Flow Disturbances and Flow Conditioners: The Effect on Multi-beam Ultrasonic Flowmeters

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1. INTRODUCTION

Over the past years a lot of experience with the five beam ultrasonic flowmeters on fiscal applications has been obtained [1], [2], [3]. Ultrasonic flowmeters have gained full acceptance and customers are using the five beam ultrasonic flowmeters in a growing number of fiscal transfer metering applications worldwide. More recently, three path ultrasonic flowmeters have been introduced for custody transfer applications [4]. The success of ultrasonic flowmeters can be attributed to their inherent benefits: no moving parts, no wear, low pressure drop, wide rangeability and minimal maintenance.

Many National Weights and Measures Authorities worldwide have approved the use of ultrasonic flowmeters for fiscal metering. An important step forward in the acceptance of ultrasonic flowmeters is the release of a standard by the American Petroleum Institute (API) "Measurement of Liquid Hydrocarbons by Ultrasonic Flow Meters" in February 2005 [5],[6].

Now that custody transfer flow measurement with multi path ultrasonic flow meters are increasingly accepted in the market, further development has been focussed on increasing robustness of installation and on simplifying calibration, commissioning and operating procedures. We have found that proper flow conditioning is an essential part of this development.

This paper describes the experience with different types of flow straighteners focussing on:

- Constructional aspects
- Effects on linearity
- Effects on disturbances
- Effects on turbulence intensity

2. FLOW CONDITIONERS: CONSTRUCTIONAL ASPECTS

2.1 ISO tube bundle flow straightener

The ISO tube bundle flow straightener (according to ISO/DIS 5167-2) consists of 19 tubes arranged in three concentric circles. The length of the bundle 'shall be between 2D and 3D, preferably as close to 2D as possible' [7]. Attention must be paid to a number of geometrical issues as mentioned in the ISO-standard.

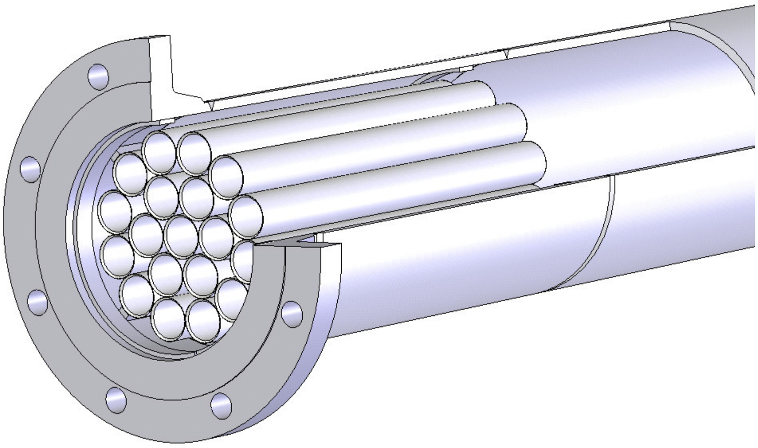

Figure 1 Example of a tube bundle flow straightener according to ISO/DIS 5167-2.

One of the important remarks in the standard is that ‘it is important to ensure that the tubes are parallel to each other and to the pipe axis’. If this is not the case the resulting flow profile will be non-symmetric. Even a swirling flow can be introduced.

An extensive flow investigation has been done to gain understanding of the effects of production tolerances on flow profiles.
A glass model of the ultrasonic flowmeter has been build which was mounted in a flow loop. This test rig was filled with a liquid with a refraction index equal to that of the glass. This enables us to carry out precise LDA measurements at any arbitrary spot in the flowmeter (see Figure 2).

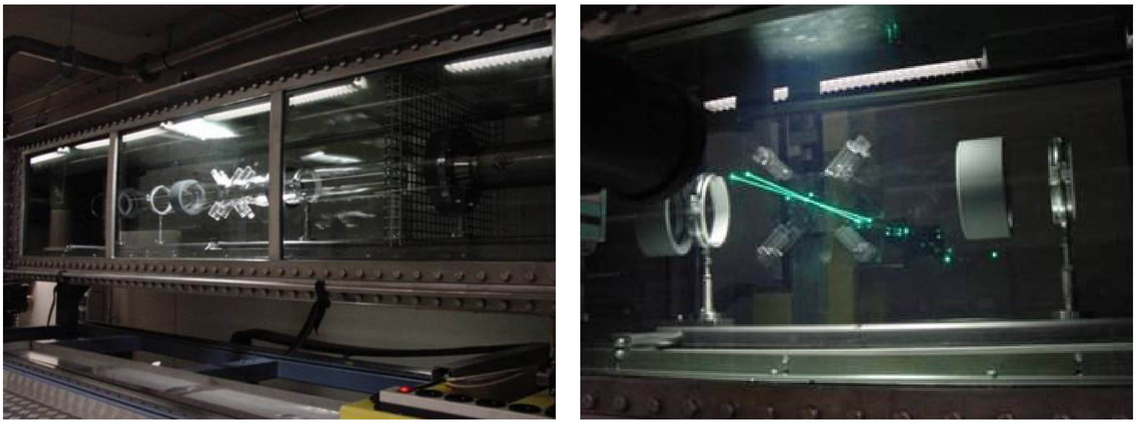

Figure 2 Experimental test rig in which the refraction index of the glass model flowmeter and the liquid are equal.

Figure 3 illustrates the sensitivity of the flow profile to the design and construction of an ISO tube bundle. During this test it turned out that the measured velocity profile was fairly non-symmetric for Reynolds number 3900 and higher (filled markers).
The results indicated by the filled markers were obtained with a tube bundle that was constructed in accordance with the ISO standard. This was confirmed by inspection afterwards.

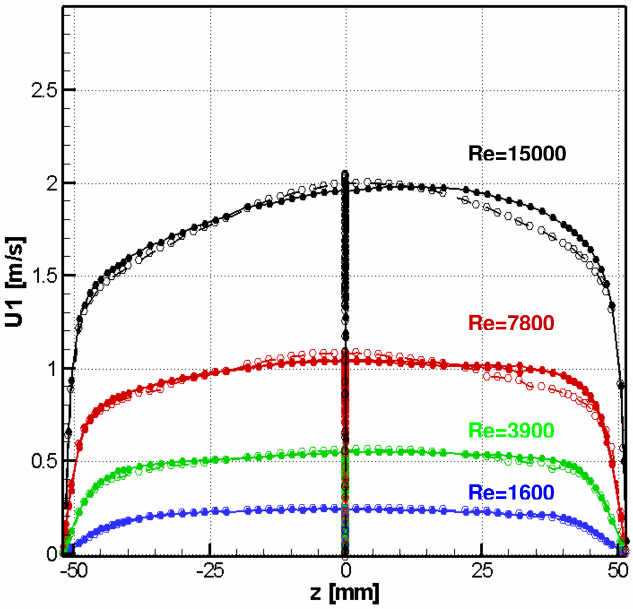

Figure 3 Velocity profile in vertical direction measured with LDA. Filled markers indicate the velocity profile about 7D behind an ISO tube bundle which is not properly constructed. The open markers indicate the velocity profile measured with a properly produced tube bundle.

We conclude that the tube bundle must be build very carefully. A regular check during the different phases in the manufacturing process is very important. Inspection afterwards is not sufficient, since important dimensions can not be measured after completion anymore. We implemented our additional procedures on top of the ISO specifications.

If these procedures are applied, the quality of the velocity profile is guaranteed (open markers). Furthermore, the experience is that a bundle length of 4D is required.

2.2 Etoile flow conditioner

Because the proper construction of an ISO tube bundle is complicated, we have looked at much simpler alternatives such as the Etoile flow conditioner.

The construction of an Etoile conditioner is based on three plates in a star-like configuration (see left-hand figure of Figure 4).

Also for the design of the Etoile flow conditioner it holds that a number of requirements must be fulfilled. The construction must be simple from the manufacturing point of view. So, the number of parts must not be too large, and it must not be too difficult to meet the production tolerances. Otherwise, the conditioner becomes too expensive.

Another requirement is that the construction must be stable during operation. Vibrations and resonance modes must be prevented in order to avoid undesired whistling sounds and rupture due to fatigue.

Since the construction of an Etoile Flow Conditioner is based on plates a thorough resonance analysis has been carried out.

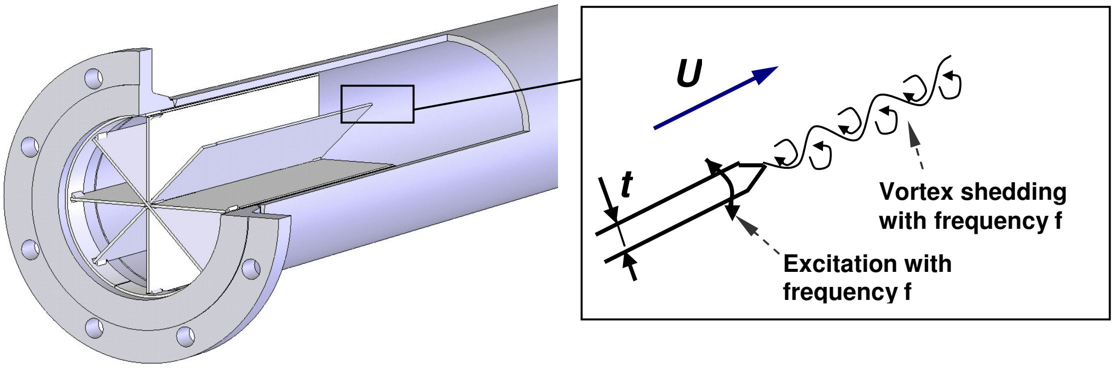

Figure 4 The construction of an Etoile flow conditioner is based on three plates that are put together. At the very end of the conditioning plates (trailing edge) vortex streets are created. As a result of this vortex shedding, an alternating pressure is acting on the conditioning plates.

From literature it's well-known that vortices are generated behind a bluff body and behind a flat plate. As a result of these vortices, an alternating force is acting on the conditioner plate (see right-hand figure of Figure 4). In the case that the vortex frequency matches the resonance frequency of the plate, the oscillation of the plate is amplified.

The vortex frequency is given by the simple relation:

$$\mathrm{Sr} = \frac{f \cdot t}{U} \qquad \text{Eq. 1}$$

Where: U=flow velocity [m/s], f=vortex frequency [Hz], t= thickness of the plate [m] and Sr is the Strouhal number [-].

In this relation the Strouhal number can be considered as constant over the normal flow range with a value of about 0.2. As a consequence the excitation frequency is directly proportional to the flow velocity.

This implies that with increasing flow velocity the excitation frequency increases (blue line in Figure 5).

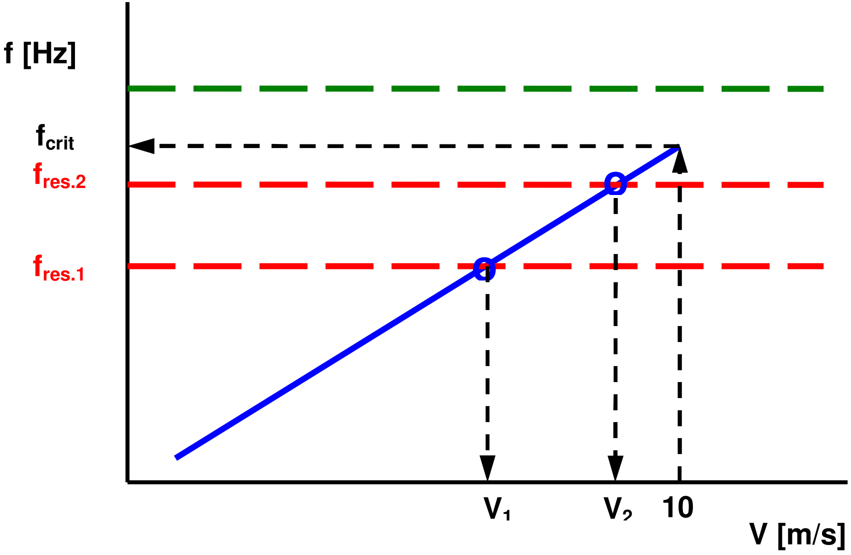

Figure 5 Blue line: relation between vortex frequency and flow velocity (Eq.1), Red lines: resonance frequencies of the conditioner that are in the normal operating range,

amplification occurs at v_1 and v_2,, Green line: resonance frequency of the conditioner above the maximum vortex frequency, $f_{crit.}$.

Because of this mechanism the construction is excited by a frequency band. If a certain frequency matches the resonance frequency of the construction, amplification occurs (crossing of blue solid line with red dashed lines in Figure 5). The solution is to increase the stiffness of the construction in such a way that the resulting resonance frequency becomes higher than the highest excitation frequency f_{crit}. (green line in Figure 5).

This mechanism has been confirmed both by numerical analysis and experiments. An example is shown in Figure 6. The numerical analysis of an Etoile straightener (3 inch pipe) shows the first resonance frequency at 394 Hz.

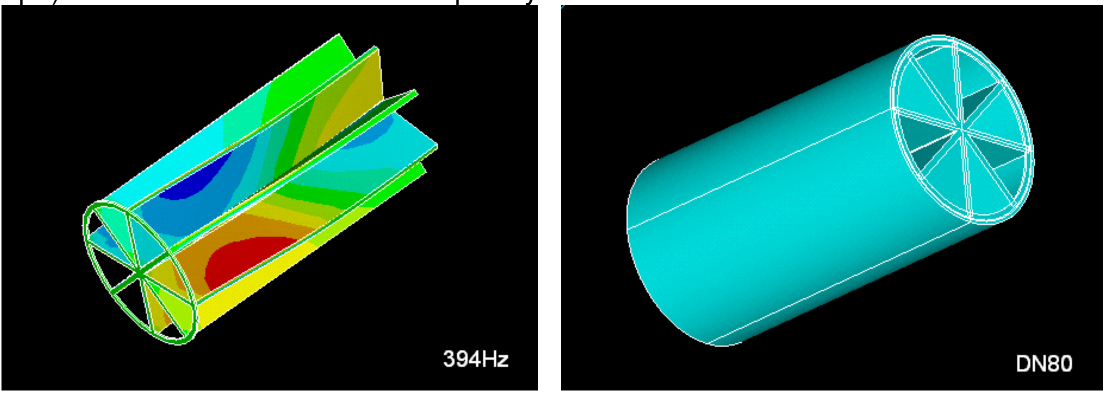

Figure 6 Resonance frequency analyses (3 inch) of an Etoile flow conditioner. The conditioner is fixed to the pipe just in the front by means of a ring. The colors indicate the strain.

According to eq. 1 the flow velocity at this vortex frequency corresponds to 5.9 m/s (with t=3 mm). Experiments in a test rig with equally constructed Etoile flow conditioner generated a whistling tune at 6 m/s. The whistle frequency that has been measured was 378 Hz. This example illustrates that the dynamic behaviour of the Etoile flow conditioner can be predicted fairly accurate.

Depending on the stiffness of the construction more or less resonance frequencies are observed. In a worst case scenario, an Etoile flow conditioner can have several resonance frequencies in the operational flow range. The first mode (with lowest frequency) can be suppressed by welding the conditioning plates to the pipe at several spots in the axial direction. Even than, different resonance modes are still possible, as shown in Figure 7.

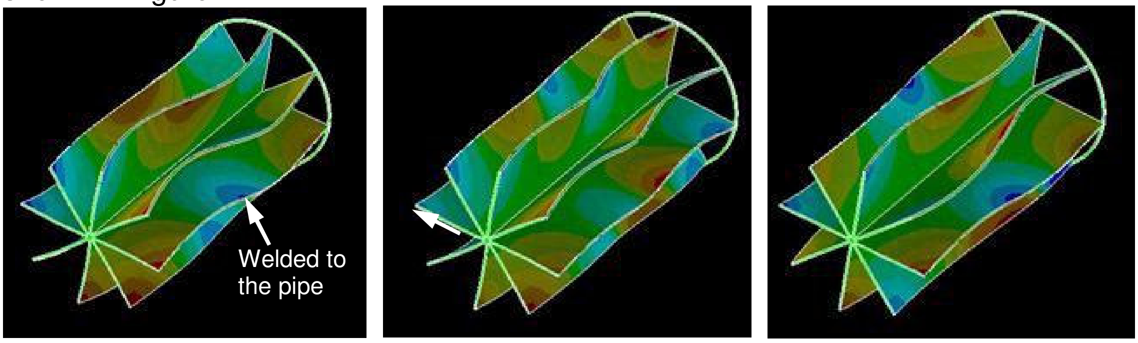

Figure 7 Example of different resonance modes of an Etoile flow conditioner in a three inch pipe. In this configuration the plates have been welded to the pipe on one spot half way the length of the plate.

Important is the requirement that the design must made in such a way that it still can be manufactured.

Design guidelines have been developed for the diameter range starting at 2 inch up to 10 inch. If these design guidelines are followed, resonance will not occur in the normal flow range up to 10 m/s.

The design of sizes of 10 inch and larger is more complex. The plates are getting less stiff and welding to the pipe along the entire length seems unavoidable. However, this is not practical during manufacturing. Increasing the stiffness by increasing the plate thickness won't help: the mass that is added destroys the stiffness that is gained.

3. EFFECT OF FLOW PROFILE DISTURBANCES

3.1 Linearity without flow conditioner

As a first step the linearity has been established in a piping configuration without flow conditioner and without active flow profile disturbances. Three uncorrected linearity curves of a three path ultrasonic flowmeter (3") are shown in Figure 8. A non-linearity of about ±0.2% is observed.

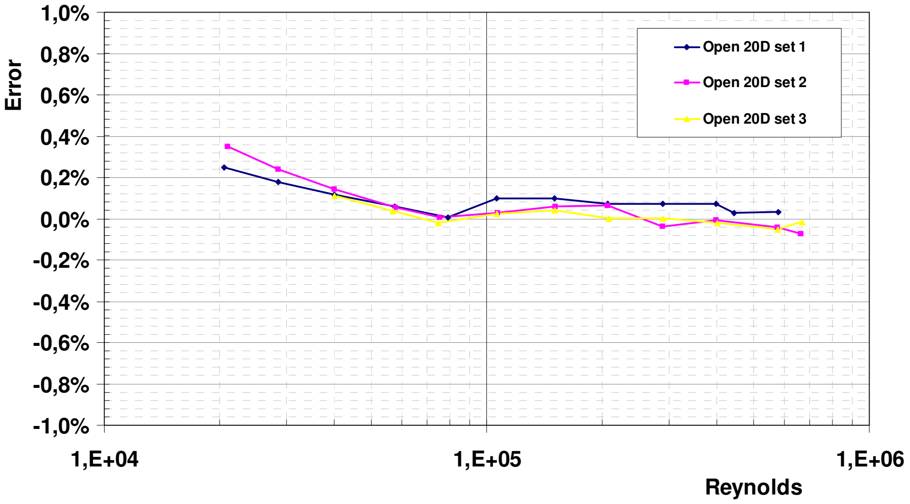

Figure 8 Three uncorrected linearity curves of a three path UFM. No flow conditioning measures have been taken.

3.2 Effect on linearity with an Etoile flow conditioner

Figure 9 shows the linearity of a three path UFM in combination with an Etoile flow conditioner.

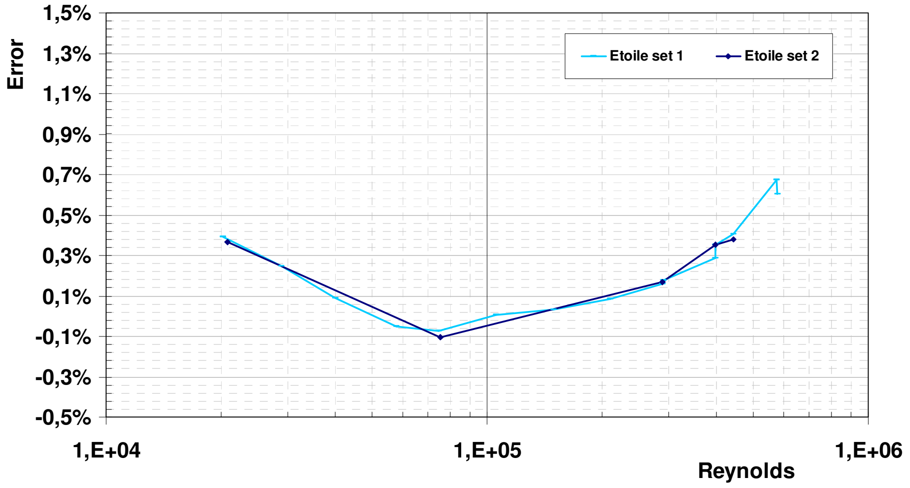

Figure 9 Linearity of a three path UFM with Etoile flow conditioner mounted in a 10D inlet pipe run.

If we compare Figure 9 with Figure 8 it can be observed that an Etoile flow conditioner introduces a non-linearity even in the absence of any disturbance. Whereas the linearity without flow conditioner is about ±0.2%, the linearity now has increased to about ±0.3%. This result is disappointing because the linearity becomes worse. Furthermore, the linearity curve doesn't become horizontal at higher Reynolds numbers.

3.3 Effect on linearity with an ISO tube bundle flow straightener

The effect of an ISO tube bundle straightener is shown in Figure 10. There is no significant change in linearity as a result of the tube bundle. The overall linearity is clearly within ±0.2%.

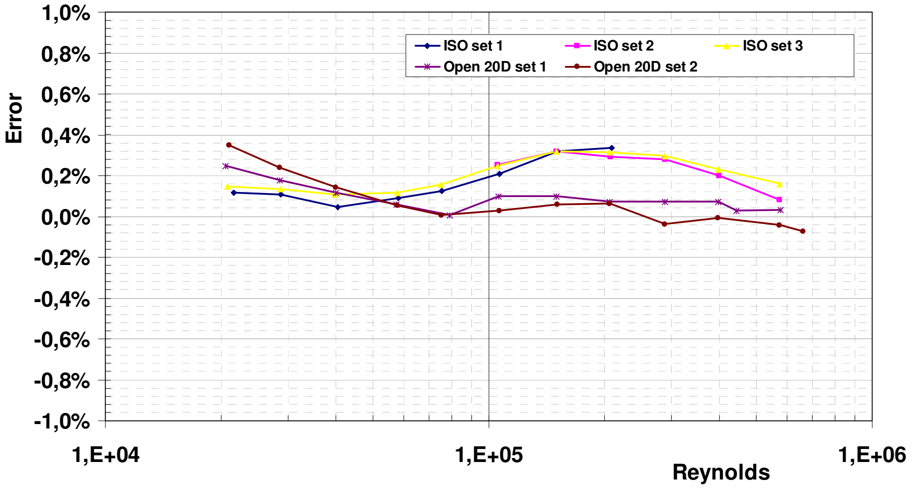

Figure 10 Linearity curves of a three path UFM with ISO tube bundle at 10D compared to the linearity curves without flow conditioner.

3.4 Effects on linearity of different types of disturbances

Different types of disturbances have been used. An overview of the disturbing plates is given in Figure 11. In addition two space bend configurations have been used. One in a normal position, the other 90º rotated along the axial axis.

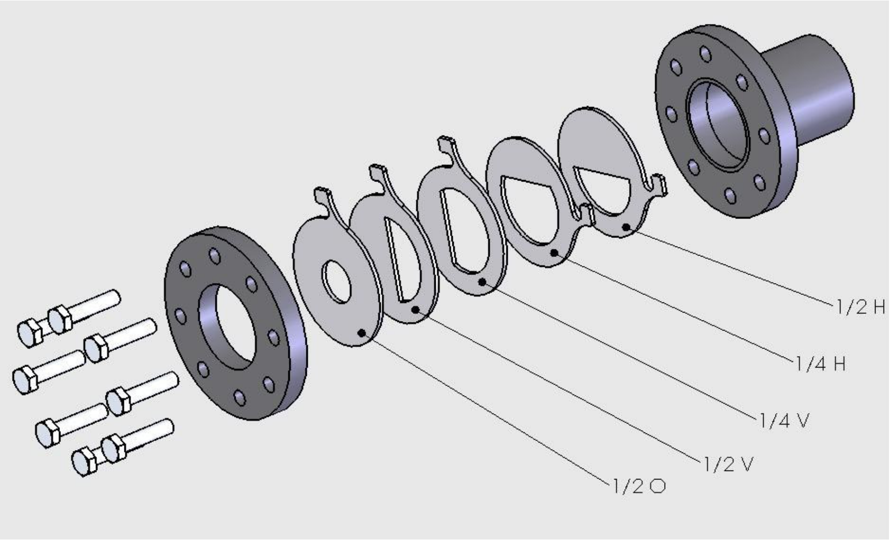

Figure 11 Five standardized flow profile disturbing plates; orifice plate with an inner diameter of ½ D (indicated by ½ O), plate of which half the diameter is blocked in

vertical (½ V) and horizontal (½ H) direction and a plate of which a quarter of the diameter is blocked in vertical (¼ V) and horizontal (¼ H) direction.

These disturbances have been offered to a three path UFM (ALTOSONIC III) in a configuration without flow conditioning. The disturbances have been introduced 20D upstream of the flowmeter. An overview of the result is shown in Figure 12.

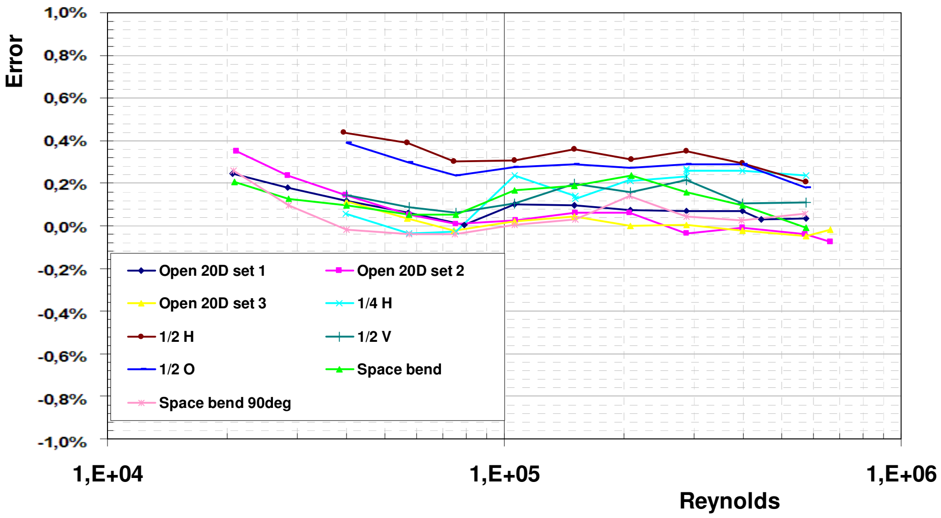

Figure 12 Effect of disturbances on a three path UFM without flow conditioner.

From this figure it can be observed that all curves fall within a bend of 0.4%. It is interesting to see that if there is a shift as a result of a disturbance, the shift is always positive.

Furthermore, it can be seen that the linearity is hardly affected. There is one exception. This is the ¼ V disturbance. The effect of this disturbance turns out to be twice as large as the effect of the ½ H which is 2nd worst.

3.5 Effect of flow disturbances with an Etoile flow conditioner

The attenuating effect of an Etoile flow conditioner is disappointing. Figure 13 shows, the effect of two types flow profiles disturbances (¼V and ¼H). The effect of the ¼V disturbance is even amplified.

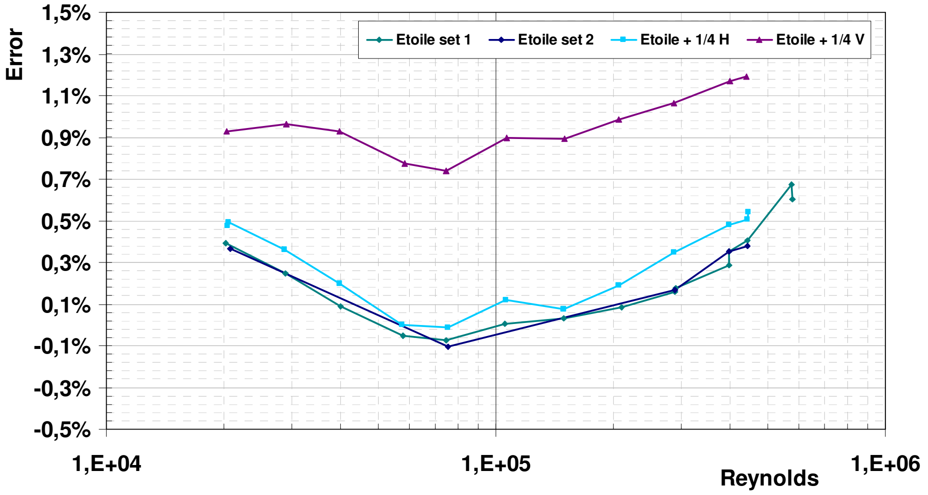

Figure 13 Effect of two different flow profile disturbances with an Etoile flow conditioner.

The linearity is not affected that much. As it was the case in the configuration without straightener, the meter shows an over reading in case of a disturbance here as well.

3.6 Effect of flow profile disturbances with an ISO tube bundle straightener

Extensive tests have been carried out on the sensitivity to flow profile disturbances of a three path UFM in combination with an ISO tube bundle flow straightener. An overview of the results is shown in Figure 14. An initial linearization (for the basis non-linearity observed in Figure 10) has been applied. It is important to note that the scale resolution of the vertical axis is twice as big as in the other figures.

From Figure 14 can be concluded that the linearity is hardly affected in this Reynolds range.

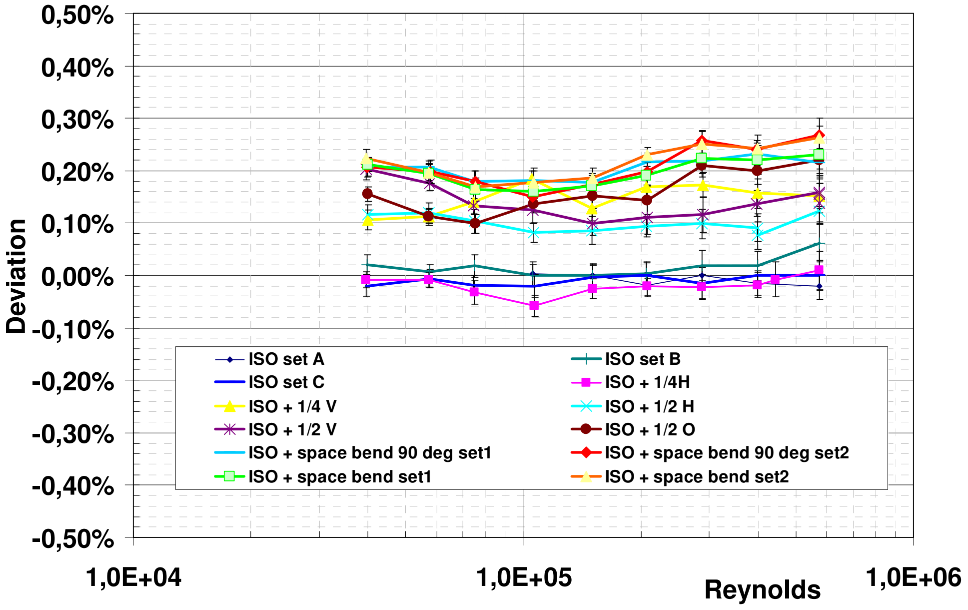

Figure 14 The effect of flow profile disturbances on a three path UFM using an ISO tube bundle flow straightener. The disturbances have been offered 10D upstream of the ISO tube bundle.

The effect on linearity is only about ±0.05%. Furthermore, the shift is always positive. Another very important conclusion is that the value of the shift is relatively low. About 0.1% to 0.2%.

This result shows that if proper measures are taken, the three path ultrasonic flowmeter reading stays within ±0.15% for all disturbances that have been tested.

4. EFFECT ON TURBULENCE INTENSITY

4.1 Turbulence intensity measurements

Turbulence intensity does have an effect on short term repeatability of an UFM. Since an UFM measures the velocity without interfering with the flow, turbulence is being measured as well. There are no inertial forces in the measuring principle that averages out the effect of turbulence. The consequence is that turbulent noise is measured on the actual flow. This can lead to a somewhat longer calibration run in order to get the right repeatability [1], [8], [9]. The higher the turbulence intensity, the stronger the effect is.

Flow straighteners do affect the turbulence intensity significantly. A very direct measure of the effect of turbulence intensity on an ultrasonic flowmeter is the standard deviation that is being measured by the flowmeter. The result of different configurations is shown in Figure 15. The relative standard deviation on the vertical axis is the standard deviation at that specific Reynolds number related to the average velocity at that Reynolds number.

The velocity which is used, is the velocity composed of velocities that are measured along the acoustical paths at three fixed positions in the pipe.

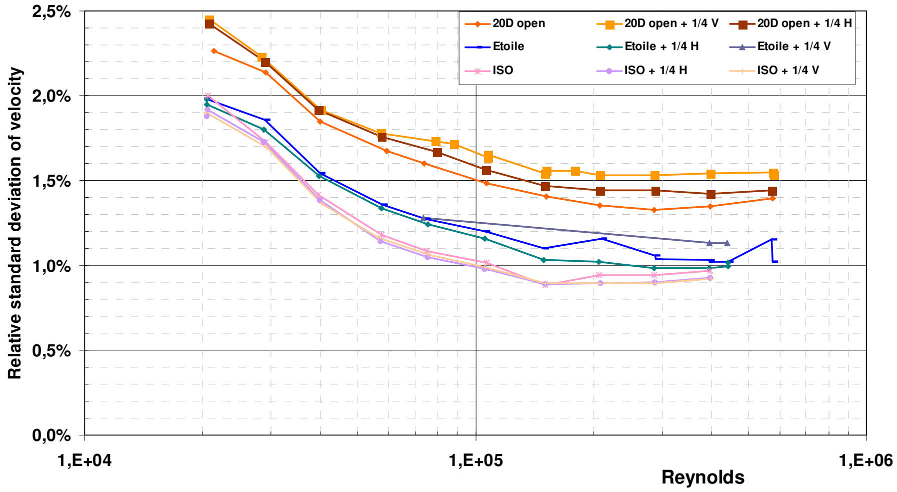

Figure 15 Relative standard deviation of the velocity as function of Reynolds for three different flow straighteners in combination with two flow profile disturbances.

Three different piping configurations have been used: a configuration without flow conditioning measures, a configuration with the Etoile flow conditioner and one with the ISO tube bundle straightener. It can clearly be seen that the configuration without flow conditioning results in the highest turbulence intensity. The configuration with the lowest intensity is the set-up with the ISO tube bundle. From the physical point of view this is expected. The smaller the straightener holes, the smaller the turbulent eddies are and the lower the measured turbulence intensity is.

It can also be observed that the effect of flow profile disturbances is the smallest when using the ISO tube bundle. No significant difference can be noticed between the undisturbed configuration and the situation where the horizontal and vertical disturbance is applied. This is not the case in the configuration with the Etoile conditioner and without conditioner. Especially in the configuration without flow conditioner the relative standard deviation increase to values above 2.0% in case of a disturbance where half the area is blocked (½H and ½V) for Reynolds numbers above 10^5.

Figure 16 shows the effect of a number of flow profile disturbances on the relative standard deviation. It interesting to observe that there is no significant difference.

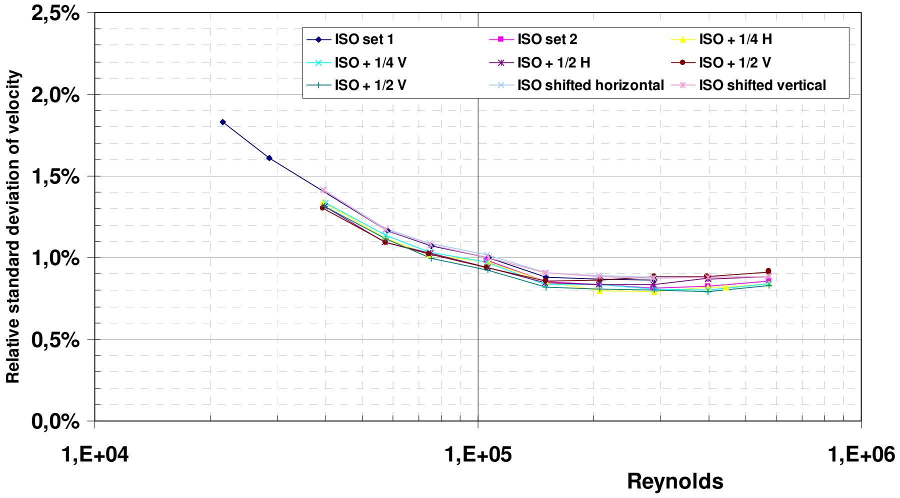

Figure 16 Relative standard deviation of the velocity as function of Reynolds for a configuration with an ISO tube bundle straightener in combination with a number of flow profile disturbances.

It is very important to note that these relative standard deviation measurements are a result of integration along a line (acoustical path). Furthermore, the path configuration is fixed. The velocity profile changes with Reynolds number and the turbulence intensity distribution changes as well. If LDA measurements are carried out in the centre of the pipe on one spot to determine the turbulence intensity as a function of Reynolds, the figure would look totally different. In that case the turbulence intensity would increase with increasing Reynolds number.

5. CONCLUSIONS

Knowing the effect of flow conditioning and upstream disturbances on ultrasonic flowmeters allows design of metering systems less influenced by the environment it is installed in thus simplifying commissioning and operation procedures. In addition this knowledge enables the application of new (offsite) calibration concepts and procedures.

5.1 Constructional aspects

Analysis has shown that both the Etoile and ISO tube bundle flow conditioner must be constructed carefully.

The Etoile conditioner easily suffers from resonance frequencies leading to whistling tunes and even damage due to fatigue. For sizes of 10” and larger it is getting very difficult to develop straight forward design rules in order to get a stable flow conditioner which can be manufactured easily.

The ISO tube bundle must be constructed carefully as well. If the tube bundle is manufactured inaccurate the resulting flow profile shall be non-symmetric and even can have a swirl.

5.2 Linearity

In general the linearity is not improved by using flow straighteners. The effect of an ISO tube bundle is not strong in the Reynolds range that has been studied. The Etoile flow conditioner clearly leads to an additional non-linearity.

5.3 Repeatability

The ISO tube bundle straightener improves the repeatability with a factor of two. This is independent whether there is a flow profile disturbance or not. When using an Etoile conditioner there is still some influence of flow profile disturbances on the short term repeatability. This is not the case with an ISO tube bundle. Consequently, it is advised to always install an ISO tube bundle to generate optimal proving conditions.

5.4 Effect of flow profile disturbances

The ISO tube bundle straightener is much more effective than the Etoile conditioner. Based on experiments with many types of disturbances, it can be concluded that, if there is a shift, the shift is always positive. The maximum shift that has been observed is 0.2%.

The shape of the linearity curve remains similar when using an ISO tube bundle. Furthermore, it has been observed that an ISO straightener reduces the effect of a disturbance approximately with a factor of two.

The Etoile conditioner is less effective. In fact, no improvement with respect to flow profile effect reduction has been observed. This does not imply that the Etoile conditioner is worthless. CFD analysis has shown that in specific cases of unstable flow profiles, the Etoile flow conditioner can be helpful [10].

Summarizing, it can be concluded that a three-beam ultrasonic flowmeter (ALTOSONIC III) stays within ±0.15% (for the disturbance types that have been tested) when using an ISO tube bundle. This conclusion can be made on the condition that the ISO tube bundle is constructed carefully.

6. REFERENCES

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7. ACKNOWLEDGEMENT

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