details). As mentioned in this document, it was critical to perform velocity runs over the same section of the tank for every velocity run to eliminate variability caused by physical tank influences (tank track geometry, overhead air vents, etc.). The tow tank runs performed at the HIF covered speeds from 0.3ft/s (~0.1m/s) to 13.2 ft/s (~4.1m/s) at 0.3ft/s (~0.1m/s) increments. This velocity range was chosen because it covers the full range of the FlowTracker2 velocity measurement capability. Only pressure data from tows running in the forward direction (with respect to the probe) are used in the analysis.

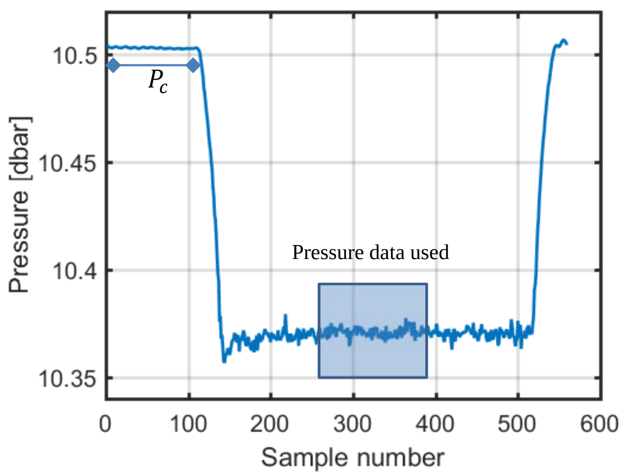

Figure 3. Pressure data for velocity run at 6ft/s (1.88m/s).

The goal is to use the towing tank data to develop a relationship between measured pressure and towing velocity. Figure 3 shows an example of pressure data from one towed run at 6ft/s (1.88m/s). The corrected pressure, P_c, is the average value of pressure when the probe is not moving, and is equal to the Hydrostatic Pressure. To eliminate ramp up and down effects during the each tow, the center 1/3 of the pressure data are used to calculate a mean P_m associated with that velocity. These mean pressure measurements are plotted against the tow cart velocity with yellow circles in Figure 4.

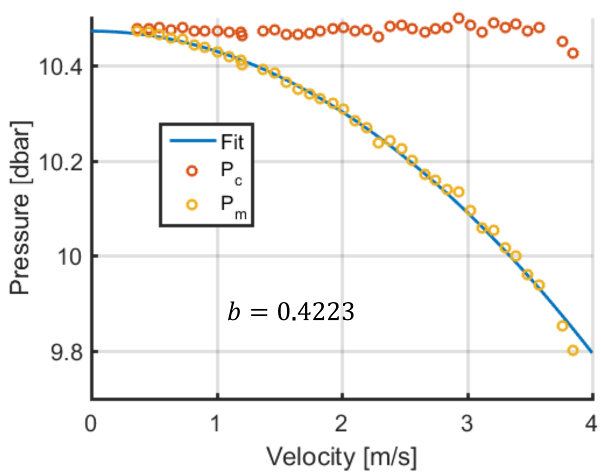

Figure 4. Mean pressure versus tow cart velocity for HIF tow tank runs. Yellow circles represent actual measurements ($\boldsymbol{P_m}$). The blue line is Equation 2 plotted with a linear regression to determine $\boldsymbol{b}$. The red circles represent the corrected pressure, $\boldsymbol{P_c}$.

The parabolic relationship between measured pressure and velocity shown in Figure 4 justifies our use of Equation 2, which predicts the Bernoulli Effect on measured pressure will increase as the speed squared. The pressure correction coefficient b is determined by the linear regression of Equation 2. The fit is shown by the blue line in Figure 4. In this set of tow tank runs, $b = 0.4223$. Values of b from different sets of tow tank runs at the HIF and at the SonTek factory were averaged. To verify the modeled correction, P_c is calculated and plotted with red circles in Figure 4. The corrected pressure values now do not exhibit a dependence on velocity, and the Bernoulli Effect is removed to obtain the proper depth measurement. During an actual measurement, the term $b\rho v^2$ in Equation 2 is calculated in real-time to produce the corrected pressure, P_c.

IV. FlowTracker2 Measurements Using Pressure Sensor Versus Traditional Wading Rod Depth Measurement

To show the validity of the pressure sensor correction and use, we show a discharge measurement that incorporated both manual wading rod readings as well as a pressure sensor reading. A measurement was taken at USGS Site 09522600 near Yuma, AZ (pictured in Figure 5).

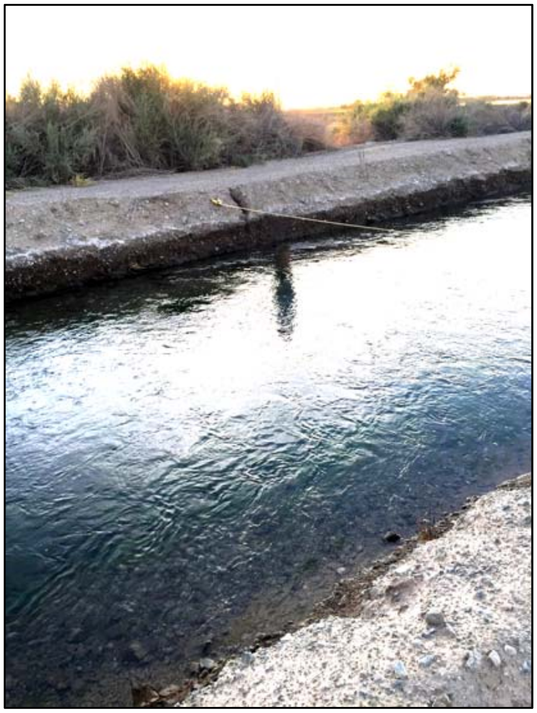

Figure 5. USGS Gauging Site 09522600

At each station location, the depth was recorded using the pressure sensor as well as using the wading rod. The depth profiles obtained over the transect are plotted in Figure 6. Depths across the transect using both methods are the same within the margin of error of a manual wading rod depth reading.

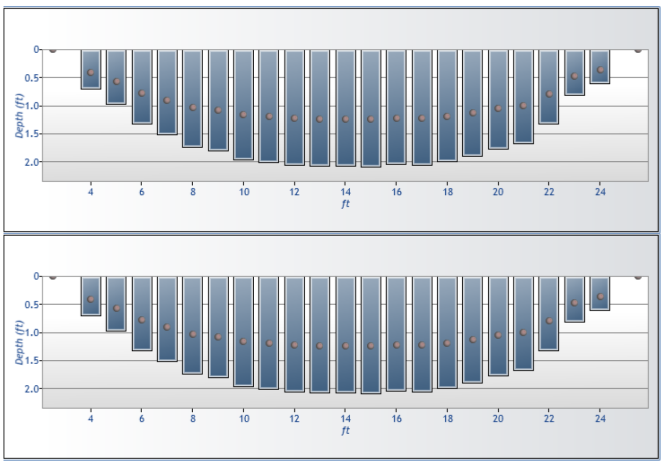

Figure 6. Depth at each station at USGS Site 09522600. The top plot represents depths recorded by the pressure sensor. The bottom plot uses depths read off manually with the wading rod.

The discharges calculated from the two methods are compared to the Rated Discharge reported at this site from the USGS gauging station, and are summarized in Table 1.

Table 1. Comparison of discharge values obtained from USGS Rating, FT2 using pressure sensor, and FT2 using wading rod.

	USGS Rated Discharge	FT2 using pressure sensor	FT2 using wading rod depth
Discharge (CFS)	58	57.0438	57.1779

Discharge values are within 2% of one another, showing that the substitution of the wading rod with the pressure sensor for a depth measurement is an accurate method for taking discharge measurement using the FlowTracker2.

V. Conclusion

This technical note serves to explain how the FlowTracker2 Pressure Sensor option and patent-pending dynamic pressure correction were implemented. The pressure sensor option provides an automatic water and probe depth reading which can standardize and streamline measurements in the field. It also offers an accurate depth reading in situations where a manual wading rod depth reading is impractical or impossible.