Disruptive clamp-on technology to reduce cost

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1 Introduction

Clamp-on flow meters will reduce flow meter total installed cost significantly. However, acceptance in the oil industry is low, due to low accuracy achievements and long-term reliability issues. Xsens AS, a Christian Michelsen Research AS spin-off company, is in the position of releasing new ultrasound clamp-on flow meters, changing the game with respect to accuracy, functionality and flow meter robustness.

Xsens new clamp-on ultrasound transmission concept, enables off-centre beam transmission, forming the functionality of a multi-beam inline transit time flow meter, with respect to flow profile compensation, hence accuracy improvements. The patented Xsens technology achieve this through disruptive acoustic guided wave transmission technology where the pipe wall is used as an advanced transmitting gateway between sensors and signals propagated helically as well as axially in the pipe (patent pending).

This paper explains how the Xsens clamp-on ultrasonic off-centre beam transmission is achieved and discusses test program results demonstrating Xsens flow meter functionality at challenging industrial conditions; installation on standard industry piping at locations down-stream single and double pipe bend configurations.

2 The ultrasonic clamp-on flow meter challenge

One of the main transit time flowmeter issues with respect to accuracy, is the integration from average path flow to a total volume flow, where the meter needs information about the velocity profile. Single path meters rely on models and external inputs only to estimate a flow profile have therefore limited capability of true accuracy improvement. Inline multi-path meters (figure 1 a) sample more points of the flow velocity profile through off-centre paths and by that obtain higher accuracy.

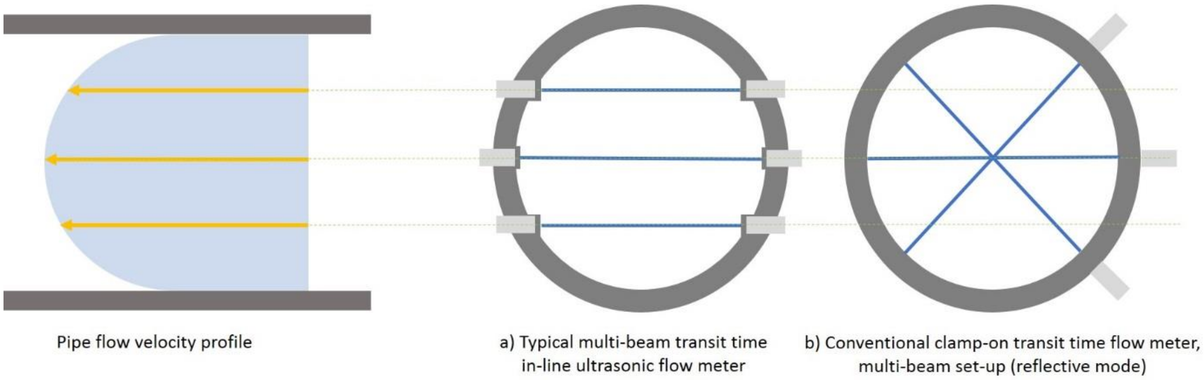

Figure 1: *In-line and clamp-on multibeam transit time flow meters, typical transducer set-up.*

Ultrasonic clamp-on flow meters are also available in multi-path configurations, but up until now without off-centre paths (figure 1b) and the ability to make real world corrections for the flow profile.

With the release of the Xsens true multipath clamp-on flowmeter, this limitation can no longer be attributed clamp-on ultrasonic transit-time flowmeters in general.

3 Principle of operation

The Xsens flow meter is a Lamb-wave type non-invasive transit-time flowmeter, which means that it uses the pipe wall in a guided-wave resonant mode as part of the acoustic transmission. The benefits with this are amplification of the signal, broader volume coverage and almost no susceptibility to beam-drift.

3.1 Transducer waveguides

The transducers are designed to single out and develop the desired guided wave mode in a transducer waveguide before transmitting the signal to the pipe. This allows us to steer the mode-selected guided wave propagation direction in the pipe.

3.2 Diameter paths

Reflective diametral paths are set up by transducer pairs directing the signal axially along the pipe. Two signals are picked up by the receiver for each direction; the direct signal that propagates solely in the pipe wall, and the fluid signal which travels partly in the wall in addition to traversing the diameter twice. The fluid signal has many equidistant paths to the receiver, forming a propagating volume rather than a single beam.

The two signals measured in each direction are used to calculate the sound speeds in the wall and fluid, the angle into the fluid, and the path flow.

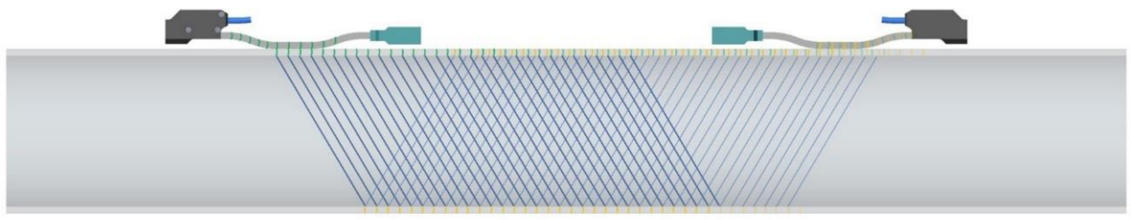

Figure 2: Xsens transducer waveguides and axial acoustic signal transmission

3.3 Annular paths

To non-invasively set-up acoustic paths outside the pipe centre, the transducer waveguides are rotated with an angle, θ_{helix}, to the pipe axis. The signal propagates helically in the pipe wall while emitting acoustic energy into the fluid. The refracted beam angle of the axial pair is used to calculate the chord. The chord is found by rotating the axial beam in accordance with the rotation angle of the helical transducer waveguide.

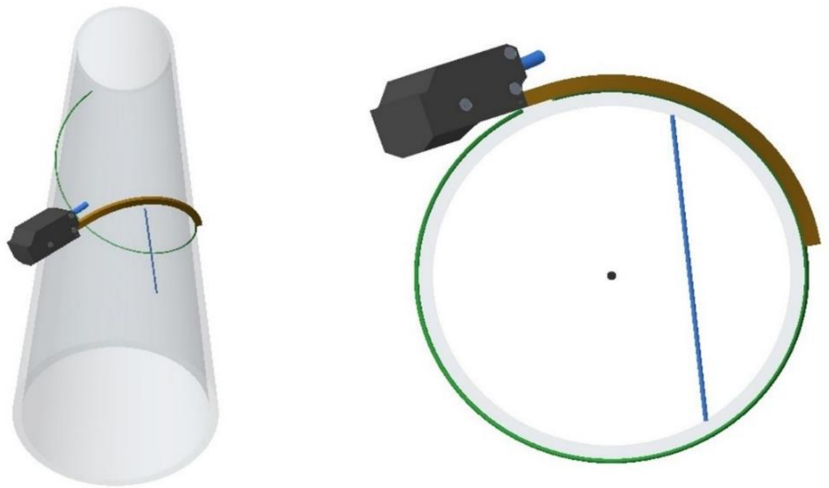

Figure 3 Xsens helical signal exitation and chordal signal transmission

The signal enters the fluid at continuously new angles while the wave propagates helically in the pipe wall (along the green path in figure 3). After having passed through the fluid, the signals enter the pipe and a new helically propagating wave is formed. As for the axial pair, the fluid signal is built up of many equidistant paths to the receiver travelling the same total length in both pipe and fluid to the receiver, see figure 4.

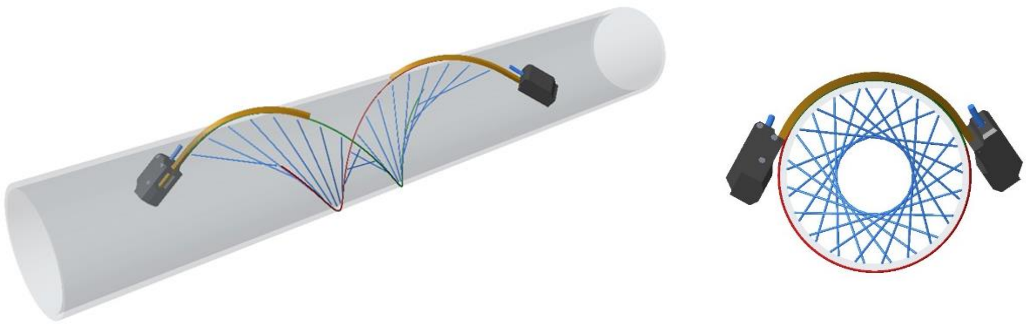

Figure 4: Xsens off-centre transit time signal transmission and set-up of an annular path

Unlike the single chords set-up by an in-line ultrasonic flow meter, wider sectors are covered in this setup. Depending on the distance between transducers, this sector can be set-up to cover a whole circle, i.e. to set up an annular path, see figure 4.

4 Demonstration of multipath operation

The new annular path provides the non-invasive meter with possibilities to correct for flow profiles which only have been available to multipath in-line meters before. A traditional centre path meter must include a Reynolds number and pipe roughness correction of the path flow velocity, typically in the range up to 10%, using *models* of the flow profile only. Centre path flowmeters cannot detect swirl.

For the present demonstration, the meter is installed with different upstream piping configurations with the objective to generate swirl. The off-centre paths are demonstrated by their use in swirl detection and flow profile integration.

4.1 Meter configuration

Figure 5 shows a path configuration and cross-sectional coverage with one reflective centre path and two swirl-cancelling annular paths. In the demonstration, the meter is configured with two additional centre path pairs, offset + and – 60 degrees from the horizontal pair. Meter orientation effects are this way limited to orientation angles less than +-30 degrees.

Figure 5: Left: Xsens flow meter axial and helical transducers.   Right: axial + helical cross-sectional area coverage

4.2 Path integration

With more points on the flow profile curve, the clamp-on meter is rigged to operate as a true multipath meter. Weights are here calculated for a two-path configuration; one at the centre and one at the chord radius for the annular paths, in a similar manner as would have been done for a multipath inline meter. Note that for flow profile integration, the number of paths is related to the *different* radial positions of the chords. The weights are based on numerical integration of fully developed flow profiles published from the Princeton University superpipe experiment data[1]. No effort has been made to compensate for any detected swirl in this work.

4.3 Swirl detection and quantification

Local vortices are cancelled out by the inherent averaging along the acoustic chordal paths within the annular region and a net symmetrical swirl component remains in the measured path flow. Clockwise and counter-clockwise directed helical pairs are used to extract and remove the swirling component from the measurements.

The ratio of the extracted swirling path flow to the mean annular path flow is here taken to calculate an angle indicative of swirling.

4.4 Meter installation, test set-up and CFD analysis.

The flow meter installed for testing is a 6" flow meter for permanent clamp-on installation on standard process piping in Ex. areas, see figure 6.

Figure 6: Xsens flowmeter

The flowmeter was installed in CMR multiphase flow loop in Bergen, Norway. The flow loop has a gravity separator, separating a diesel oil phase from a salted water phase and nitrogen gas phase. The test set-up mimic real offshore/onshore conditions for separator liquid outlet flow measurement, for which Xsens is testing and preparing several measurement systems for offshore installation, first in October 2018.

[1] Zagarola, M. V. and Smits, A. J.: "Experiments in high Reynolds number turbulent pipe flow". *Phys. Rev. Lett.* 78, (1997).

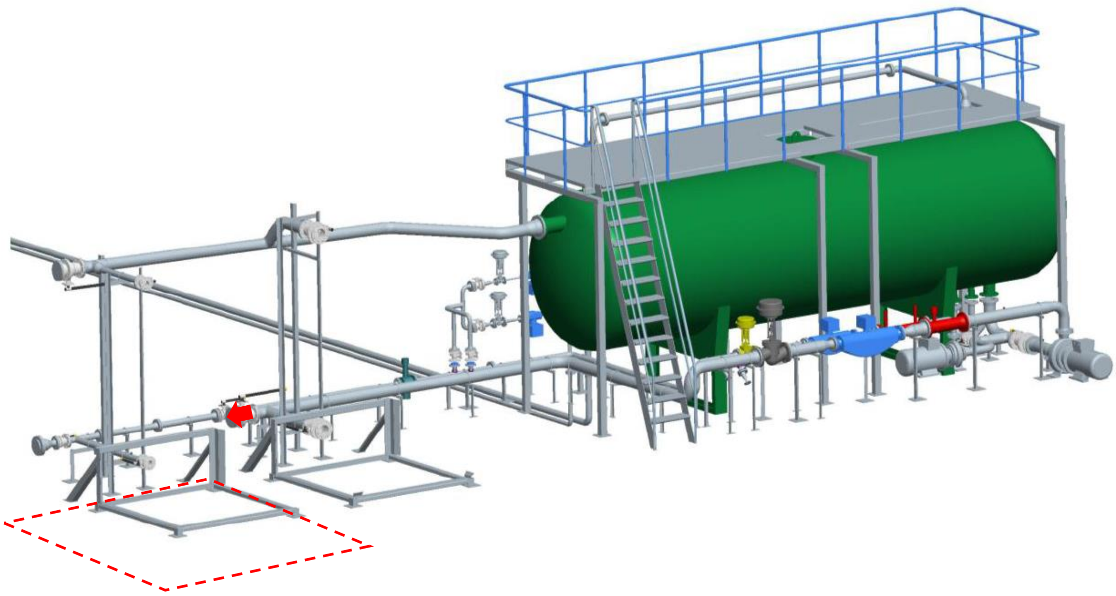

Figure 7: CMR multiphase flow loop. Red arrow and dotted line shows the test set-up start and installation area.

Reference flow meter used was Coriolis flow meter (flow meter position marked blue in Figure 7) calibrated with an uncertainty of < 0,5%.

The meter was installed with several upstream piping configurations as further discussed below. No flow-conditioner was used throughout these tests. The pipe set-up, including different bend configurations, was implemented down-stream a +30D straight pipe (between 90 deg. bend and entry of test set-up, see red arrow at figure 7). *All pipes* used in the test set-up were 6" standard industry spec piping at standard roughness with exception of one 6" 5 m rubber hose at the entry of the test set-up (see pictures included for each set-up). All tests were run on oil.

CFD analysis was established for each pipe bend configuration for simulation of expected swirl effect introduced. The CFD data input consider the conditions swirl free at the entry of the test set-up.

4.5 Flow measurement at single 90 degrees bend inlet conditions

A single 90 degrees bend is expected to introduce Dean vortices in the flow. Along with these vortices, the flow profile is characterised by cross-flow, axial asymmetry and a dip in the centre in the axial profile. CFD simulations 5 and 10 diameters downstream the single bend, has been run, see figure 8 and 9. These show that the intensities of the vortices and the dip in the axial profile increase towards the bend. Symmetry of the vortices should result in a low "net symmetric swirling".

The Xsens flowmeter is installed in two locations; 5 and 10 diameters downstream the single bend, see pictures included in figure 8 and 9.

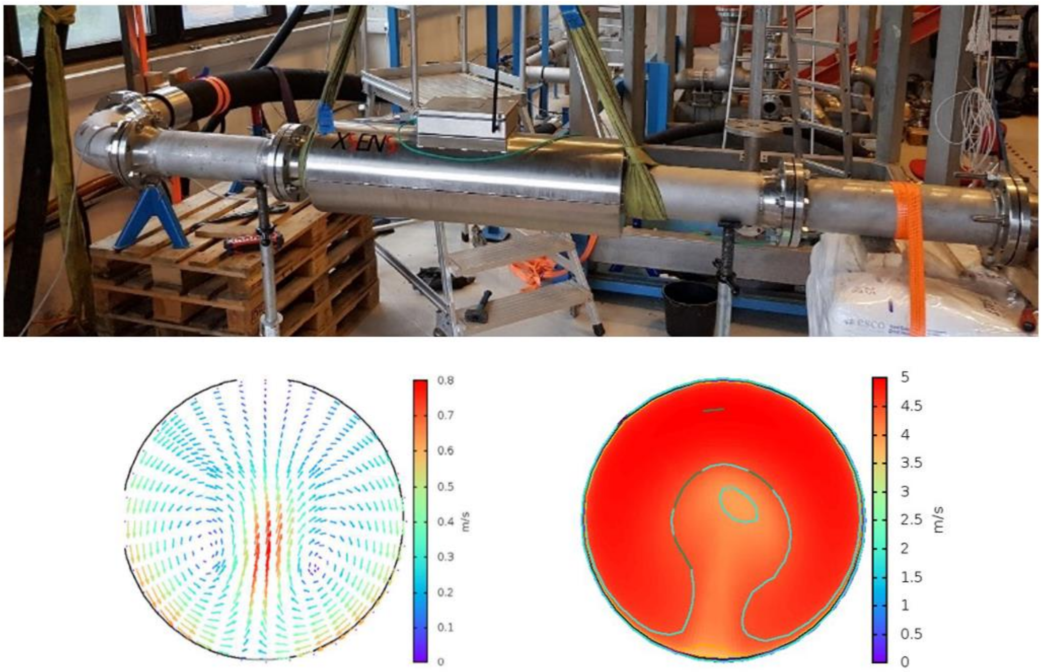

Figure 8: Meter installation after single bend + 5D, CFD @ Reynolds number 200 000

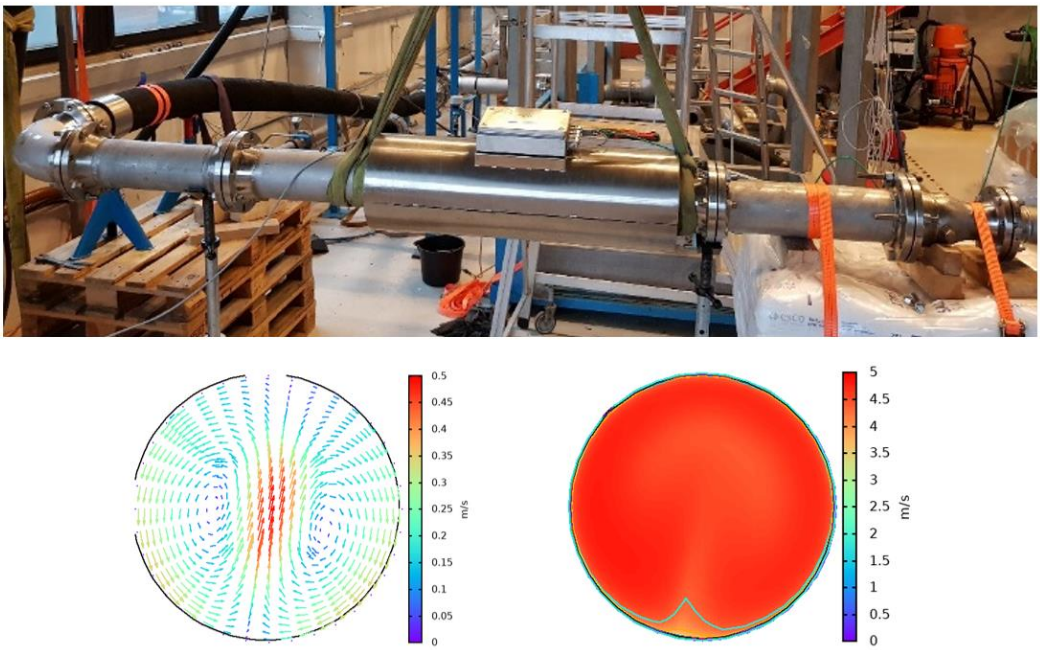

Figure 9: Meter installation after single bend + 10D, CFD @ Reynolds number 200 000

4.6 Double bend in-plane

A less predictive characteristic flow profile is found in the simulations of a double bend in-plane (figure 10). The swirling pattern changes dramatically with Reynolds number. Asymmetric vortices indicate a higher net symmetric swirling than for the single bend case.

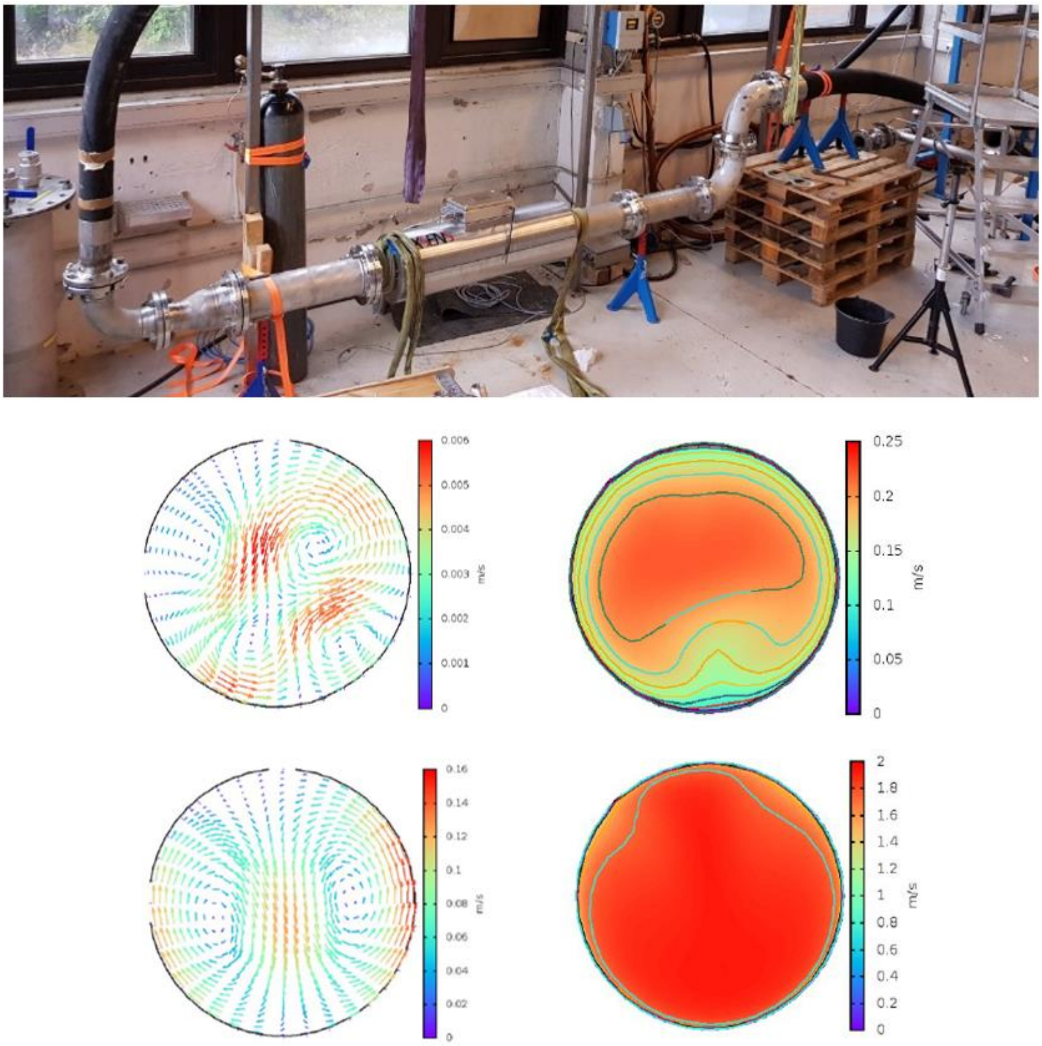

Figure 10: Meter installation after double bend in plane + 10D, CFD @ Reynolds number 20 000 and 200 000

4.7 Double bend out-of-plane

The meter installation and CFD simulations for this configuration are shown in figure 11. A much higher net symmetric swirl is indicated by the simulations as only one vortex remains.

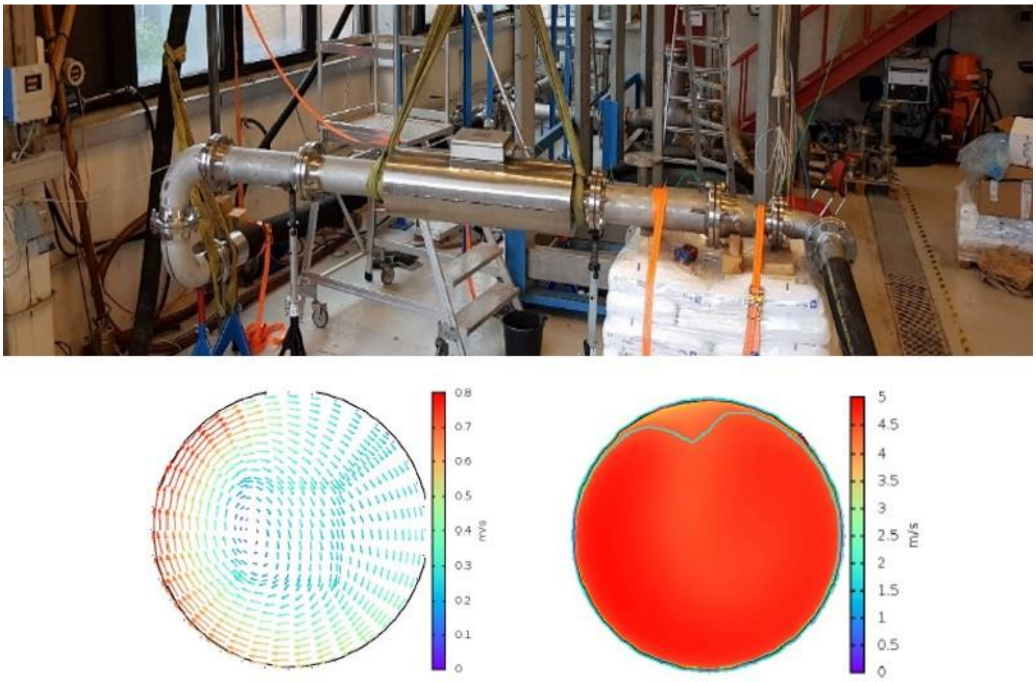

Figure 11: Meter installation after double bend out of plane + 10D, CFD @ Reynolds number 200 000

5 Results

In the test runs for this demonstration, flow rates have been set and held steady for 6 minutes. The path flows are compared to the average flow velocity in the cross section of the pipe read from the reference instrumentation. The centre path flow is the average of the three axial pairs. The swirl angle is calculated as the tangent to the ratio of the difference to the mean of the annular paths. Counter-clockwise, as seen in the direction of the flow, is defined as positive angle. Flow profile integration is performed by weights and the meter had not stored any information about the flowing medium. The meter continuously calculated the chord radius of the annular paths. On the average, this chord radius was 0.499R throughout these tests. Gridlines at ±1% are included in the deviance plots to visualise the shifts in range on the y-axis.

5.1 Single bend

Installation requirements for ultrasonic flowmeters are typically at least 10 diameters downstream a single bend. Our results from such a location are shown in figure 12.

The annular paths here clearly picked up a swirl (clockwise with an angle in the range 12-18°). Notice the large deviation from reference and the difference between the two annular paths.

The meter flow reading shows that the swirl is successfully cancelled out and flow profile integration efficiently corrects for the diameter path flow over-reading to keep the results within 1%. With respect to the test objectives, this clearly demonstrates the multipath operation of the non-invasive meter. Note, however, that by the CFD simulations this upstream pipe configuration was not expected to produce such a significant swirling.

The flow profile is even more distorted closer to the bend. Five diameters downstream the bend (figure 8) the swirl angle has increased, but only by a few degrees. It is also more clearly increasing with Reynolds number.

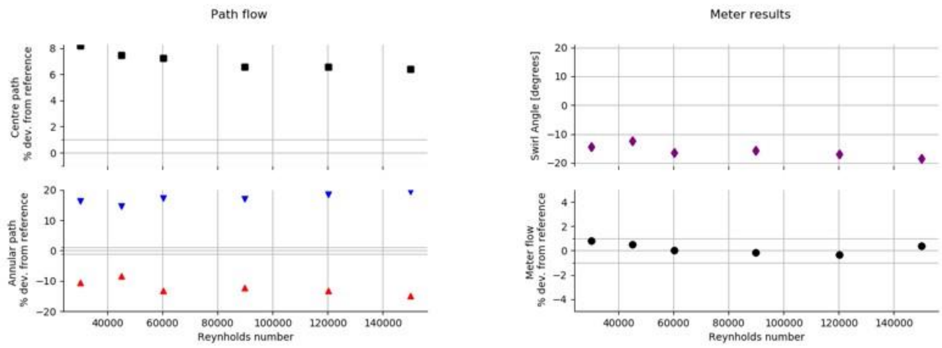

Figure 12: Single bend+10D, results.

The meter flow has an offset of about +2.2%, see figure 13, this could be due to a distorted axial profile (deviances from the fully developed flow profile), where for this profile the annular paths are weighted too high.

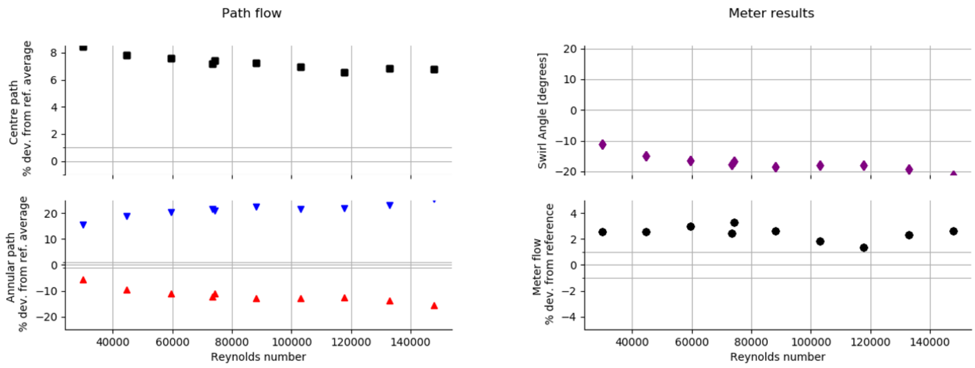

Figure 13: Single bend + 5D, results

5.2 Double bend in-plane

Similar to the single bend configurations, the double bend in-plane test showed a somewhat unexpected swirling, see figure 14. The clockwise swirling was here around 10°.

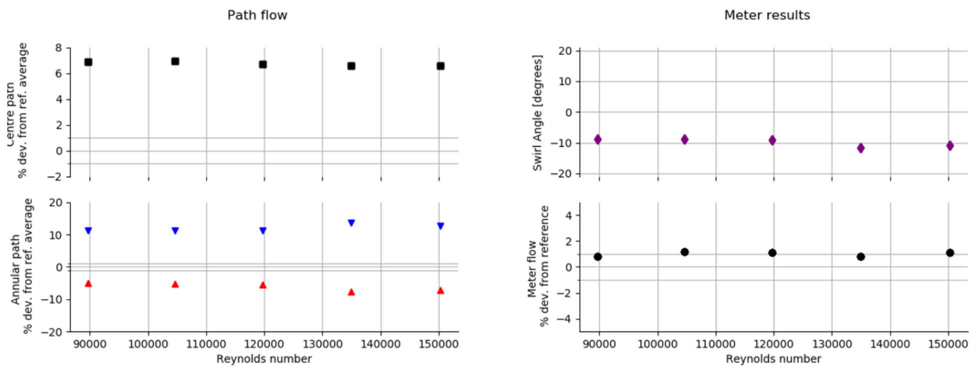

Figure 14: Double bend in-plane, results.

5.3 Double bend out-of-plane

To increase the bend complexity further, an out-of-plane double bend was installed upstream the flow meter. Results showed (figure 15) a weaker net symmetrical swirl, oppositely directed compared to the previous configurations. The meter reading was in the 1% band.

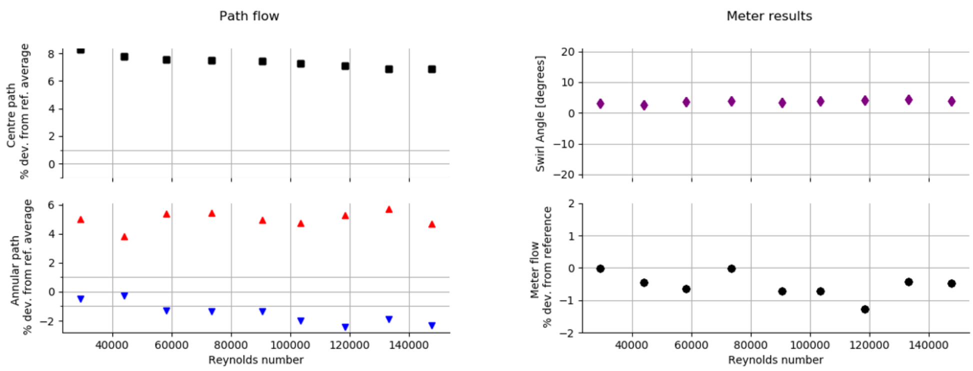

Figure 15: Double bend out-of-plane, results

6 Discussion

Velocity profiles are quite complex, and for disturbed flows even more so. A significant net clock-wise swirling was detected for both the in-plane and single bend pipe configurations, while the "left-handed" the out-of-plane upstream bends resulted in a weaker and counter-clockwise swirl. This contrasts with the flow profiles simulated using CFD. These results could be explained by an upstream distortion in the form of a clockwise swirl. Swirls can "survive" over long distances and could have been created in the complex piping at the outlet of the separator. Notice also the flexible hose, which in effect introduces a double in-plane bend over its 5 meters length, when lifted. Such distortions could follow through the first two pipe configurations while be equalized by the double bend, as observed in the results.

This suggests that, if CFD is used to estimate a flow profile at the meter location, sufficient upstream piping must be included in the simulations.

7 Conclusion

A non-invasive transit-time ultrasonic flowmeter with off-centre paths has been realized with no requirements for modifications to a pipe with circular cross section for clamp-on installation. Off-centre acoustic path propagation was demonstrated by its ability to detect swirl and compensate for changing flow profiles using weighting factors to integrate the measured path flow. Xsens has by this opened for possibilities to improve measurement accuracy with methods that hereto only has been available to in-line multipath ultrasonic flowmeters.