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Technical Paper

Underplayed Ultrasonic Meter Diagnostic Capabilities – A Pattern Recognition Case Study

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1 INTRODUCTION

As part of various on-going consultancy contracts throughout the Middle East, starting in 2018 Kelton consulted on the calibration and Site Acceptance Tests (SAT) of a set of carbon steel Honeywell Q Sonic-Max 8-path ultrasonic meters (see Figure 1) for a gas transmission network. Whereas the calibration of such meters are often witnessed in person, Covid 19 travel restrictions dictated that these meter calibrations be witnessed by less effective remote monitoring. Furthermore, on the meters arrival at site the installation date was delayed causing these meters to have an unplanned storage for several months.

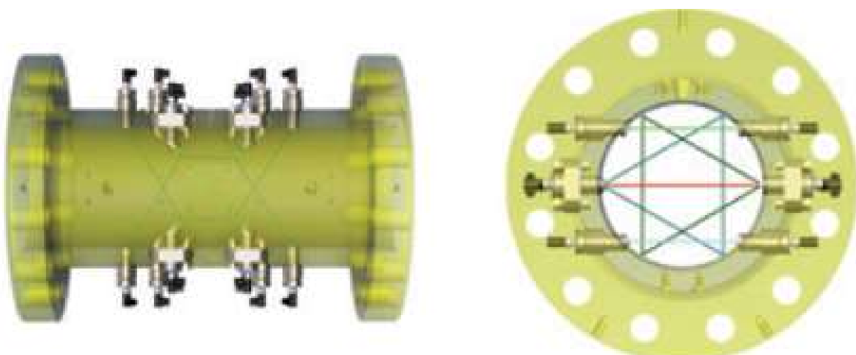

Figure 1. Honeywell Image of the Q Sonic-Max 8-path Ultrasonic Meter.

The consequence of these changed plans caused issues which resulted in discussion on the nature and utility of ultrasonic meter diagnostic suites. Specifically, during the SAT it was found that the meters had corroded during storage. This lead to a review of the calibration vs. SAT diagnostics results, the ISO 17089 diagnostic statements, objective vs. subjective diagnostic parameters, diagnostic check alarm thresholds, or lack thereof, and diagnostic pattern recognition capabilities, or lack thereof. Although several of this project's meters were similarly affected, for brevity, and as it serves to express this projects findings satisfactorily, a single 4" meter case study is hereby discussed.

2 Laboratory Calibration and ISO 17089 Calibration Stipulations

Although at the time of the meter SAT ISO 17089 (2019) was published the project contract was signed in 2017 making ISO 17089 (2010) the contract's stipulated standard. ISO 17089 (2010) Section 6.3.3 titled "Judging the Measurement Quality of the Meter" states:

"*The judgement of the measurement quality of the meter **should** therefore be based on the combination of the calibration curve and a linear* offset ***only***."

That is, ISO 17089 (2010) advises that the *only* consideration on whether an ultrasonic meter has acceptable calibration performance is whether the 'calibration curve' falls within the ISO stipulated allowable performance range for the meter class, as seen in Figure 6, or not. ISO 17089 (2019) Section 6.3.3 titled "Judging the Measurement Performance of the Meter" subsequently states:

"*The judgement of the measurement performance of the meter* ***shall*** *be based on the combination of the calibration curve and a linear offset related to the flow-weighted mean error (FWME)* ***only***."

That is, the ISO 17089 (2010) suggests and ISO 17089 (2019) subsequently mandates that an ultrasonic meter calibration performance is to be judged solely on the calibration curve, i.e. the comparison of the meter to laboratory predicted reference flowrates. The practical consequence of this is if using ISO 17089 the diagnostic suite output is not required to be considered when judging calibration meter performance[1]. Hence, strictly speaking, an ultrasonic meter's diagnostic suite can be in alarm during calibration and the ISO 17089 text effectively states this should not be taken into account when analyzing the calibration results.

Nevertheless, ISO approves of the ultrasonic meter diagnostics. For example, the introduction of both ISO 17089 (2010 and 2019) says:

"USMs can deliver extended diagnostic information through which it may be possible to demonstrate the functionality of an USM." And "Due to the extended diagnostic capabilities, this document advocates the addition and use of automated diagnostics instead of labour - intensive quality checks."

ISO 17089 (2010) Section 7.6.2 titled 'Recalibration interval' states: '*The interval between successive recalibrations depends upon a number of issues including: e) the interpretation of diagnostic information'*. ISO 17089 (2019) Section 8.8.2 titled 'Service Related Diagnostics' states: *"… it is recommended that diagnostic log files and signal waveform captures are obtained both for reference and assistance in diagnosing any meter or process related issues"*. Hence, it would be somewhat contradictory of ISO to deliberately say the ultrasonic meter diagnostic system is a capable and required component in the judgement of when re-calibration is required, but not a capable and required component in the judgement of the re-calibration results. Furthermore, ISO 17089 (2010) Sections 6.3.2.10.2 / 3 states *all* data taken at the calibration, including diagnostic parameters SoS and transducer S/N, are to be recorded, while ISO 17089 (2019) Section 6.3.4.2 goes further by explicitly stating all diagnostics data taken during calibration shall be recorded. Hence, again, it would be somewhat contradictory to explicitly say ultrasonic meter calibration diagnostic data is to be recorded but never used.

ISO Section 6.3.3 is not legally ambiguous; it explicitly excludes all forms of calibration performance analysis other than the calibration curve, inclusive of the meter's diagnostic suite. However, when read in context to the overall document it is clear that the "*sprit, if not the letter of the law"* is such that this statement is singularly aimed at prohibiting any data fitting techniques being applied before the primary meter performance analysis is conducted. Data fitting manipulates raw data and could mask underlying fundamental issues. Most ultrasonic meters during calibration are fully serviceable, with clean single phase gas and a fully developed flow profile. It is uncommon for there to be a diagnostic alarm during calibration. Hence, there is often a presupposition when assessing new ultrasonic meter calibration data that the diagnostic system will not be in alarm. Therefore, the intent of this ISO 17089 Section 6.3.3 clause is certainly to prohibit data fitting before analysis of the meter calibration performance, but almost certainly not meant to prohibit consideration of the calibration diagnostic suite results.

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[1] AGA 9 (2022) Table 1 does insist the calibration MSoS is checked to be < 0.5 m/s and the average MSoS agrees with the theoretical Sos (TSoS) to within 0.2% before the calibration data is deemed accepted. AGA 9 does not require any other calibration diagnostic parameter to be checked. Nevertheless, the AGA inclusion of this single diagnostic check at calibration is beneficial. This example shows that there are subtle important differences between ISO 17089 and AGA 9 standards, and procedures can be subtly different depending on which standard is stipulated in a contract.

Nevertheless, although logged, neither ISO 17089 (2010) nor (2019) stipulate that calibration diagnostic results must be analyzed or be part of a calibration report. There is no ISO stipulation that an ultrasonic meter calibration report has to include the diagnostic results. In this case the laboratory calibrated the meter in full adherence to the ISO calibration stipulations but did not present the diagnostics in the calibration report. As will be seen, this lead to valuable information regarding the meter's performance during calibration being initially unnoticed.

3 Meter FAT and Calibration Results

The meter was supplied to a reputable blinded test facility after passing the manufacturer's Factory Acceptance Test (FAT). Figure 2 shows the manufacturer's FAT document. The meter was no flow tested with 100% nitrogen at 10.43Bar and 22.67^{0}C. The equation of state (EoS) calculated the speed of sound (SoS) to 352.17 m/s. The average SoS measured by the six chordal paths is reported as 352.17 m/s, i.e. exactly the same result to two decimal places. The largest deviation was with chords 2 and 6 which only deviated from the EoS result by 0.01 m/s / 0.003%. ISO 17089 (2019) states the allowable difference in EoS and meter SOS readings is < 0.2%. This ultrasonic meter's chordal paths passed the SoS check.

Item	Description
1	Dimensional Inspection of the US gas flow meter. Visual Inspection of meter configuration and name plates.
2	Preparation of FAT: - Isolation of US gas flow meter (blind flanges). - Pressurized with: 100,0% N2 - Test pressure: 10,43 bara - Test temperature: 22,67 degrees C - Calculated velocity of sound: 352,17 m/s
3	Execution of FAT: - Installation of meter parameters. - Monitoring and logging of zero flow test. - Measured mean velocity of sound: 352,17 m/s - Measured per path: 1: 352,17; 2: 352,18; 3: 352,17; 4: 352,17; 5: 352,17; 6: 352,18 - Measured mean flow velocity offset: 0,000 m/s
4	Final Inspection completed.
5	Preservation and packaging completed.

Figure 2. Manufacturer Factory Acceptance Test Document.

However, this Honeywell Q Sonic-Max 8-path ultrasonic meter also has two reflective (aka 'bounce') paths that have not been included in the FAT. The manufacturer states in the meter's sale collateral that: "*The reflective paths with their sophisticated diagnostics mean the meter quickly identifies swirl, fouling or liquids inside the meter.*" It is not known why the FAT, which is conducted specifically to check the meters functionality, does not include two paths stated by the manufacturer to be very appropriate for such a task. As will be seen, later events were such that the logging and documentation of the reflective path results at the FAT would have been beneficial.

Figure 3 shows the meter being calibrated. The plate has been blacked out to maintain the blinded nature of the project. Figure 4 shows the manufacturer drawing indicating the meter pressure tap is downstream of the transducers. Hence, flow in Figure 3 is right to left. Figure 5 shows that the meter under calibration had a long straight inlet run to assure a fully develop flow profile as required.

Figure 6 shows the calibration result as required by ISO 17089 (2010 and 2019) for the 0.5 class meter. The results are well within the ISO stipulated boundaries.

As discussed in Section 2, ISO 17089 stipulates that an ultrasonic meters calibration result is 'judged' solely by the calibration curve, and nothing else. Hence, the results shown in Figure 6 is a success, the meter has performed acceptably at the calibration.

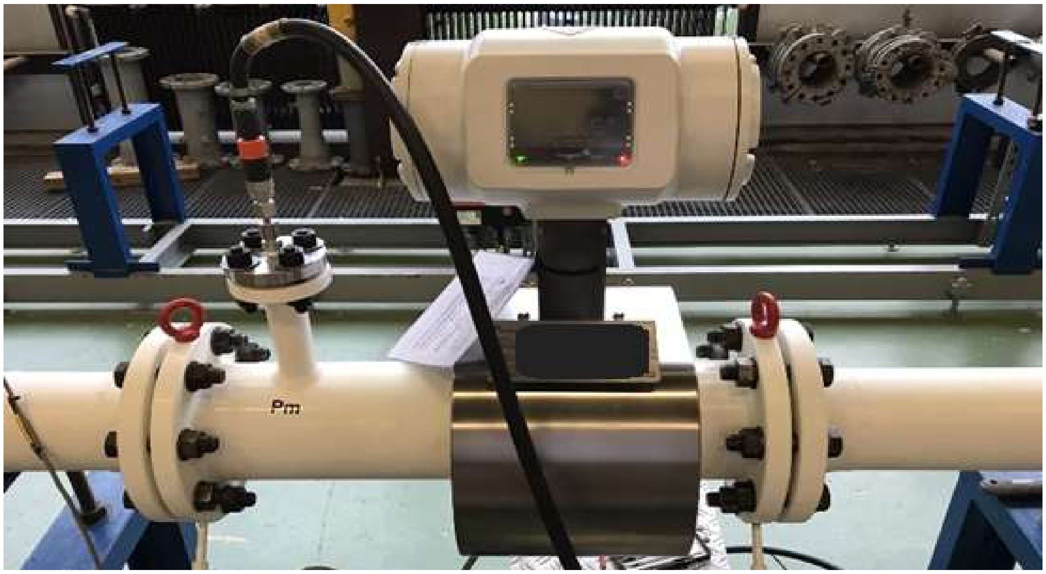

Figure 3. The 4" Honeywell Q Sonic-Max 8-path Ultrasonic Meter Installed at Calibration Facility.

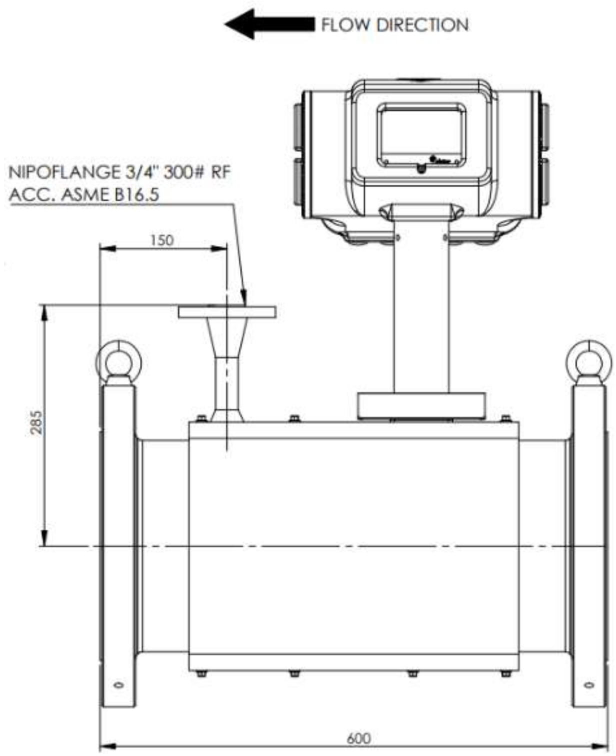

Figure 4. Schematic of Ultrasonic Meter

Hence, the meter was shipped to site. The diagnostic results had been duly logged but not analysed. Again, as discussed in Section 2 there is no ISO mandated need for the calibration diagnostic results to be checked.

Figure 5. Overview of Calibration Inlet Run.

Kelton would usually have witnessed such a calibration, and in the process review the live calibration diagnostic data. However, due to Covid 19 it was not possible to witness in person. Witnessing opportunity was reduced to remote witnessing from a significantly different time zone with intermittent internet access. The live diagnostics were not readily viewable. The calibration diagnostic log was to be sent after the meter had been shipped to site.

On arrival at site Covid 19 had caused the project timeline to slip. The carbon steel meters were put in local storage until they were required. They were retrieved and installed several months later. The fitters that installed them did not inspect the meters, but rather installed them as found out the storage. The SAT then commenced.

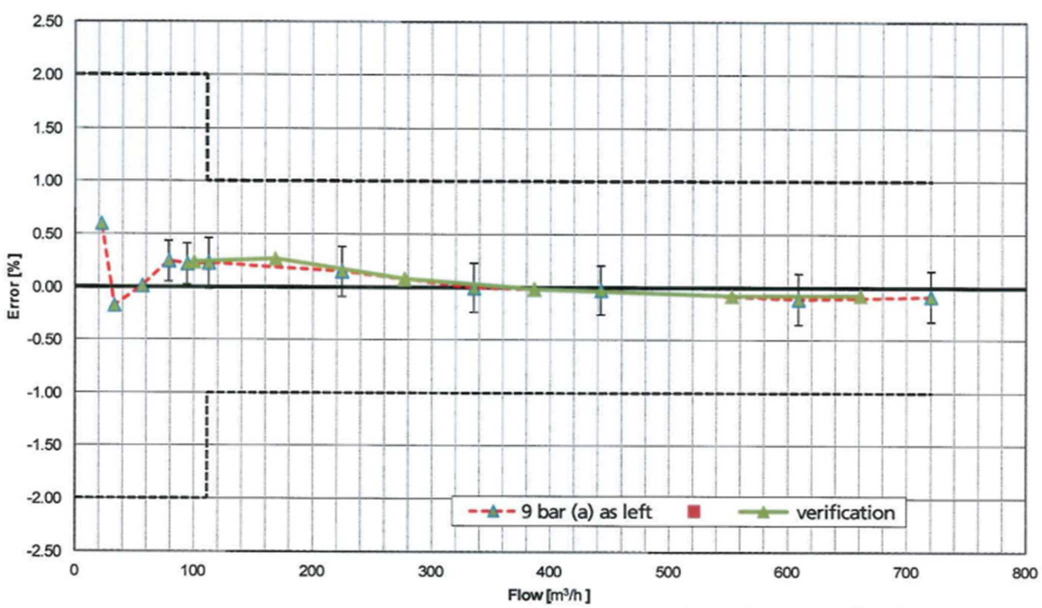

Figure 6. 4” Honeywell Q Sonic-Max 8-path Ultrasonic Meter Calibration Result.

4 Field Commissioning Issues

On commencement of commissioning the 4” Q Sonic-Max 8-path ultrasonic meter diagnostic system immediately went into alarm. Figure 7 shows a sample data set of the eight paths SoS readings. A chordal path (D-LT) and a reflective path (B1CCW) have SoS readings that differ by an average of 0.85 m/s (0.19%). Two chordal paths (D-LT and D-RT) have SoS readings that differ by an average of 0.55 m/s (0.12%).

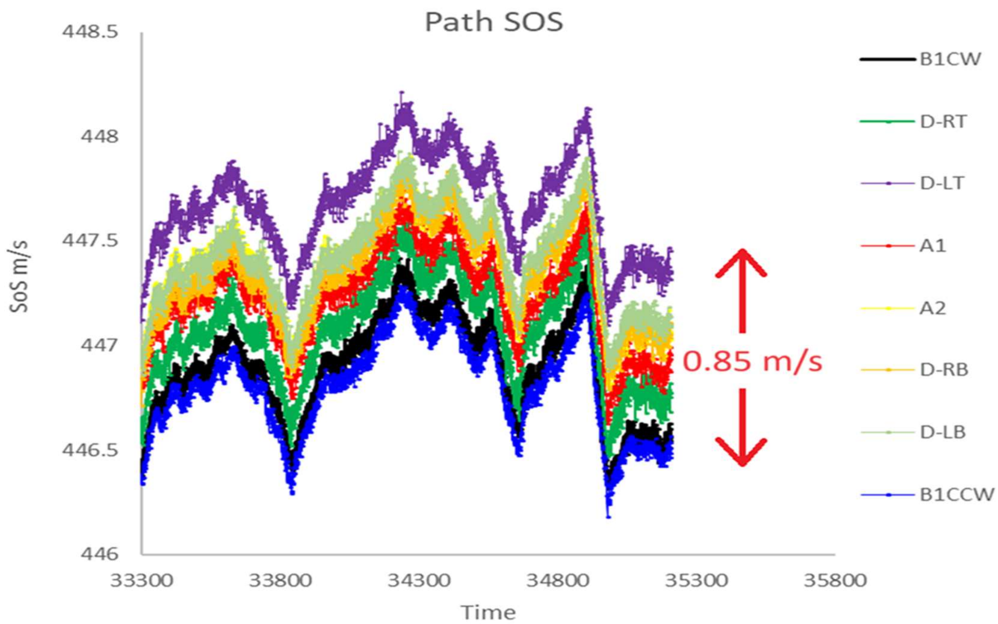

Figure 7. 4” Honeywell Q Sonic-Max 8-path Ultrasonic Meter Commissioning Path SoS Results.

ISO 17089 (2010) does not state any MSoS diagnostic alarm thresholds. However, ISO 17089 (2019) Section 5.8.2 on accuracy requirements states a multipath ultrasonic meter’s paths shall have a SoS reading difference ≤ 0.5 m/s. ISO 17089 (2019) Section 8.7.1 then states the ‘MSOS Ratio comparison’, i.e. meaning the difference between any two path SoS readings, is to be < 0.2% for no warning, between 0.2% and 0.3% for a warning, and > 0.3% for an alarm.

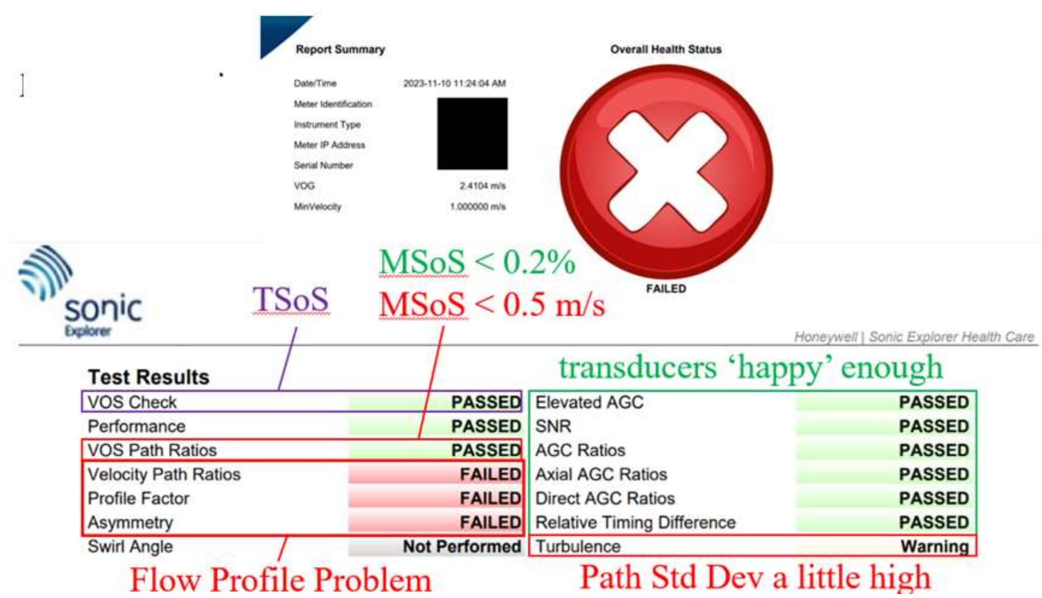

Figure 8. 4” Honeywell Q Sonic-Max 8-path Ultrasonic Meter Diagnostic Report Summary.

These two ISO 17089 (2019) stipulations appear to discuss the same meter output, i.e. two path’s SoS readings, but give different alarm thresholds. A difference of 0.5 m/s is not equivalent to a 0.2%. For example, during commissioning of the meter path B1CCW read

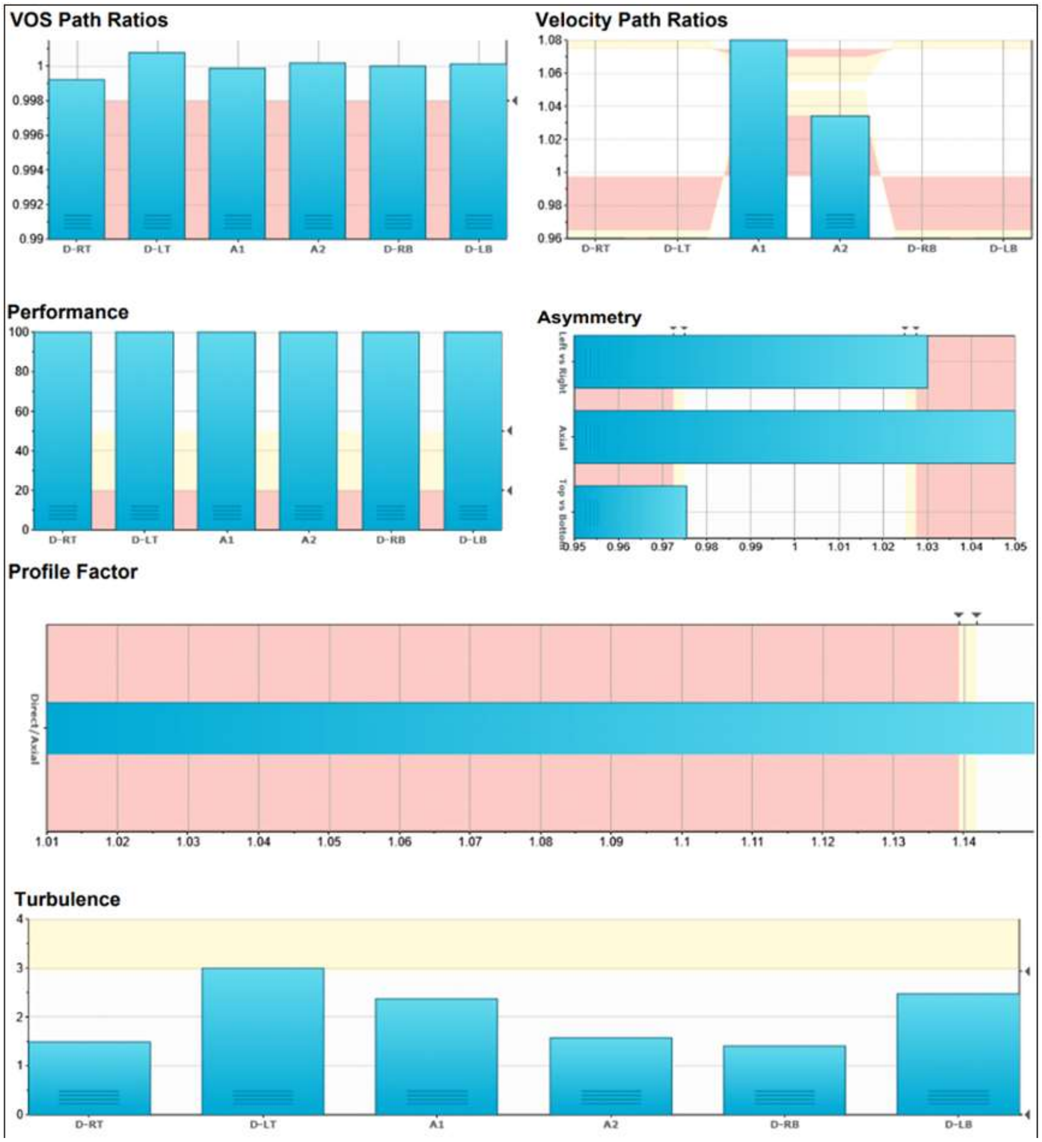

Figure 9. Detailed Flow Meter Diagnostic Report.

447.6 m/s, path D-LT read 448.5 m/s. The difference is 0.87 m/s while the difference is 0.19%. In general, during the commissioning there was a path difference > 0.5 m/s which corresponds to a ISO 17089 (2019) Section 5.8.2 alarm, while the same data had a percentage difference < 0.2% which corresponds to ISO 17089 (2019) Section 8.7.1 giving no warning. It is not clear why ISO 17089 (2019) has two distinct and different MSoS diagnostic threshold criteria? Nevertheless, normal operation of a multipath ultrasonic meter has the performance well inside the tighter of these two alarms, i.e. the < 0.5 m/s, and therefore this is a bona fide diagnostic alarm.

Figure 7 shows the reflective paths had notably lower SoS readings than the six chordal paths. It was decided by operators at the SAT to disable the reflective paths and operate with the six chordal paths only. The meter diagnostic system still showed alarms. A SAT diagnostic report was printed. Figure 8 shows the results summary for the six chordal paths only, with comments superimposed by Kelton.

The primary result of the "Overall Health Check" is a fail. Let us go through the diagnostic checks in turn. It is notable that the meter has passed the SoS Check (called Velocity of Sound, i.e. 'VOS' by Honeywell). This may superficially seem at odds with Figure 7, but it should be noted that there are two ultrasonic meter MSoS checks. There is the comparison of the Theoretical Speed of Sound (TSoS) found from an equation of state with the meters average read speed of sound (MSoS), and then there is the intercomparison of the different individual path SoS readings. It is understood that the 'VoS check' in Figure 8 is the TSoS to MSoS comparison, and this indeed is a pass. Of more note is the 'VoS Path Ratios' result. This is the comparison of pairs of path SoS readings. The diagnostic report says this is a pass. Hence, it is likely this check considers ISO 17089 (2019) Section 8.7.1's warning threshold of ≥ 0.2%. In that respect this meter did pass. However, if ISO 17089 (2019) Section 5.8.2 threshold of ≥ 0.5 m/s was considered this diagnostic check would produce an alarm. Even with the reflective paths disabled there is still a ≈ 0.55 m/s difference.

The velocity profile checks are in alarm. Clearly something is disturbing the flow. The transducer diagnostic checks, e.g. auto gain control (AGC), Signal to Noise Ratio (S/N), performance, and relative timing difference are all seen to be operating correctly. Only the 'turbulence', i.e. the standard deviation in Δt signals, hints at an issue giving a warning, i.e. the level below alarm.

5 Field Inspection

Due to the diagnostic alarms the meter was removed from the system. Figure 10 shows a photograph looking upstream inside of the meter; the transducers can be seen at the entrance to the meter body. The meter body material is corroded. This is a consequence of purchasing carbon steel meters coupled with inappropriate preservation procedures.

Figure 11 shows corrosion particulate that was analysed and shown to be Fe_2O_3 magnetite, i.e. common carbon steel rust. Figures 12 and 13 show the removed flow conditioner and a removed transducer respectively. They have a very light dusting of rust, but not nearly enough to induce any noticeable performance issues.

CAPEX is saved by purchasing carbon steel meters instead of stainless-steel, but at the cost of extra OPEX. ISO 17089 (2010 and 2019) Section 5.2.10 states "Immediately after production, the inner surface of the meter, spool pieces, and flow conditioners should be protected from corrosion". ISO 17089 (2010 and 2019) Section 5.9.4 says "consider post-production protection of the meter and spools against corrosion by purging with inert gas prior to transport". These statements may seem obvious, but they are important, the process needs to be done thoroughly and properly and failure to do so can have significant later operational and financial consequences.

It was noted from the SAT diagnostic results that the transducer D-LT seemed to be the source of the highest level alarms. It was decided to replace this transducer (see Figure 13) and carry out a no-flow nitrogen test. Figure 14 show the results. Replacing the D-LT transducer had no effect on improving the meter performance. In fact, the SoS diagnostic results were now marginally worse. The maximum spread of SoS between the meters was 0.84 m/s but now with the lower nitrogen SoS the MSoS ratio was 0.23%, i.e. now within the ISO 17089 (2017) warning range of 0.2 < speed (m/s) < 0.3. Hence, the issue is not due to a faulty transducer but most likely corrosion based.

Whereas it was accepted the meter was compromised in terms of flowrate prediction uncertainty, there were no readily available replacement available at short notice, the meter was not corroded enough to cause any pressure vessel concerns and the end user needed an interim metering solution. It was decided to continue to operate the meters until replacements were available. It was at this juncture that the original calibration diagnostic data was retrieved.

Figure 10. Photograph of Inside of Meter After Being Uninstalled.

Figure 11. Rust Particulate Removed from Inside of Meter

Figure12. Removed Flow Conditioner with Light Rust Dusting

Figure 13. Removed Flow Conditioner with Light Rust Dusting

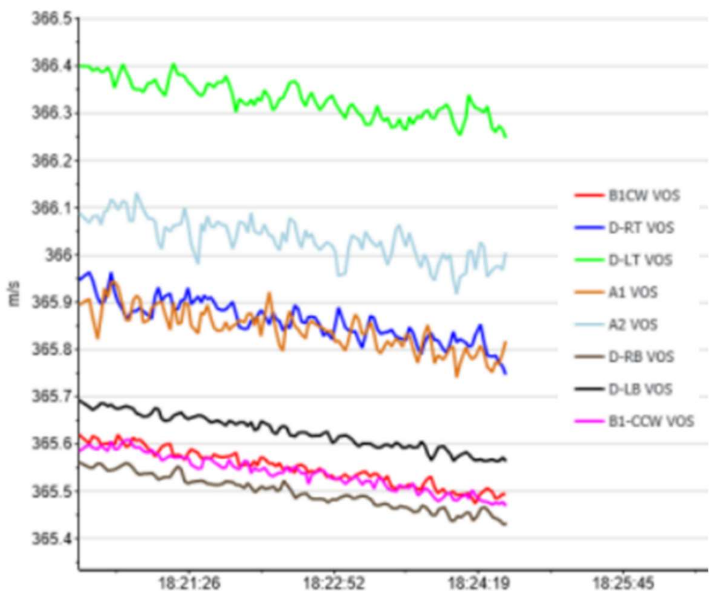

Figure 14. 4” Honeywell Q Sonic-Max 8-path Ultrasonic Meter On-Site No Flow Nitrogen Test SoS Results.

6 Calibration Diagnostic Data

Figure 15 shows a screenshot of a diagnostic result captured during calibration and supplied to Kelton after the SAT issues. Figure 16 magnifies the data summary. The meter had diagnostic alarms during calibration.

In normal low noise applications the performance of each path, i.e. the percentage of the transducer’s initiated to received signals, should be close to 100%. It is typical for a path performance to be considered valid down to 20%, although such a degraded performance is expected if there is noise attenuating all signals. In such applications it would be expected that all paths have similar low performance. However, here the performance of the reflective paths B1CW and B1CC are 61.67% and 98.22% respectively. It is the difference in performance that is of diagnostic interest here. This is a notable performance difference between the reflective paths and as such the reason is unlikely to be noise.

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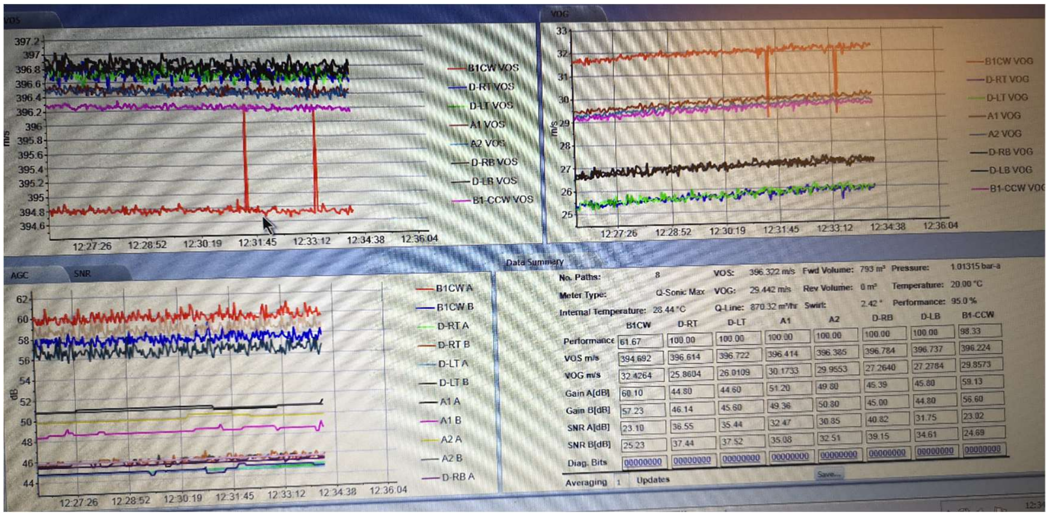
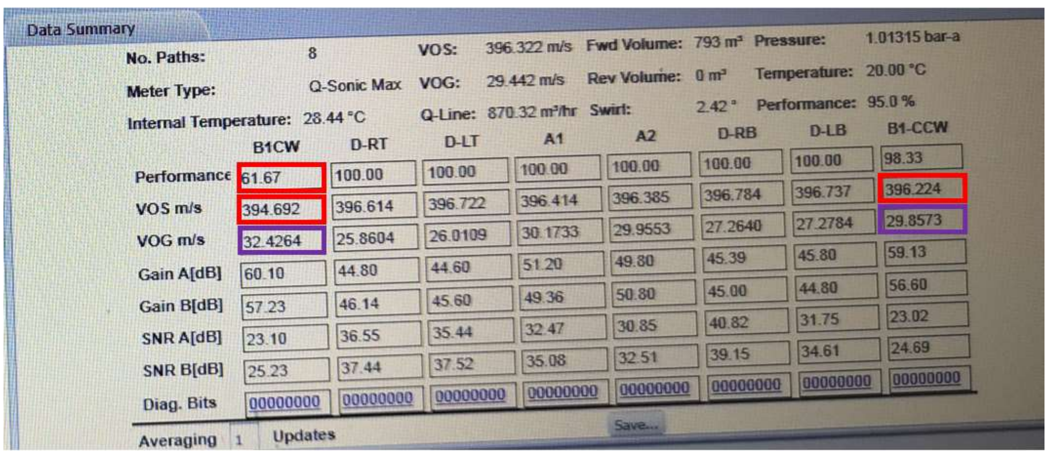


Figure 15. Screenshot of the Ultrasonic Meter's Diagnostics Output During Calibration.


Data Summary

No. Paths: 8 VOS: 396.322 m/s Fwd Volume: 793 m³ Pressure: 1.01315 bar-a
Meter Type: Q-Sonic Max VOG: 29.442 m/s Rev Volume: 0 m³ Temperature: 20.00 °C
Internal Temperature: 28.44 °C Q-Line: 870.32 m³/hr Swirl: 2.42 ° Performance: 95.0 %

	B1CW	D-RT	D-LT	A1	A2	D-RB	D-LB	B1-CCW
Performance	61.67	100.00	100.00	100.00	100.00	100.00	100.00	98.33
VOS m/s	394.692	396.614	396.722	396.414	396.385	396.784	396.737	396.224
VOG m/s	32.4264	25.8604	26.0109	30.1733	29.9553	27.2640	27.2784	29.8573
Gain A[dB]	60.10	44.80	44.60	51.20	49.80	45.39	45.80	59.13
Gain B[dB]	57.23	46.14	45.60	49.36	50.80	45.00	44.80	56.60
SNR A[dB]	23.10	36.55	35.44	32.47	30.85	40.82	31.75	23.02
SNR B[dB]	25.23	37.44	37.52	35.08	32.51	39.15	34.61	24.69
Diag. Bits	00000000	00000000	00000000	00000000	00000000	00000000	00000000	00000000

Averaging 1 Updates Save...

Figure 16. Diagnostics Data Summary During Calibration with Superimposed Highlights.

Further evidence of a path issue during calibration is seen in the comparison of reflective path SoS (ΔMSoS) and velocity (ΔVoG) readings. The SoS difference between paths B1-CCW and B1-CW is ΔMSoS = 396.2 m/s - 394.7 m/s = 1.5 m/s, i.e. 0.38%. The velocity difference between paths B1-CCW and B1-CW is 29.9 m/s – 32.4 m/s = -2.5 m/s. ISO 17089 (2010) does not give warning or alarm thresholds, but ISO 17089 (2019) Section 5.8.2 states the difference in SoS measured between paths that initiates an alarm is > 0.5 m/s, while Section 8.7.1 states the SoS measured between paths that initiates an alarm is > 0.3%, or > 0.2% to initiate a warning. Hence, the calibration diagnostic results show path B1CW is in alarm. Furthermore, for fully developed flow the correctly operating B1CW and B1CCW paths should have nominally identical velocity results. The respective velocity readings should not differ by -2.5 m/s. Finally, it was noted that when considering the six chordal paths only there is no clear and obvious diagnostic alarm. Hence, during the calibration there is clearly an issue with the B1-CW path.

Nevertheless, the SAT diagnostic results does not show any performance problem with B1-CW path, the performance of paths B1-CW and B1-CCW match closely throughout the 48 hr SAT data set. Figure 17 shows a sample representative SAT data set comparing the reflective paths MsoS over a period of time. That B1-CW path problem evident at the calibration is not present during the SAT. The SAT diagnostic results showed a velocity profile issue, not a path performance issue (see Figure 9). The reason for this B1-CW issue at calibration is unknown;

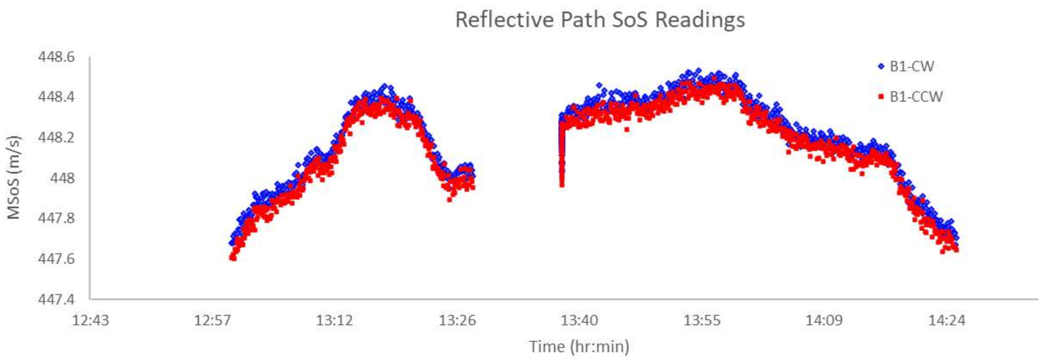


Figure 17. 4” Honeywell Q Sonic-Max 8-path Ultrasonic Meter
Reflective Path MSoS Comparison

it would have been better to analyse the calibration diagnostic data at the time of the calibration and find the issue at that time.

In summary, ISO 17089 does not stipulate an ultrasonic meter’s calibration diagnostic data must be analysed at the time of the calibration, only recorded. Even if it did, ISO 17089 offers limited guidance on specific diagnostic parameter alarm thresholds, i.e. what result constitutes a meter anomaly and what does not? For example, there is nothing in ISO 17089 that states a B1-CW and B1-CCW path performance difference of 61.67% and 98.33% constitutes the meter diagnostic system being in alarm. That is left to manufacturer default settings or operator engineering judgement. The ΔMSoS > 0.5 m/s & ΔMSoS > 0.2% crosses an ISO 17089 diagnostic alarm threshold but there is no equivalent for path performance or the other ultrasonic meter diagnostic parameters.

Although the meter was to be replaced, through necessity the meter would remain in place until the new meter was available. The reflective paths were disabled, and the meter continued to operate with the six chordal paths only, with the diagnostics as per Figure 9, i.e. with a flow profile alarm and a ‘turbulence’ warning.

7 Ultrasonic Meter Diagnostic Suite Pattern Recognition

The ultrasonic meter’s diagnostic system identified an unspecified problem existed at the SAT, but did not state what the specific problem could be. The specific problem was only identified manually, after the SAT was completed and the meter was removed for inspection. However, could ultrasonic meter diagnostic suite pattern recognition be applied?

There is little in the public literature about how to interpret ultrasonic meter diagnostic results. Such capability would be very beneficial to industry. ISO 17089 (2010) has a Pattern Recognition table (see Figure 18). ISO 17089 (2019) develops this (see Figure 19). There are a few changes between 2010 and 2019. The diagnostic parameter ‘turbulence’, i.e. ‘standard deviation’ of the Δt signal has been added, the name ‘Performance’ is changed to its technical name ‘Signal Acceptance’, and the ISO committee has changed its mind on a ‘S/N’ alarm being present with fouling.

Does this ISO pattern recognition table (Figure 19) predict a corroded meter from the diagnostics alone? The first hurdle is what constitutes each ultrasonic meter diagnostic parameter being in alarm, i.e. what are the alarm thresholds? It is all well and good giving a ultrasonic meter diagnostic pattern recognition table, but this is only useful once it is decided what result constitutes each parameter being in alarm or not in alarm. That is, what are the alarm thresholds!? ISO 17089 does not give a comprehensive list of diagnostic parameter alarm thresholds. There are several diagnostic parameters where no threshold is proposed. However, this subject is well worth study and R&D by ultrasonic meter proponents.

Relational diagnostic diagram	Performance	Automatic gain control per path	S/N per path	SOS per path	Flow velocity per path
Transducer failure	×	×	—	×	×
Detection problems	×	×	—	×	×
Ultrasonic noise	×	×	×	—	—
Process conditions pressure	—	—	×	—	—
Process conditions temperature	—	—	—	×	—
Fouling	×	×	—	×	×
Changes in the flow profile	—	—	—	—	×
High velocity	×	×	×	—	—

Figure 18. ISO 17089 (2010) Pattern Recognition Table.

Relational diagnostic	Per path					
	Signal Acceptance	Automatic gain control	S/N	MSOS	Flow velocity	Standard Deviation
Transducer failure	×	×	—	×	×	×
Detection problems	×	×	×	×	×	×
Ultrasonic noise	×	×	×	—	—	—
Process conditions pressure	—	×	×	—	—	—
Process conditions temper-ature	—	—	—	×	—	—
Fouling	×	×	×	×	×	×
Changes in the flow profile	—	—	—	—	×	×
High velocity	×	×	×	—	—	×

Figure 19. ISO 17089 (2019) Pattern Recognition Table.

In order to learn more from ultrasonic flow meter diagnostics it is first necessary understand more about ultrasonic meter diagnostics. All flow meter diagnostic suites tend contain both subjective and objective diagnostic tests.

An objective diagnostic check can be defined as a check derived from comparison with physical law. It is not derived from comparison with intuition, opinion, or some general rule of thumb set by experience. It compares a measurable diagnostic value to a baseline fixed by physical law, thereby creating an absolute numerical result. It is a clear and precise diagnostic statement. Objective diagnostic tests are useful for measuring both absolute changes and monitoring relative changes in a system's performance.

In practice no diagnostic test is entirely objective. All instrumentation readings have uncertainties that are subjective. Hence, even theoretically objective diagnostic tests have an element of subjectivity. Nevertheless, in practice this is not too problematic. The influence on theoretical objective results of the instrument uncertainties are small, often trivial.

Parameters found by calibration can be considered objective. A key axiom in science can be paraphrased as: "Whatever is true of everything we've seen here and now is true of everything everywhere in the future". If the flow meter remains physically unchanged, and the installation between the calibration and field application is effectively the same, then the flow meter's output will remain unchanged. Therefore, if a calibration parameter result is reproducible between calibration and the field, e.g. an ultrasonic meter's profile factor, then it is effectively an objective result. However, if a calibration parameter result is not reproducible between calibration and the field, e.g. an ultrasonic meter's path Automatic Gain Control, then it is a subjective diagnostic result.

A subjective diagnostic check compares a measured diagnostic value to an arbitrary assigned baseline. A subjective diagnostic is not derived from comparison with physical law, but rather comparison with intuition, opinion, or some general rule of thumb set by experience. The ambiguous nature of this baseline produces a qualitative result relative to some arbitrary baseline. Subjective diagnostic tests are useful for monitoring relative changes in a system's performance.

Objective diagnostic tests tend to be more powerful, i.e. more useful, than subjective diagnostic tests. That is, not all diagnostic tests are created equal. Some inherently contain more useful information than others. Nevertheless, subjective diagnostic tests do have their place. A subjective diagnostic test is far better than no diagnostic test, and an objective test coupled with a subjective test is more useful than an objective test alone. The more distinct separate pieces of information a diagnostic suite contains, the more unique the corresponding diagnostic pattern for each malfunction and the more conducive to successful pattern recognition it is.

Considering individual ultrasonic meter diagnostic checks:

- Path SoS – (**objective**)
  For fixed composition, pressure and temperature, and with no stratification density gradient there is one constant SoS throughout the meter body. Therefore, all paths should read the same SoS with and no difference between them ($\Delta MSoS = 0$). Any discrepancy is an absolute measurement, i.e. is relative to a precise defensible baseline.

- Path Velocity – (**objective**) PF, Symmetry (S), Crossflow (CF)
  For each flow condition across the calibration the profile factor (PF) is recorded, i.e. the shape of the velocity profile, as is any discrepancies in symmetry (S) and swirl / cross flow (CF). The Profile Factor is transferable to the field and is therefore an objective test. Fully developed flow is symmetrical, i.e. by theory S =1, and fully developed flow has no swirl / crossflow (CF=0). Hence, symmetry and crossflow are objective tests.

- Signal to Noise – (**objective / subjective**)
  Strictly speaking Signal to Noise (S/N) is a subjective check. The S/N can change from calibration to application, between transducers, and for a given application with changing flow conditions. Nevertheless, ISO has enough massed data showing reproducibility that ISO 17089 (2019) Section 8.7.3 titled 'S/N ratios warning & alarm levels' has a diagnostic warnings at $6 < S/N\ (dB) < 9$, and an alarm at ≥ 9 dB. Massed reproducible field data can be argued to be as sound as a calibration, and as such there is an argument for claiming S/N is therefore an objective diagnostic.

- Auto Gain Control – (**subjective**)
  Auto Gain Control (AGC) is a subjective check. The AGC can change from calibration to application, between transducers, and for a given application with changing flow conditions. ISO does not offer any AGC alarm threshold but simply notes the AGC should be logged during the SAT for future comparison. AGC is a subjective diagnostic.

- Standard Deviation aka 'Turbulence' – (**subjective**)
  'Turbulence' generally means the standard deviation of each primary signal, i.e. the paths Δt. However, the standard deviation of any diagnostic parameter can be considered. For all standard deviations, this is a subjective diagnostic. For example, the primary signal Δt standard deviation is flow condition dependent. ISO does not offer any turbulence alarm threshold.

- ‘Performance’ or ‘Signal Acceptance’– (**subjective**)[2]
  Path’s ‘performance’ is the number of transmitted to received signals per unit time. Ideally the performance is 100%. However, high gas velocity and / or low pressure can cause signals to be attenuated and lost. Hence, path performance is flow condition dependent; it is a subjective diagnostic. ISO does not offer any performance alarm threshold.

Regardless of whether a diagnostic check is objective or subjective, if the diagnostic is to be used as part of pattern recognition an alarm thresholds still need to be set. As we have seen ISO suggests MSoS and S/N warning or alarm thresholds. The other diagnostic checks, both objective and subjective have warning and alarm thresholds left ambiguous.

Meter manufacturers tend to have default settings to all diagnostic checks that can be changed by the meter user. It is the default settings of the Honeywell Q Sonic-Max 8-path Ultrasonic Meter that produced the results in Figure 9. It is interesting to take these manufacture setting results and compare them to ISO’s pattern recognition table (see Figure19).

In this case study the issue is known from the outset via manual intervention to be corrosion, which both pitted the wall and caused significant fouling (i.e. see Figures 10 and 20). ISO offers a proposed pattern recognition for fouling. It is reproduced here as Figure 21, where only the proposed fouling pattern is shown along with superimposed agreement or disagreement comments.

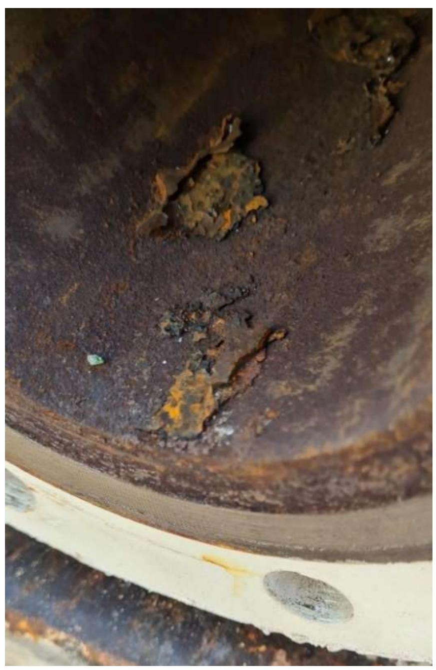


Figure 20. Meter As Found With Corrosion Induced Fouling

[2] Performance may superficially appear to be objective as there is a default expected result of 100%, e.g. the Factory Acceptance Test (FAT) requires 100%. However, a performance less than 100% does not to contradict any physical law. Noise attenuating a signal such that the signal is not received causing performance to drop below 100% is not a violation of any physical law. A noise level can produce a 80% performance, i.e. 20% drop from the expected value, and this does not mean there is anything wrong with the metering or something does not make physical sense. On the contrary, if MSoS readings were different by 20% this would mean that there was a problem with the metering. The MSoS diagnostic is an objective test, the path performance diagnostic is subjective.

Data Agrees (✓) / Disagrees (✗)

Relational diagnostic	Per path					
	Signal Acceptance	Automatic gain control	S/N	MSOS	Flow velocity	Standard Deviation
Fouling	×	×	×	×	×	×
	✗	✗	✗	✓	✓	✓

Figure 21. ISO 17089 (2019) Ultrasonic Meter Diagnostic Suite Suggested Fouling Pattern.

Fouling is a catch all term for every and all types of contamination, from grease, compressor oil, scale deposits, to corrosion particulate presence in the meter. Some contaminants are high viscous liquids, Bingham plastics, or solid particulates that flow through the meter, while some such a scale adhered to the wetted wall do not. No two contaminated meters are contaminated in just the same way. The type, amount and spatial distribution of the contaminate is unique to each case. It can even change for a specific contaminated meter over time. Hence, the term ‘fouling’ is a general term.

Corrosion causes both fouling in the form of rust particulate, but also pitting of the wetted wall (e.g. see Figure 10). Hence, it is noted here that modelling corrosion as a type of fouling is an approximation. There is particulate fouling the meter, but there is also damage to the wetted wall.

Figure 21 shows that ISO objective diagnostics of the path Speed of Sound (MSoS) and flow velocity measured per path (i.e. flow profile) are correctly in alarm. However, the S/N diagnostic which ISO does give an alarm threshold for based on massed data, and is therefore arguably objective, is contrary to ISO’s suggestion not in alarm.

Objective diagnostic tests tend to be more reliable than subjective diagnostic tests. It is more difficult to set a diagnostic alarm threshold for subjective diagnostic checks. The authors do not know what diagnostic warning or alarm settings were in place for these subjective tests, but they are the normal default values many end users automatically use.

According to the Honeywell default diagnostic warning setting, the standard deviation (‘turbulence’) subjective diagnostic is as ISO suggests in alarm. However, according to the Honeywell default diagnostic warning settings the other two subjective diagnostics, i.e. the path performance (or ‘signal acceptance’) and Automatic Gain Control (AGC), do not issue a warning or alarm. Nevertheless, it is accepted here that different types of fouling to this could cause subtly different ultrasonic meter diagnostic responses. Some type of fouling may cause issues with the signal acceptance, automatic gain control and signal to noise ratio diagnostic checks.

Pattern recognition of a complex instrument’s diagnostic result is challenging. Ultrasonic meter diagnostics are very useful but pattern recognition is still a work in progress. There is more uncertainty regarding subjective than objective diagnostics.

8 Conclusions

It is beneficial to include the ultrasonic meter’s diagnostic suite result as a part of the meter’s calibration analysis. The meter should not be assumed to be fully serviceable at the calibration, as this is not guaranteed. If the ultrasonic meter’s diagnostic suite is considered powerful enough to be part of maintenance and re-calibration scheduling decisions, then it should also be considered powerful enough to be part of the calibration process. AGA 9 does state that a meter under calibration has to pass the MSoS diagnostic tests, which is better than ISO 17089’s silence on the matter, but there is a scope for more diagnostic results to be considered at calibration.

ISO 17089 (2019) appears to give two different path Speed of Sound comparison diagnostic check alarm thresholds. ISO 17089 (2019) Section 5.8.2 states the difference in any two paths SoS must be < 0.5 m/s. ISO 17089 (2019) Section 8.7.1 states the ratio of any two paths SoS must be < 0.2% for no warning to be given, and < 0.3% for no alarm to be given. These two statements on difference and ratio are not equivalent. It would be useful for ISO to have one consistent MSoS alarm threshold. If Section's 5.8.2 and Section 8.7.1 do not contradict each other, then the ISO 17089 document could be written with more clarity to explain this.

ISO 17089 (2019) Section 5.2.10's discussion on corrosion protection is an important statement. Whenever CAPEX is saved by choosing carbon steel instead of a stainless steel, an additional OPEX is incurred in then having to make double sure the meters are suitably sealed and protected. As is seen in this case study, failure to do so can result in significant further CAPEX and potential metering errors.

As with all instrumentation and machinery, the ultrasonic meter objective diagnostics are more powerful than the subjective diagnostics, although the subjective diagnostics still do have a valuable place in aiding pattern recognition.

Ultrasonic meter diagnostic suites are very useful, but they are still a work in progress. ISO 17089 (2019) has a basic diagnostic suite pattern recognition table predicting what pattern of diagnostic check alarms and no alarms means what issues. However, in order to apply such a pattern recognition table it is first necessary to know which diagnostic checks have passed the diagnostic alarm threshold and which have not. For that, the various diagnostic checks need to be assigned alarm thresholds. For several ultrasonic meter diagnostic parameters these thresholds are not published, neither by ISO, another standards body, or by manufacturers. This issue is especially acute for the subjective diagnostic checks. Independently ratified ultrasonic meter diagnostic suites alarm thresholds development would be an important milestone in ultrasonic meter technology progress.

9 REFERENCES

[1] ISO 17089 (2010) Ed 1 "Measurement of fluid flow in closed conduits — Ultrasonic meters for gas — Part 1: Meters for custody transfer and allocation measurement."

[2] ISO 17089 (2019) Ed 2 "Measurement of fluid flow in closed conduits — Ultrasonic meters for gas — Part 1: Meters for custody transfer and allocation measurement."