

ДИАГНОСТИЧНА ОЦЕНКА НА УЛТРАЗВУКОВ ДЕБИТОМЕР С ИЗМЕРВАНЕ НА ПРЕХОДНО ВРЕМЕ ПРИ ГРАНИЧЕН, ПРЕХОДЕН И УСТАНОВЕН РЕЖИМ НА ПОТОКА

инж. Павел Димитров

Технически университет - Варна

доц. д-р инж. Мариела Александрова

Технически университет - Варна

Резюме: Съвременните ултразвукови дебитомери с измерване на преходно време разчитат на диагностични параметри, за да осигурят акуратно отчитане на дебита при променливи хидравлични условия. В настоящото изследване се оценяват измервателните характеристики на дебитомер Flexim FLUXUS F601, базирайки се на три набора от данни - А, В и С, получени експериментално. Набор А представя условия, близки до прага на измерване, по време на стартиране на системата (около 0 m/s скорост на потока), набор С съответства на преходен режим от нисък към висок дебит (от 0.18 до 0.7 m/s), а набор В представя установен режим на потока (приблизително 0.42 m/s). Анализът разглежда скоростта на потока, скоростта на разпространение на звука, отношението сигнал-корелационен шум (SCNR), отношението сигнал-шум (SNR), автоматичното регулиране на усилването (AGC), показателите за качество и диагностичните флагове в контекста на теорията за измерване на преходното време. Резултатите потвърждават, че валидността на измерването зависи до голяма степен от хидравличната стабилност и качеството на сигнала, а не дотолкова от скоростта на потока. Точни измервания са възможни и при ниски скорости на потока, в условия на постоянна скоростта на звука и високи нива на SCNR. В същото време диагностичният алгоритъм на устройството отхвърля измервателните данни, в случаи, при които системата доближава границата на разделителна си способност.

Ключови думи: ултразвуков дебитомер; измерване на скоростта на потока чрез преходно време; диагностика на поток с нисък дебит; скорост на звука; експериментално валидиране.

DIAGNOSTIC EVALUATION OF A TRANSIT-TIME ULTRASONIC FLOWMETER IN NEAR CUT-OFF, TRANSITIONAL, AND STEADY FLOW REGIMES

Eng. Pavel Dimitrov

Technical University – Varna

Assoc. Prof. Dr. Eng. Mariela Alexandrova

Technical University – Varna

Abstract: *Modern transit-time ultrasonic flowmeters rely on internal diagnostic parameters to determine accurate measurement of the flow rate under variable hydraulic conditions. This study experimentally evaluates the performance of one such device (Flexim FLUXUS F601), using three independently acquired datasets labeled A, B, and C. Dataset A represents near cut-off conditions during system startup (around 0 m/s flow velocity), dataset C corresponds to a transitional low to high flow regime (from 0.18 to 0.7 m/s), and dataset B represents a steady flow regime (approximately 0.42 m/s). The analysis considers flow velocity, sound speed, signal-to-correlation noise ratio (SCNR), signal-to-noise ratio (SNR), automatic gain control (AGC), quality indicators, and diagnostic flags in the context of transit-time measurement theory. The results show that measurement validity depends more on hydraulic stability and signal quality than on flow velocity alone. Reliable measurements remain possible at low velocities when sound speed is consistent, and SCNR remains high. At the same time the built-in diagnostic logic rejects data as the system approaches its physical resolution limit.*

Keywords: ultrasonic flowmeter; transit-time flow velocity measurement; low flow diagnostics; sound speed; experimental validation.

1. Introduction

Transit-time ultrasonic flowmeters are primarily used for industrial liquid flow measurement because they can be mounted externally on the pipeline, do not obstruct the flow, and are suitable for retrofit applications [1]. Their behavior under nominal conditions is well established, but performance near zero flow is more difficult to assess. Since the transit-time difference becomes very small, the velocity estimate becomes increasingly sensitive to timing uncertainty and signal noise. Under these conditions, hydraulic disturbances and loss of acoustic coherence can have a noticeable negative effect on the measurement [3,5]. Diagnostic parameters, therefore become important in determining whether a low indicated velocity corresponds to an actual flow condition or to reduced measurement reliability, leading to cut-off flow.

In this study, sound speed, signal-to-correlation ratio (SCNR), gain behavior, and related quality indicators are analyzed using three datasets (A, B, C) obtained from a DCS-based experimental system, covering near cut-off, steady nominal, and transitional flow regimes.

2. Transit-Time Measurement and Diagnostic Indicators

2.1 Fundamental Transit-Time Relations

In a transit-time ultrasonic flowmeter, ultrasonic pulses are transmitted and received alternately in the downstream and upstream directions along an acoustic path of length L , inclined at an angle θ to the pipe axis. The corresponding downstream and upstream transit times are expressed as [1,2]:

$$t_{down} = \frac{L}{c+v\cos\theta} \quad (1)$$

$$t_{up} = \frac{L}{c-v\cos\theta} \quad (2)$$

where c is the speed of sound in the fluid and v is the averaged flow velocity.

2.2 Flow Velocity and Sound Speed Estimation

$$v = \frac{L}{2\cos\theta} \left(\frac{1}{t_{up}} - \frac{1}{t_{down}} \right) \quad (3)$$

$$c = \frac{L}{2} \left(\frac{1}{t_{up}} + \frac{1}{t_{down}} \right) \quad (4)$$

Equation (3) reveals an inherent limitation of transit-time flow measurement at low velocities. As $v \rightarrow 0$, the transit-time difference diminishes, which increases the sensitivity of the velocity estimate to timing uncertainty and electronic noise. In contrast, the sound speed estimate in (4) is considerably less dependent on flow magnitude and thus remains consistent [8,9,10]. This makes sound speed a valuable diagnostic variable for evaluating fluid condition, acoustic coupling quality, and transducer alignment.

2.3 Signal Correlation, SCNR, and Deviation

For industrial flowmeters, transit times are estimated via cross-correlation of received ultrasonic signals. The sharpness of the correlation peak is quantified by the SCNR. The deviation of the transit-time estimate can be approximated as [5]:

$$\sigma_t \propto \frac{1}{SCNR} \quad (5)$$

Through (3) yields a velocity deviation that increases rapidly at low flow velocities [3,5]:

$$\sigma_v \propto \frac{c^2}{2l\cos\theta} \sigma_t \quad (6)$$

These relationships provide the theoretical basis for treating SCNR as a principal indicator of measurement confidence. A reduction in SCNR expands the uncertainty of the

estimated transit time and, consequently, has a direct effect on the reliability of the derived flow velocity.

2.4 Automatic Gain Control

Automatic gain control compensates for reduced signal amplitude caused by attenuation or decorrelation. However, increased gain amplifies both signal and induced noise and may reduce effective SCNR if acoustic coherence is lost [4]. Accordingly, gain behavior should be evaluated with SCNR and quality indicators to distinguish simple amplitude compensation from degradation in signal quality.

3. Tested Device and Experimental Platform

3.1 Transit-time Ultrasonic Flowmeter

The tested device is Flexim FLUXUS F601 clamp-on ultrasonic flowmeter (Fig. 1), operating in transit-time mode. The flowmeter determines flow velocity from the measured transit-time difference with an acoustic calibration factor and a Reynolds number dependent correction. In addition to calculating flow velocity, it continuously monitors signal quality and suppresses measurements when signal correlation falls below an acceptable level.

The flowmeter transducers are mounted externally (Fig. 2) in accordance with the manufacturer's recommendations [6], with a transducer distance of 62 mm on a pipeline with an outer diameter of 108 mm. This configuration ensures fully filled pipe conditions with the recommended straight-run lengths of 10D upstream and 5D downstream of the tested flowmeter.



Fig.1. FLUXUS F601 Transmitter

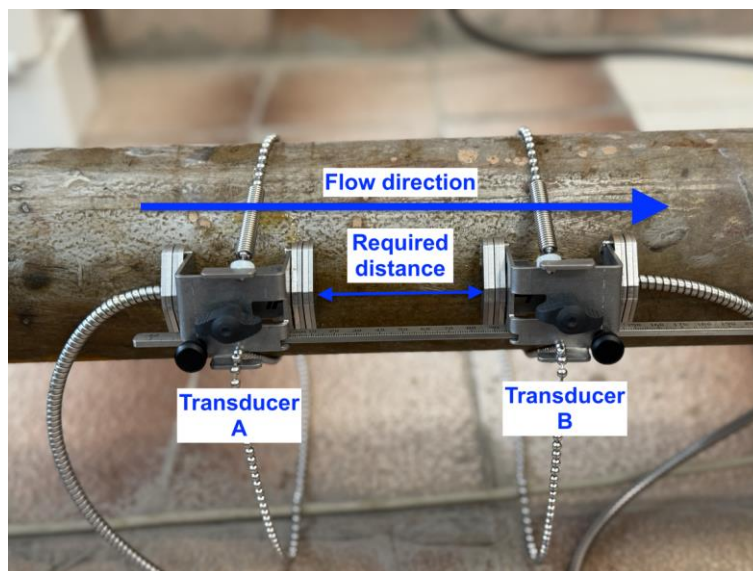


Fig. 2. FLUXUS F601 Transducers arrangement

3.2 Experimental Platform

The experiments were carried out on a DCS experimental platform developed for standardized evaluation of industrial flowmeters. The control system is based on a DeltaV SQ controller, distributed I/O, and a PC-based engineering station. The installation comprises a centrifugal pump, a 6000 L buffer tank, a secondary 1506 L reference tank, and an automated flow control loop based on a Proportionally Integral (PI) controlled valve. An electromagnetic flowmeter (FT-1) is used as a reference device, while volumetric accumulation serves as an independent validation method. All test procedures, including flow stabilization, data acquisition, and result logging, were executed automatically through the DCS system.

4. Experiments and Results

Three independent datasets, A, B, and C, were obtained under comparable operational conditions. To ensure the reliability of the results, each experimental procedure was repeated eight times (Fig. 3a and 3b). In all the tests, water was used as the working fluid, with an average temperature of approximately 30 °C, a density of 996 kg/m³, and an absolute in-line pressure of around 110 kPa. Dataset A captures near cut-off (Table 1) and transient flow conditions, including periods during which the flowmeter rejected the measurement and issued a “Fail” indication. Dataset B represents steady nominal flow at approximately 0.42 m/s. Dataset C covers a transitional regime with low flow conditions in the range of approximately 0.12–0.18 m/s and extending to a higher flow profile of about 0.7 m/s. For each dataset, the recorded variables include flow velocity, sound speed, gain, SCNR, SNR, quality index, and diagnostic flags.

Table 1.

Representative samples of Dataset A

Flow velocity [m/s]	Volumetric flow rate [m ³ /h]	Sound speed [m/s]	Amplitude [%]	Gain [dB]	Quality [%]	SCNR [dB]	SNR [dB]	Cut-off flow
0,00	0,00	1509,37	64,0	53,640	100,0	39,0	41,0	Yes
0,16	4,47	-	40,0	89,400	0,0	40,0	37,0	No
0,27	7,51	-	32,0	101,320	89,0	41,0	24,0	No
Fail	Fail	-	31,0	102,810	89,0	41,0	15,0	No
Fail	Fail	-	31,0	102,810	89,0	41,0	11,0	No
0,00	0,00	-	31,0	102,810	68,0	0,0	-	Yes
Fail	Fail	-	30,0	104,300	63,0	0,0	-	Yes
Fail	Fail	-	31,0	102,810	56,0	0,0	-	Yes
Fail	Fail	-	30,0	104,300	56,0	0,0	-	Yes
0,29	8,13	1511,85	54,0	68,540	96,0	40,0	13,0	No
0,19	5,31	1511,85	54,0	68,540	97,0	35,0	27,0	No
0,33	9,14	1511,61	54,0	68,540	93,0	37,0	41,0	No
0,51	14,22	1511,99	54,0	68,540	99,0	36,0	43,0	No

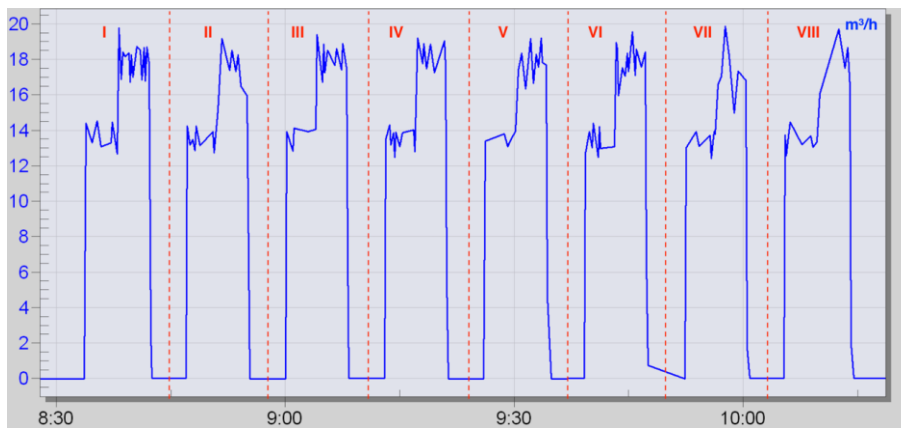


Fig. 3a. Flow profile during experimental procedure from system start up

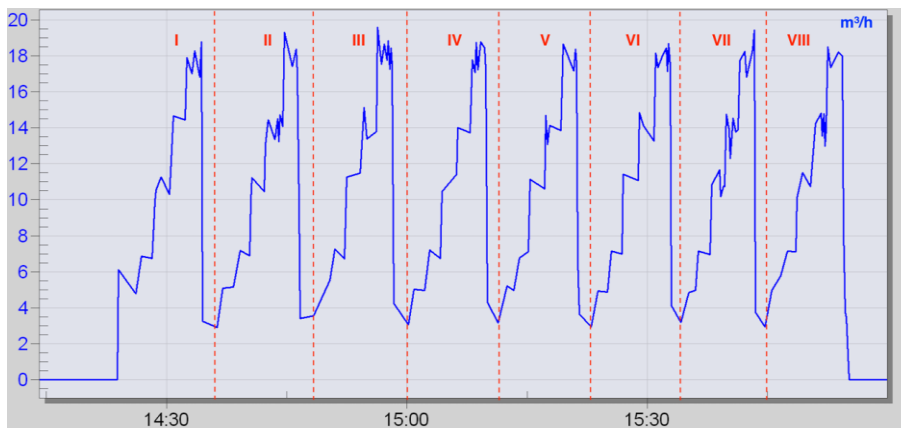


Fig. 3b. Flow profile during experimental procedure under stepwise flow regulation

4.1 Diagnostic Behavior Across Flow Regimes

As shown in Figure 4, Dataset A is characterized with elevated gain, reduced SCNR, and intermittent measurement suppression in the near cut-off region during system start up. In contrast, Datasets B (Fig. 5) and C (Fig. 6) exhibit consistent gain levels (about 68 dB), high SCNR values (>38 dB), and continuously valid measurements. The sound speed remains within a narrow range (approximately 1508–1515 m/s) in all cases, supporting the conclusion that installation conditions remained consistent throughout all tests.

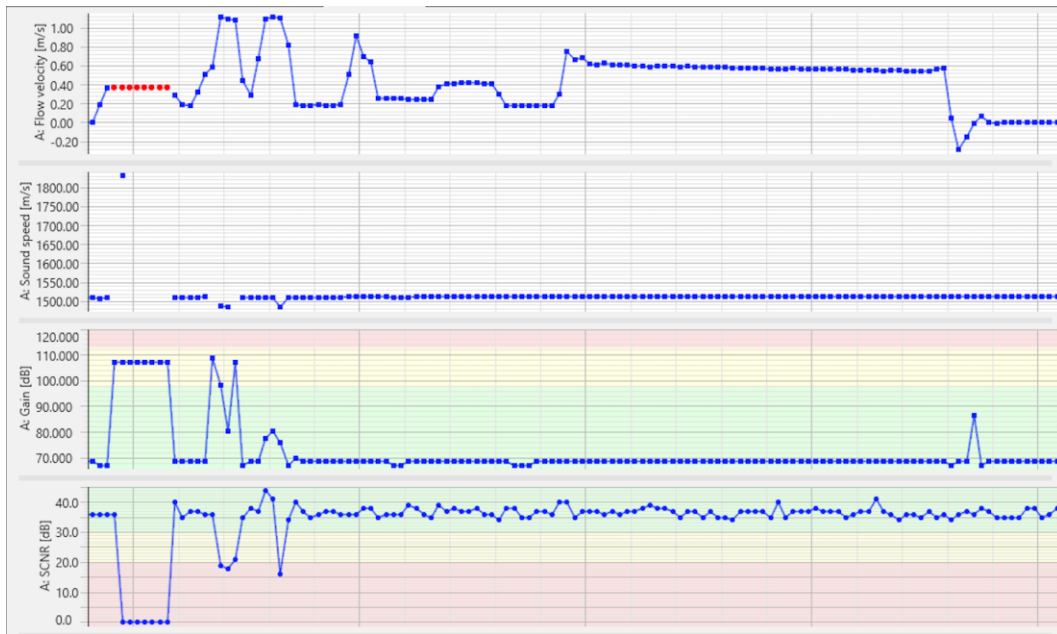


Fig. 4. Near cut-off and transient flow profile

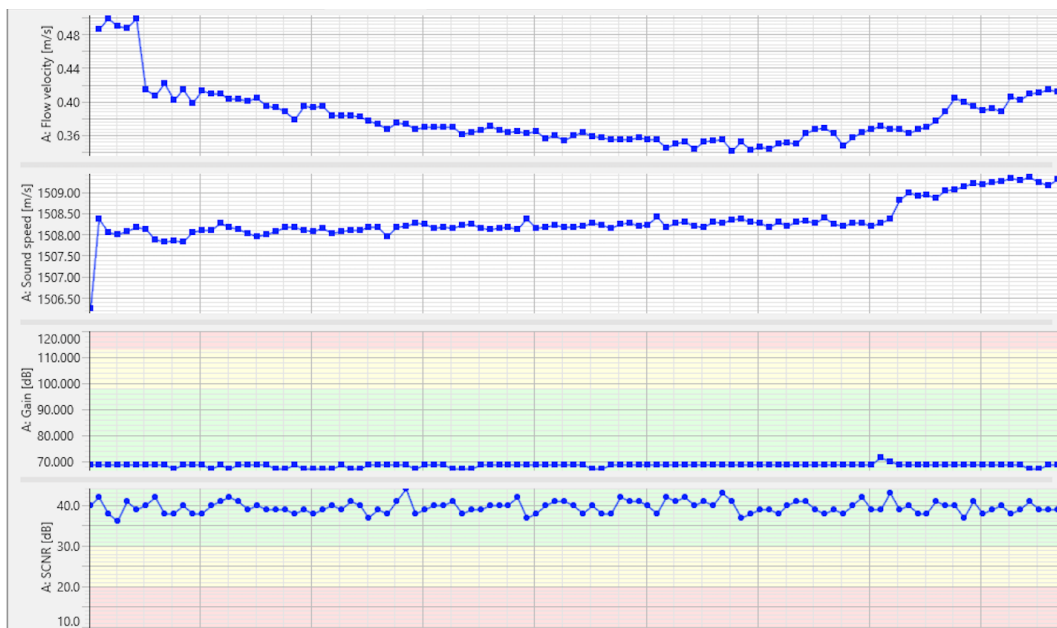


Fig. 5. Steady nominal flow profile

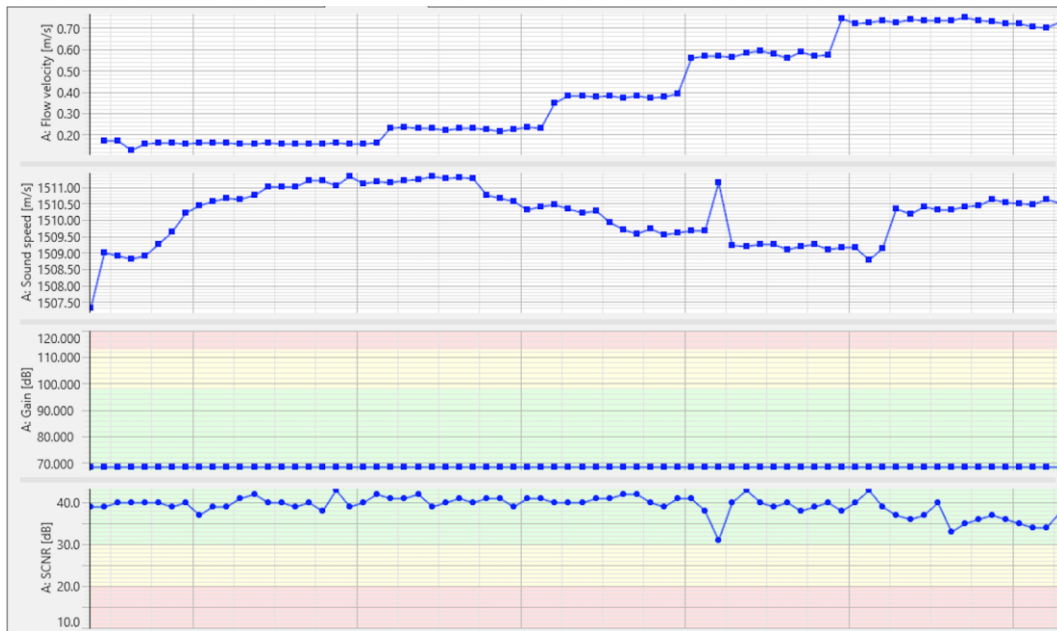


Fig. 6. Transitional low flow to high flow profile

4.2 Comparison with FT-1

Comparison with the reference electromagnetic flowmeter (FT-1) shows a proportional response and close steady state tracking (Fig. 7). The observed offset remains consistent over time, indicating a systematic and repeatable bias rather than measurement noise. No loss of signal or saturation effects are present. Since the experiments were conducted under hydraulically developed flow conditions at velocities of 0.7–0.9 m/s, i.e., well above the near cut-off region, the influence of flow profile distortion and low velocity sensitivity is expected to be limited. Therefore, the tested device (FT-2) exhibits predictable performance, with an offset that could be addressed through calibration.

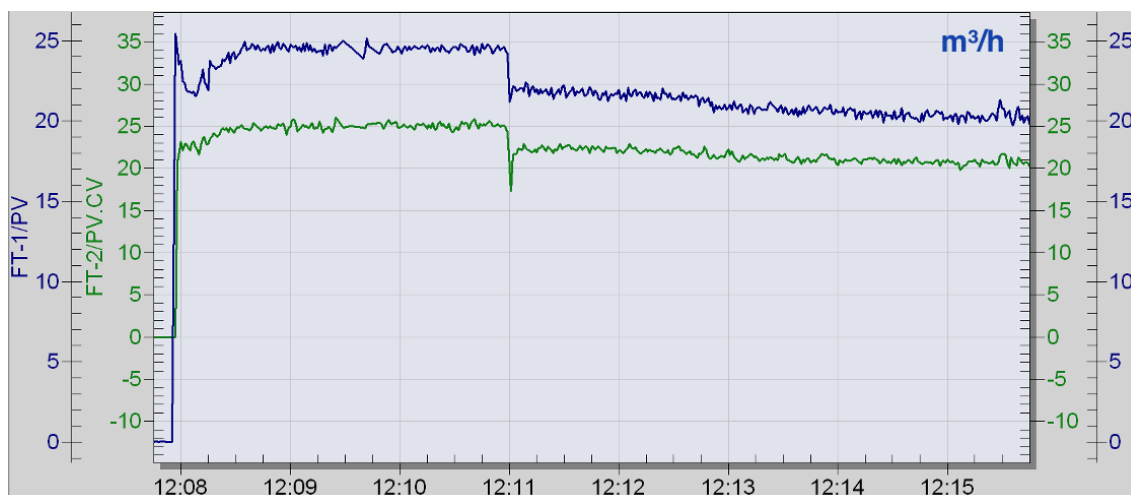


Fig. 7. Comparison of flow profile of tested device against reference flowmeter

4.3. Summary of Realized Experimental Results

Table 2.

Flow conditions					
Dataset	Flow regime	Velocity range [m/s]	Approx. flow rate [m³/h]	Flow stability	Valid measurements
A	Near cut-off /transient flow	≈ 0 – 0.7	0 – 18	Low to moderate	Intermittent
B	Steady nominal flow	≈ 0.42	≈ 12	High	Continuous
C	Transitional low to high flow	≈ 0.12 – 0.18 to 0.7	≈ 3.5–5 to 18	High	Continuous

Table 3.

Diagnostic parameters						
Dataset	Mean sound speed [m/s]	Sound speed stability	Mean gain [dB]	Gain behavior	Mean SCNR [dB]	Mean SNR [dB]
A	≈ 1512	Moderate	70–100+	Highly variable	≈ 34	≈ 42
B	≈ 1508	Very high	≈ 68	Consistent	≈ 40	≈ 44
C	≈ 1510	High	≈ 68.5	Consistent	≈ 39	≈ 44

Table 4.

Measurement validity					
Dataset	SCNR above threshold	Gain limit events	Cut-off flow flag	Diagnostic errors	Data suppression
A	Partially	Yes	Yes	Present	Yes
B	Yes	No	No	None	No
C	Yes	No	No	None	No

5. Comparative Analysis

The experimental results are consistent with the behavior expected from the transit-time principle. The lower robustness observed at low flow rates is mainly due to the very small transit-time difference, which makes the measurement increasingly sensitive to timing uncertainty. Under these conditions, even small fluctuations in signal timing can have a noticeable effect on the calculated velocity. The sound speed values remain consistent across all datasets, indicating proper acoustic coupling. This suggests that the observed variations are related mainly to measurement conditions rather than to installation problems. Therefore, SCNR and gain behavior are more informative than flow velocity alone because they reflect

the quality of the received ultrasonic signal and the reliability of the correlation process. Taken together, these indicators provide a more complete basis for judging measurement validity, particularly in the low flow range where the method approaches its practical resolution limits.

Table 5.
Comparison of the collected data

Parameter	Dataset A	Dataset B	Dataset C
Velocity range [m/s]	~0–0.7	~0.42	~0.12–0.18 to 0.7
Measurement validity	Intermittent	Continuous	Continuous
Average sound speed [m/s]	~1512	~1508	~1510
Gain behavior	Variable (peaks >100 dB)	Consistent (~68.3 dB)	Consistent (~68.5 dB)
Mean SCNR [dB]	~34 (high variance)	~40	~39
Diagnostic errors	Present	None	None

6. Conclusion

This study demonstrates that clamp-on transit-time ultrasonic flowmeters are capable of providing reliable measurements at low flow velocities when diagnostic indicators confirm adequate signal quality. The deterioration in performance observed near zero flow is a result primarily from the intrinsic resolution limits of the transit-time method, rather than from sensor failure or incorrect installation. Among the diagnostic variables considered, sound speed emerges as a particularly reliable parameter because of its weak dependence on flow magnitude and its ability to confirm stable acoustic coupling and fluid conditions. At the same time, SCNR and automatic gain behavior prove to be more sensitive indicators of measurement confidence than velocity alone. The results support the use of diagnostic-based validation as a practical means of extending confidence in ultrasonic flowmeter performance across a broad flow range, including operating conditions traditionally considered difficult for transit-time measurement.

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