



Utilising Diffraction to Exploit Chordal Paths for Swirl Measurements In Clamp-On Ultrasonic Array Flowmeters

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Transit Time Difference Flowmeter Background

- Velocity determined by **transit time difference Δt (TTD)**

$$v_W = \frac{H c_s^2 \Delta t}{2D \tan(\theta_W)} \quad (1)$$

- **H** – Hydrodynamic Correction factor – accounts for difference between average velocity across cross section vs along acoustic path – function of angle [1]

$$H = \frac{\overline{v_{true}}}{v_{TTD}} = \frac{\int \vec{v}_W \cdot d\vec{S}}{\int \vec{v}_W \cdot d\vec{r}} \quad (2)$$

- **S** – Orientation Sensitivity – How much does the meter result change with installation orientation [1]

$$S = H_{max} - H_{min} \quad (3)$$

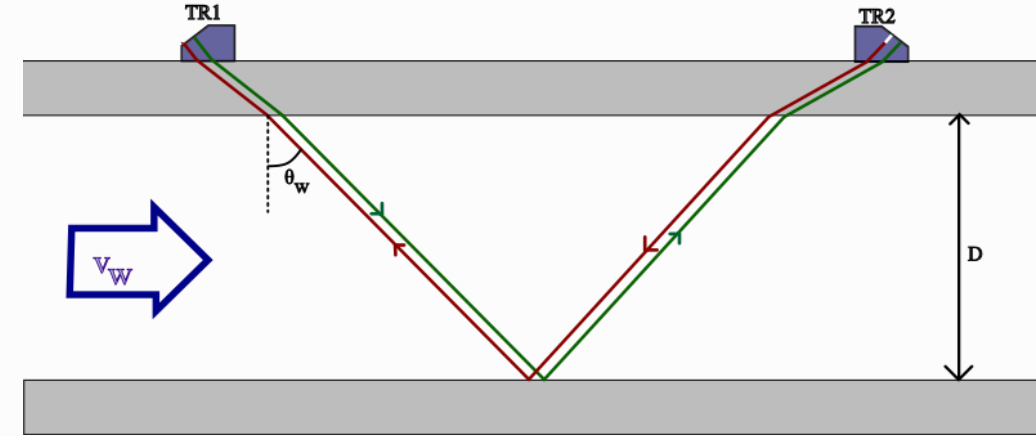


Fig 1. Basic Flowmeter geometry

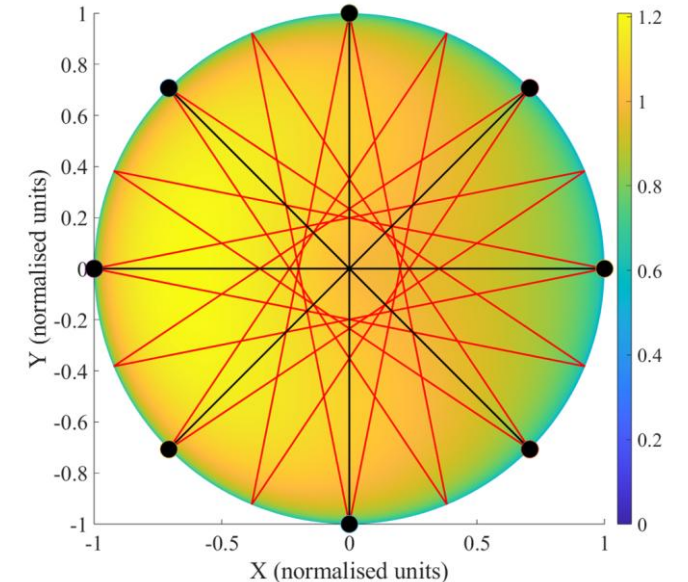


Fig 2. Proposed acoustic paths overlaid on no swirl analytic profile A7 used by Moore and Brown [1].

Chordal Acoustic Paths

- Can utilise diffracted beam to receive pulse at off axis transducer
- Using narrow transducers – 6.5mm as aperture, shallow chord angle of 11.25°
- Predicted peak voltage amplitude: -14.1 dB relative to the diametric path.
- IRIS configuration has 2x acoustic paths available compared to standard DORTH configuration
- Optimized spacing for transducer rings for IRIS compared to DORTH differs by factor of $\cos(11.25^\circ) \approx 0.98$
- Does not prohibit use of DORTH in addition due to close optimal spacings

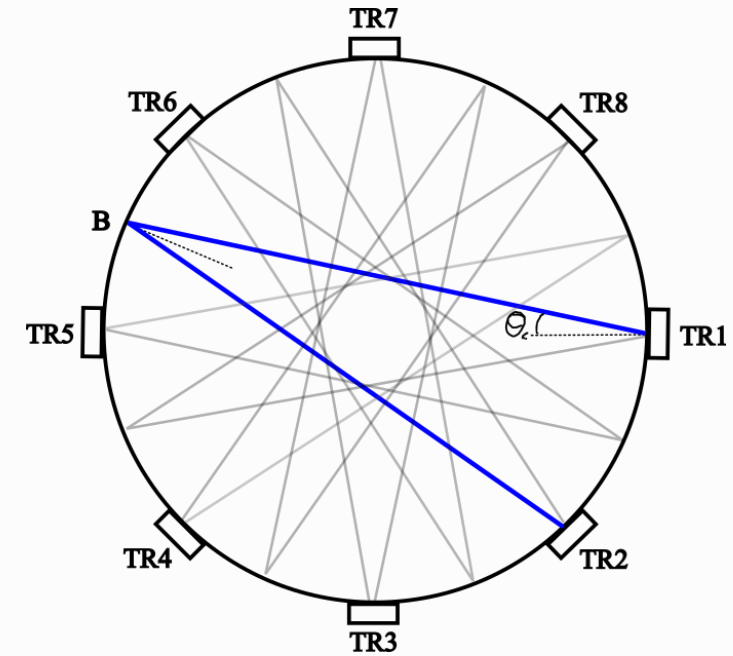


Fig. 3. IRIS Path configuration in axial view

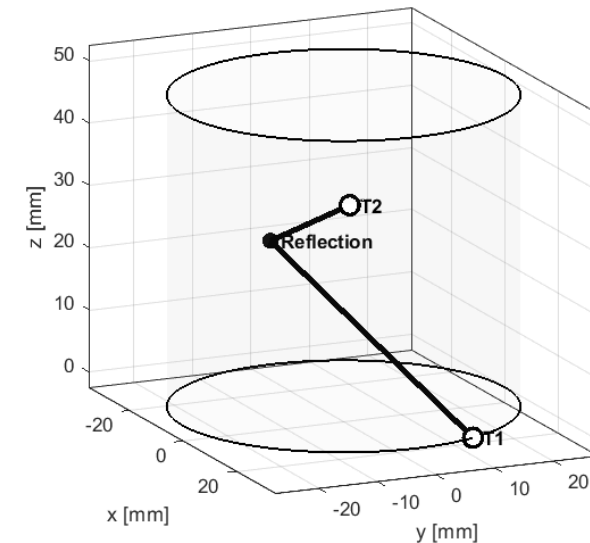


Fig 4. Single chordal path in 3D view

Chordal Acoustic Paths – Analytic profile modelling

- Different acoustic path configurations can be tested by integrating analytic flow profiles
- H and S are computed by numerical integration of equation (2)
- IRIS reduces S to average of 9% of DORTH in path integration models in selected Moore and Brown axial flow profiles
- Advantage comes from increased rotational symmetry.
- Model lacks effects of decreased amplitude or cross flows/swirl

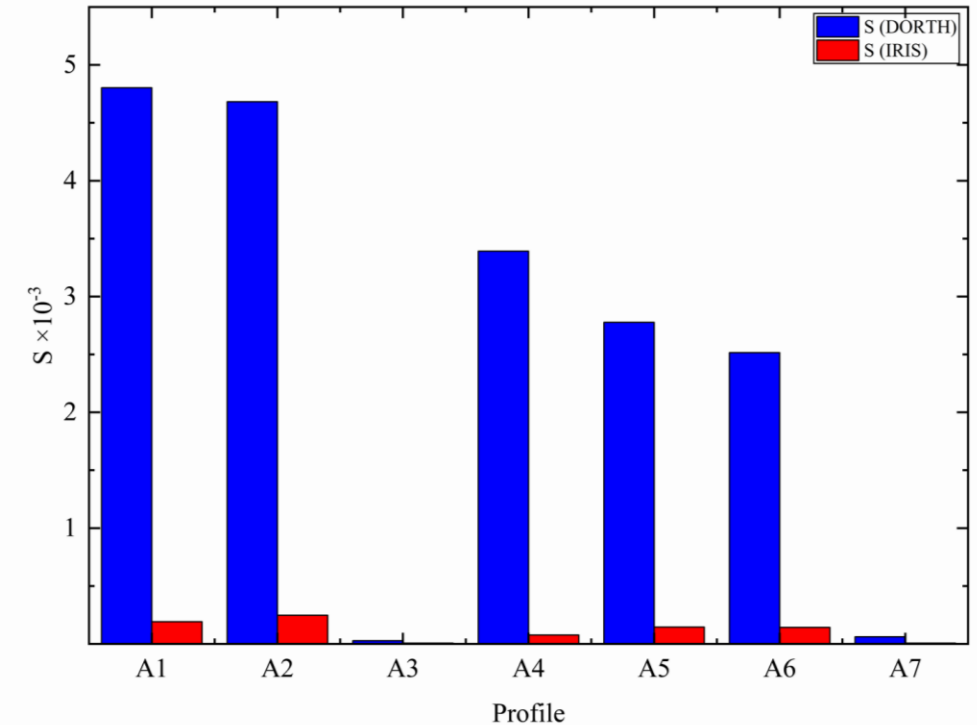


Fig 5. Comparison of S between DORTH and IRIS configuration on selection of axial flow analytic profiles

Swirl Measurement

- Chordal path TTD is sensitive to swirl, so the transit time difference is comprised of two parts TTD due to axial flow (Δt_A) and the swirl (Δt_S)

$$\Delta t_{AD} = \Delta t_A + \Delta t_S$$

$$\Delta t_{BC} = \Delta t_A - \Delta t_S$$

- Swirl can be removed/isolated by appropriate combinations:

$$\Delta t_A = \frac{\Delta t_{AD} + \Delta t_{BC}}{2} \quad (\text{mean of both paths})$$

$$\Delta t_S = \frac{\Delta t_{AD} - \Delta t_{BC}}{2} \quad (\text{half difference of both paths})$$

- Chordal acoustic paths have opposing sensitivity to swirl

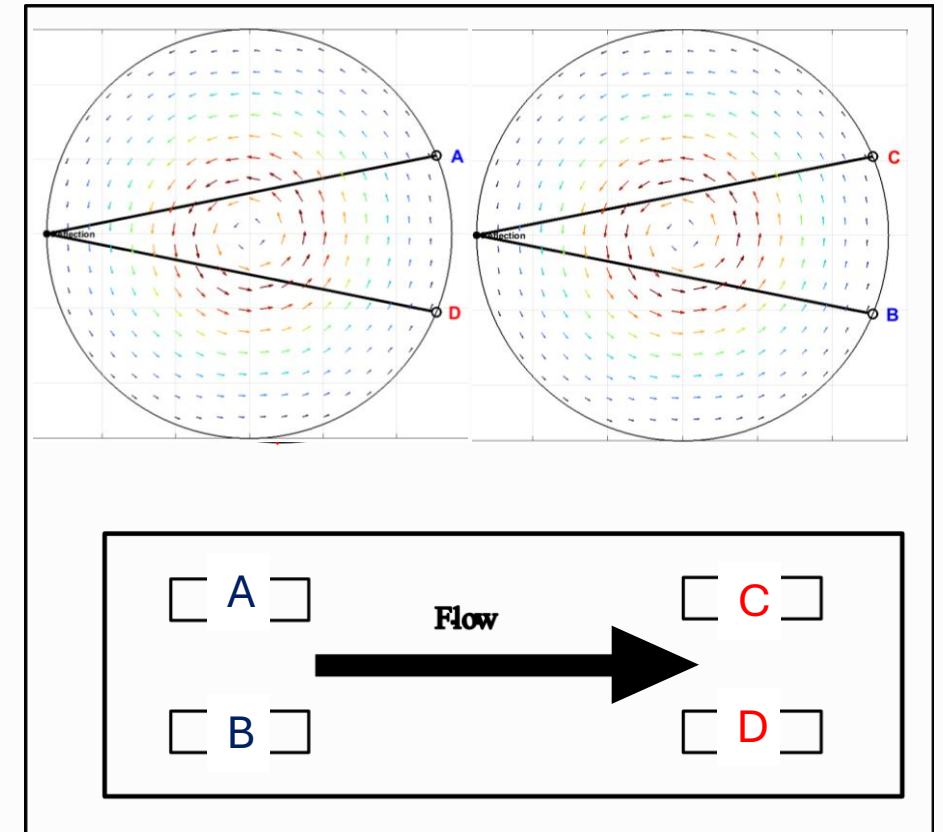


Fig 6. Swirl measurement schematic

Experimental Validation of amplitude drop

- Prototype transducers operated at 1MHz.
- The measured chordal peak voltage was 14.4 dB below the diametrical-path signal vs prediction of 14.1dB
- Pulse is significantly changed in both shape and amplitude

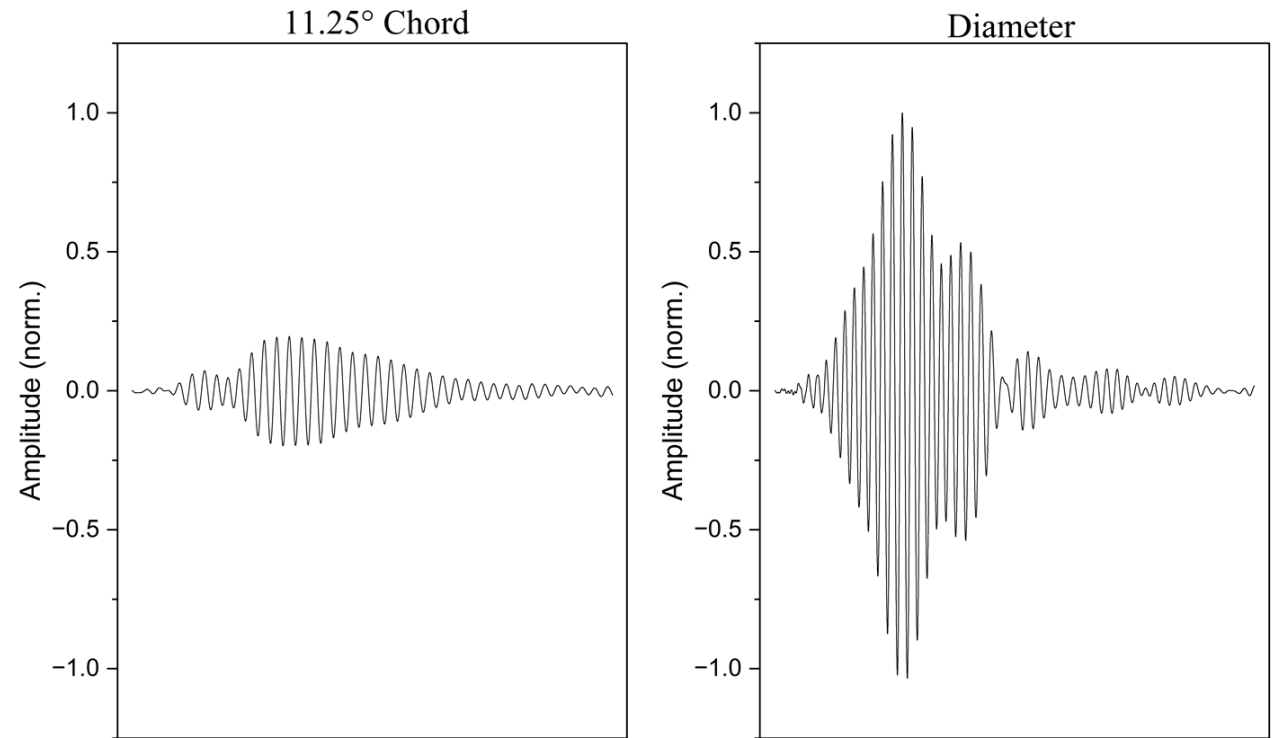


Fig 7. Comparison of chordal and diametrical path received pulses

Experimental Measurement of repeatability loss

- Resulting standard deviation over 100 TTD measurements increases from 0.209ns to 0.556ns from diametrical to chordal

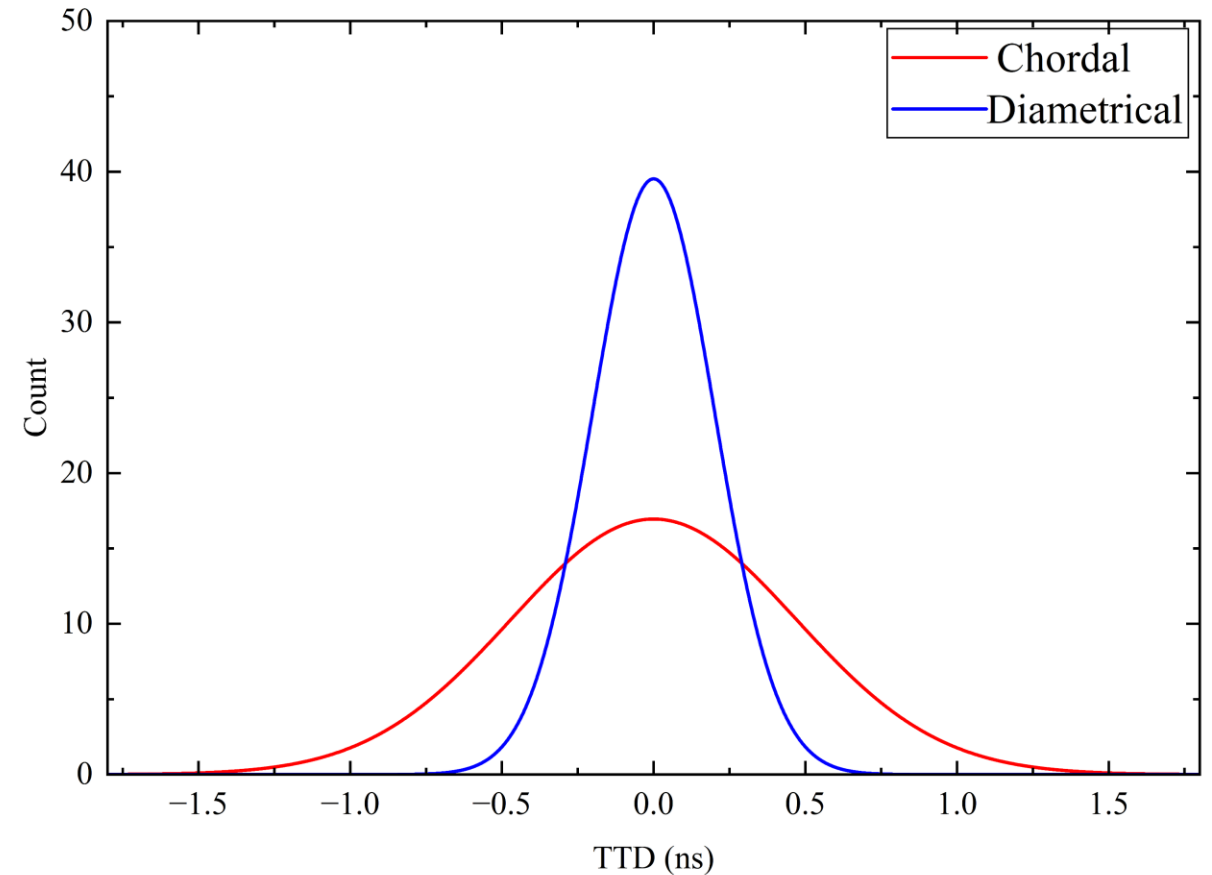


Fig 8. Differing TTD spread between chordal and diametrical path under zero flow conditions. $\sigma_{\text{chordal}} = 0.556\text{ns}$ $\sigma_{\text{diametrical}} = 0.209\text{ns}$

Swirl Measurement – Proof of concept

- Drill driven fan placed upstream of sealed section of 55mm diameter stainless steel pipe
- Spun at ~1000RPM to generate nominally axisymmetric swirl.
- Meter operating area placed 25mm from fan end - the swirl source
- Zero axial flow to test swirl sensitivity only
- Similar swirl profile to after turbine meters [2]

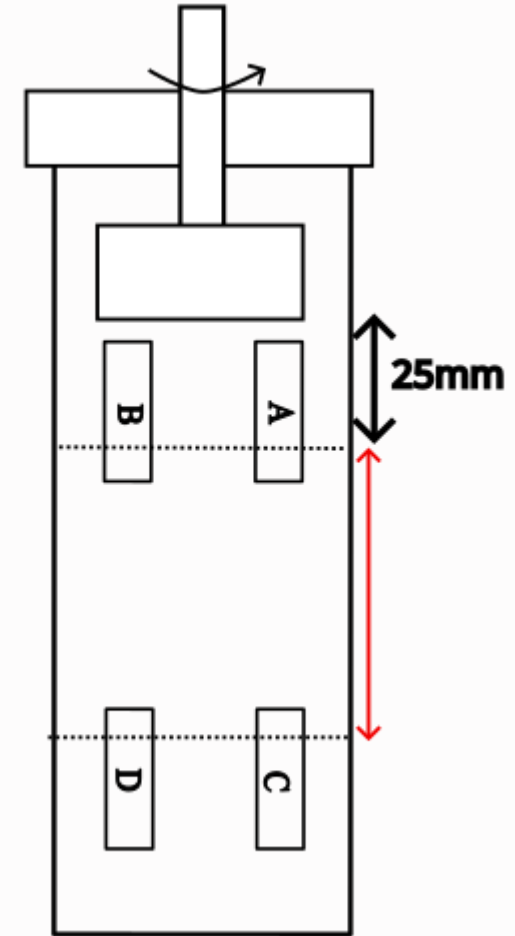


Fig 9. Experimental setup for swirl measurement validation.

Swirl Measurement – Proof of concept

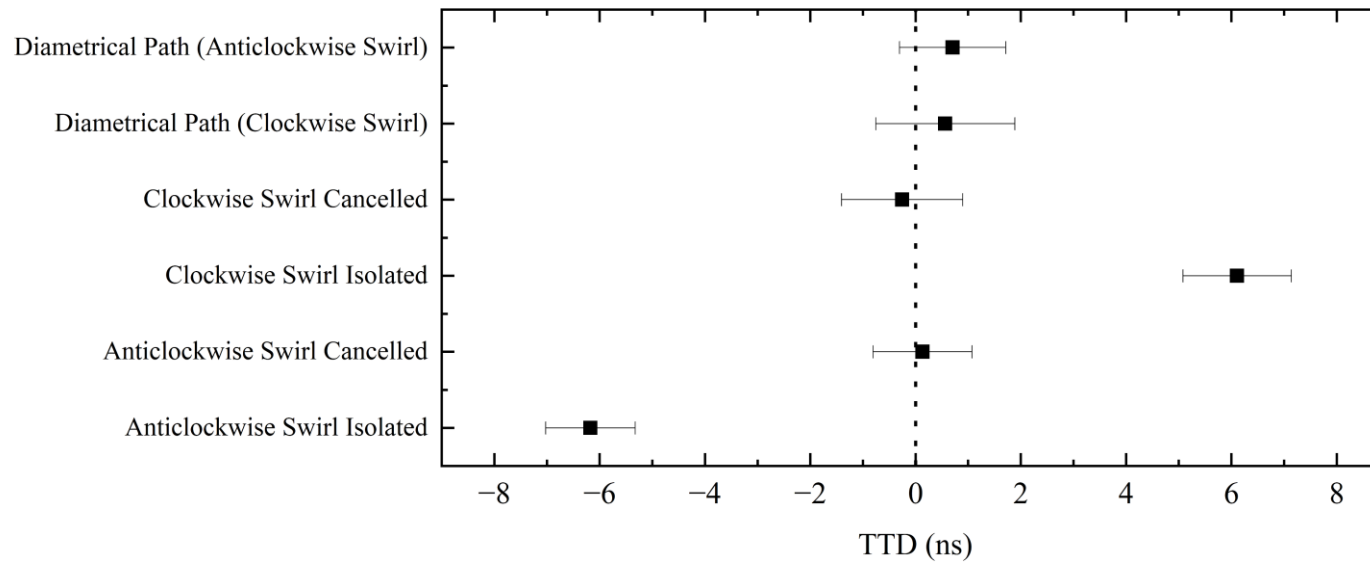


Fig 10. TTDs recorded under swirl proof of concept experiment n = 100.

- TTD measurements show clear separation between swirl conditions.
- Cancellation reduces mean TTD to 1σ of zero
- Promising proof of concept for future experiments
- All standard deviations are relatively comparable

Early CFD Simulation

- CFD simulations 5D from 90° bend numerically integrated as in equation 2
- Orientation sensitivity reduced significantly with IRIS configuration over DORTH .
($S_{\text{IRIS}} = 0.7 \times 10^{-3}$, $S_{\text{DORTH}} = 6.3 \times 10^{-3}$)
- Limited range of data currently
- Experimental confirmation pending

The CFD data used in this slide was provided by I and P services from work done under contract with NEL.

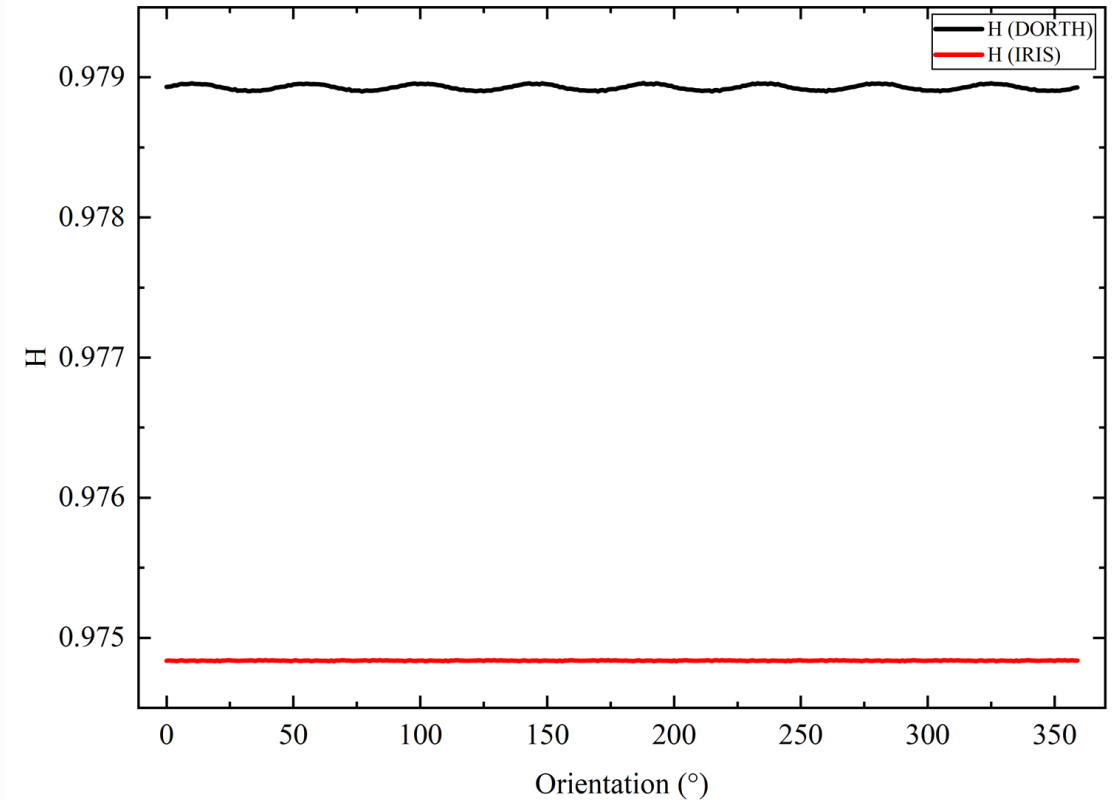


Fig 11. H computed as a function of meter orientation 5D from a 90° bend

Benefits and Limitations

Advantages

- Greater axial symmetry provides larger cross-sectional coverage over DORTH
- Provides external sensitivity to swirl
- Does not prohibit use of DORTH configuration in addition to IRIS, optimal spacing is very similar for both

Disadvantages

- Lower signal amplitude inherently decreases meter repeatability
- More complex swirl patterns are difficult to interpret from transit time differences

Future Work

- Larger range of CFD simulations
 - Double out of plane bend
 - Upstream valves
 - Varying distances from flow disturbances
- Validation of CFD and path integration models with experimental results.

Conclusions

- Modelling shows the IRIS configuration to be 10x less sensitive to installation angle compared to DORTH across simulated axial profiles.
- The measured chordal signal was approximately 14.4 dB below the diametric signal, with correspondingly poorer repeatability.
- Opposing chordal paths isolated an approximately ± 6.14 ns direction-dependent swirl response while diametric paths remained near zero
- The benefits of the IRIS configuration can be gained without losing any of the benefits of DORTH, both can be used in tandem in a flowmeter