Experimental and numerical investigation of new bluff body design for vortex flow meters

Tournillon, Sylvain and Krisch, Henrik
KROHNE Messtechnik GmbH
Ludwig-Krohne-Straße 5
47058 Duisburg, Germany

von Lavante, Ernst and Gedikli, Ali
University of Duisburg-Essen
Lotharstr. 20
47057 Duisburg, Germany

Abstract

In the present investigation, the task of further improvement of accuracy of determination of volumetric flows by employing the so-called vortex-shedding flow meter by using a novel design of the bluff body has been studied. Based on earlier investigation, in which the focus was on signal processing, it was decided by the present authors to study in more detail cylindrical bluff bodies with thread or with grooved surface, with ring-type ribs of various high and width arranged circumferentially. Unlike in the case of a smooth cylinder, the ribs obviously stabilized the flow in the boundary layer und suppressed the development of axially oriented vortices. The resulting frequency variation as a function of the flow velocity and, with that, the Reynolds number, was much more regular, displaying good linearity. Correspondingly, the so called k-factor also showed a great improvement as compared to a simple smooth cylindrical bluff body.

Introduction

Many chemical and environmental processes found in the corresponding industries require volume- or mass flow data for their completion. Number of promising new methods for flow rate measurement have been recently developed. One relatively simple flow measurement device is the so-called vortex-shedding flow meter, in which the volumetric flow is determined by observing the relationship between the vortex-shedding frequency from a bluff body attached inside a channel, and the corresponding mean velocity about it. The bluff body causes production of a system of periodic vortices (von Karman vortex street), whose frequency can be correlated with the mean flow velocity and, therefore, the volumetric flow. This procedure assumes a regular and well defined vortex structure as well as shedding mechanism, resulting mostly in linear dependency of the volumetric flow on the shedding frequency over a wide range of Reynolds numbers.

In principle, the vortex-shedding flow meters (VSFM) use the separation frequency of vortices behind a bluff body to measure the mean flow velocity of a fluid flow. Downstream of the bluff body, von Karman vortex street develops; its width D and distance T between the vortices depend on this frequency, and therefore on the bluff body's shape. Preferably, the vortex-shedding frequency should depend linearly on the mean flow velocity for a wide Reynolds number range. The dependency of the vortex frequency f, the mean flow (bulk) velocity u_m and the width of the bluff body D is expressed by the dimensionless Strouhal number Sr:

$$Sr = (D \cdot f\,) / u_m$$

or the dimensional k-factor:

$$k = f / Q$$

with Q being the volumetric flow rate.

By now, commercial vortex flow meters use a large variety of bluff body shapes, test sections (conical inflow and outflow, constrictors of various shapes) and signal detection systems (pick-up). The corresponding flow fields have been studied by, among others, Johnson [4], Fureby [1] and Madabhushi et. al. [5] using mostly numerical simulations. The signal detection and processing have been discussed by Hans et. al. [2] and [3]. The potential for improvement of signal quality by modifying the shape of the bluff body was investigated by von Lavante et al. [6]), It has been also observed that a slight uncontrolled modification of the assumed geometry of a particular VSFM, e.g. shape, location relative to the surrounding casing and change of shape due to wear caused by particles suspended in the metered fluid, could cause a shift of its characteristic frequencies, leading to unreliable volumetric flow data. The influence of the manufacturing tolerances on the accuracy of VSFMs and abrasion by particles suspended in the metered fluid has been investigated in [7] and [8] by von Lavante et al. A detailed study of the flow field in small size commercial VSFMs with inflow and outflow conditioned by a Venturi nozzle and a diffusor has been published by von Lavante et al. In [9]. Finally, the effects of upstream disturbances on the accuracy of VSFMs have been studied by von Lavante et al. [10, 11].

In the present work, the flow in typical vortex flow meters of a size DN25 and DN50 were investigated experimentally as well as using numerical flow simulation, where the emphasis was put on the details of the flow field about the bluff body. The working fluid was in both cases air and water at atmospheric conditions. The threaded bluff bodies inserted into the meter section had diameters of between 14 mm and 16 mm for DN50 test section. The computations were carried out using a commercial three-dimensional, unsteady, incompressible solver of the Navier-Stokes equations. The effects of turbulence were modelled using the realizable k-e turbulence model. The resulting flow fields were analyzed using various methods, including visualization, evaluation of several of their global features and DFT of properly chosen variables. The experimental work using air and water has confirmed the favourable behaviour of the new bluff bodies for a useful range of Reynolds numbers.

Experimental Work

In the experimental approach, a commercial vortex-shedding flow meter manufactured by Krohne Messtechnik GmbH has been modified to include a selection of threaded rods of different diameters. Subsequently, it was subjected to investigation in the testing facility at Krohne Messtechnik GmbH. The fluid being metered was water at pressures of up to 3 bar; the measuring section of the meter was DN50 with a vortex detection by means of a paddel at various distances downstream of the bluff body. The experimental study included rod sizes M14 and M16 with the paddle at 2.5 behind the trailing edge of the rods. In all cases, the piping could be considered hydraulically smooth. Each configuration was studied at bulk velocities of approximately 1.0, 1.5, 3.0 and 6.0 m/s. The corresponding Reynolds numbers Re_D were between 50000 and 250000. The facility included two pumps of different size that were differentially controlled by a CPU using signals from the reference meter (MID).

A schematic picture of the test section of the meter can be seen in Fig.1. The data chosen are those for the numerical flow simulation; however, it can serve as a guide for the over all configuration.

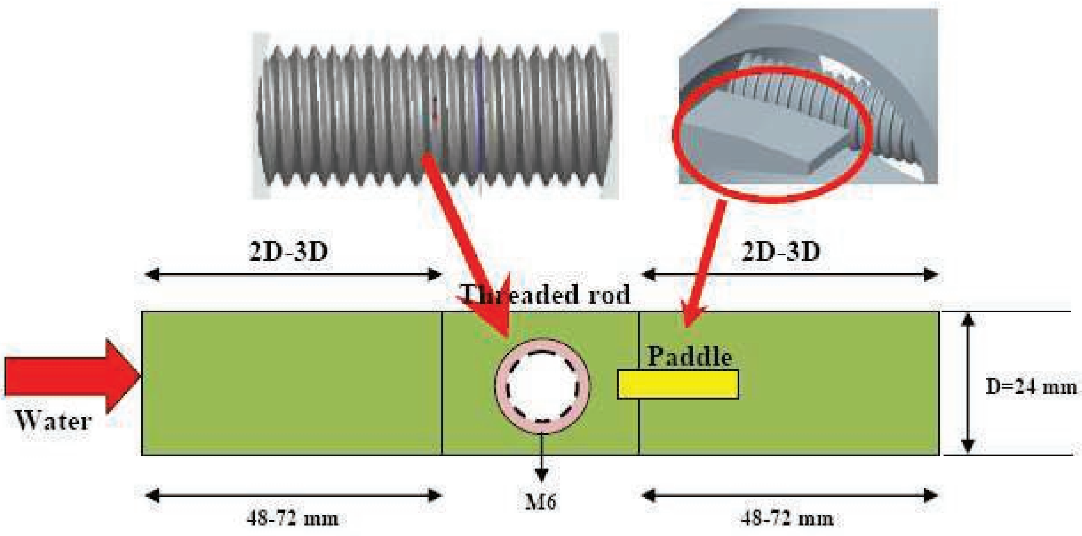

Figure 1: Schematic view of the presently investigated configuration.

At low velocities, the resulting k-factor displayed good linearity, while the signal given by the shedded vortices as acting on the paddle was of good amplitude and quality. However, at higher velocities, the quality of the signal deteriorated to the point were it was hardly detectable.

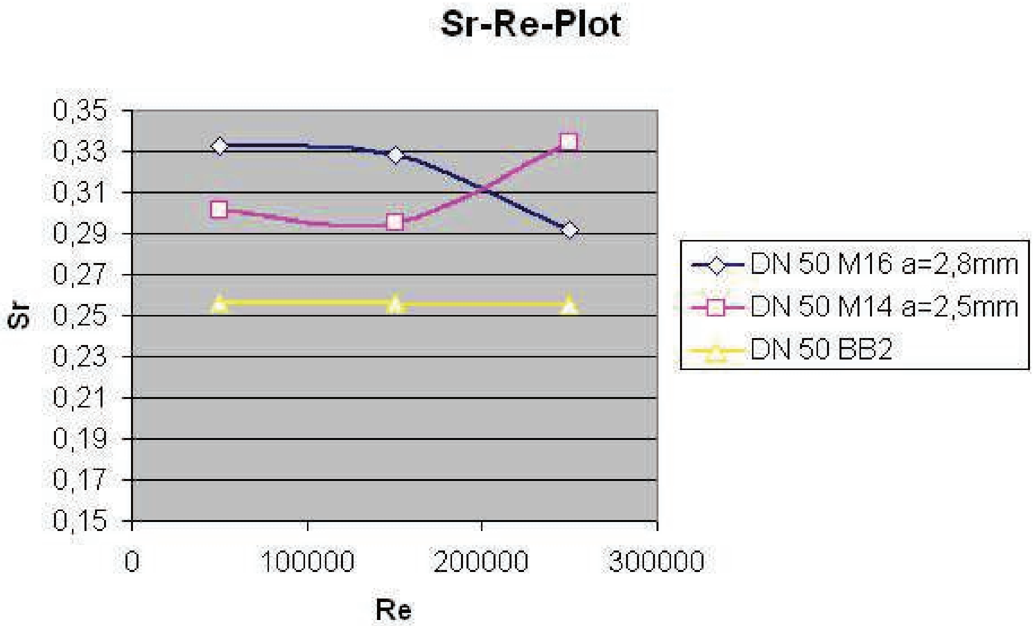

Figure 2: Resulting Strouhal number vs. Reynolds number diagram as obtained from the experiments.

As seen in Fig. 2, both threaded rods resulted in a higher Strouhal number than the basic bluff body called BB2. Consequently, it was decided to carry out a detailed study of the corresponding flow field by numerical flow simulation in order to explain the disappointing behavior at higher flow rates.

Numerical Flow Simulation

The numerical flow simulation of the entire flow field within the modified VSFM was accomplished using a commercial flow simulation system Fluent Ver. 6.1. The threaded rod was to be resolved accurately by the computational grid, implying an extremely large number of the grid cells. Assuming that the usual similarity with respect to the Reynolds number applied, it was decided to reduce the size of the meter to DN25 and install a rod of M6, limiting the number of grid cells to approximately 1.4 million. The distance between the paddle and the rod was taken to be 3.0 mm.

The grid generation for this case was extremely tedious due to the very complex geometry and the non-symmetry of the thread. Initially, a completely unstructured grid was used. However, the authors had to find out that in all the commercial codes employed presently, an unstructured grid in the boundary- and shear-layers lead to severe numerical instabilities. Subsequently, a hybrid grid with a layer of structured grid at the solid surfaces and in the grooves of the thread combined with an unstructured grid elsewhere was constructed. This grid, shown in selected detail Fig. 3, worked to satisfaction and delivered plausible results.

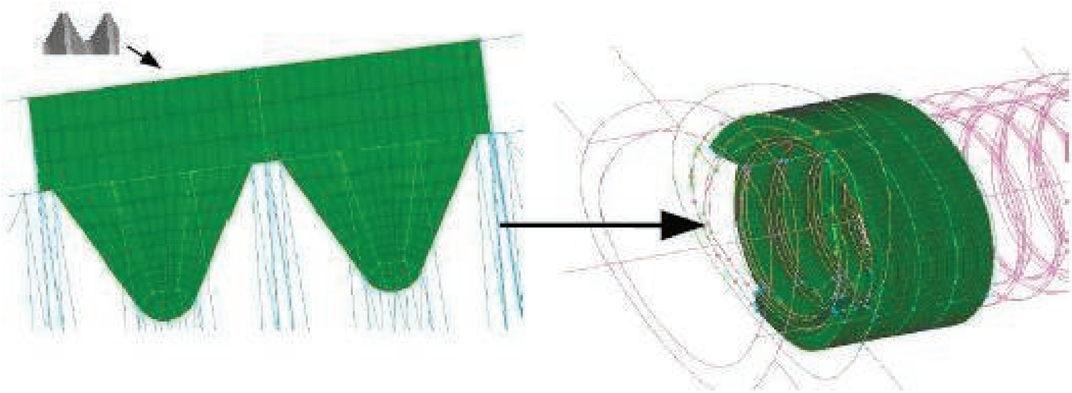

Figure 3: Detail of the structured subgrid in the thread.

The resulting flow field is displayed in Fig. 4, along with the simulated Strouhal number.

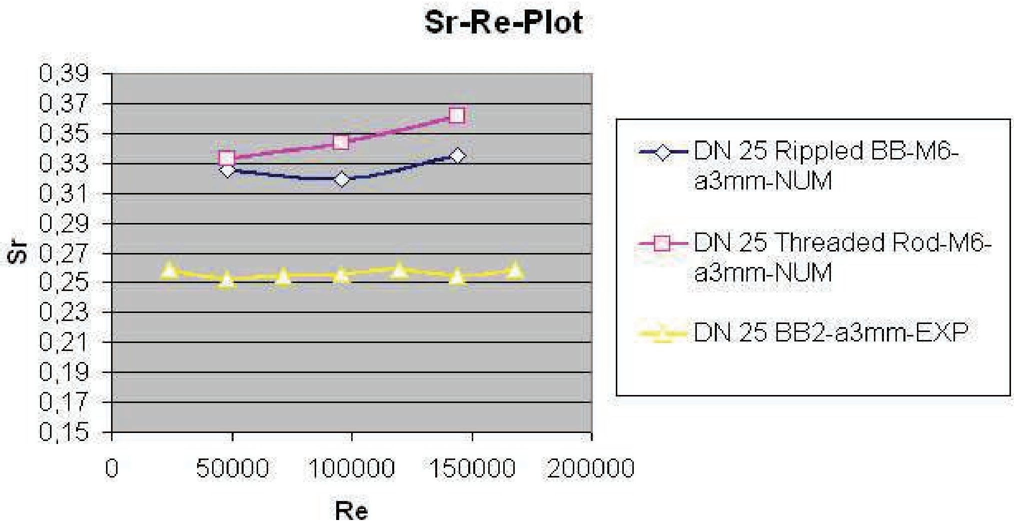

Figure 4: Resulting Strouhal number vs. Reynolds number obtained from numerical simulations.

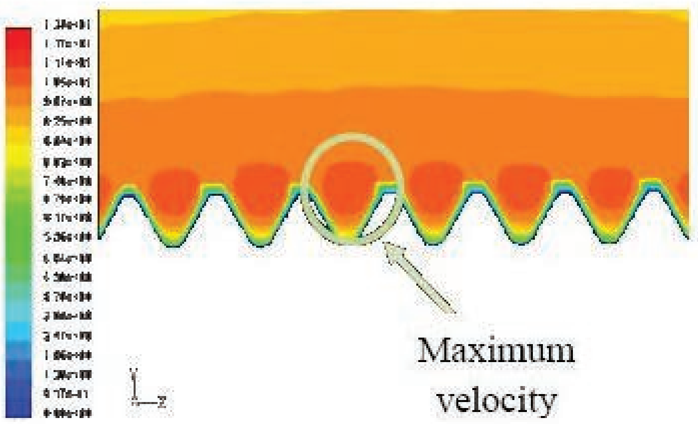

Figure 5: Velocity distribution in the thread – simulated flow field.

The simulated frequency of vortex shedding shown in Fig. 4 was qualitatively correctly predicted as being higher for the threaded rods. The Strouhal number is also in the same range as given by the experimental work. The increase of the Strouhal number at higher velocities is, however, somewhat smaller as measured experimentally. Parallel to the threaded rod, a rippled rod (with annual grooves instead of spiraling thread) was also simulated for comparison. Its performance was similar to the threaded rod, but it is by far more difficult to obtain, so that further work concentrated on the threaded bluff body. Again, the original production bluff body BB2 was included for comparison.

A closer look at Fig. 5 reveals that between the threads of the bluff body, the velocity significantly increases due to cross flow over and through the peaks and valleys of the thread. The high velocity indicates a possibility of local static pressure reaching values below evaporation, leading to cavitation within the thread. This in turn could give rise to physical nonlinearities and therefore cause irregular behavior of the vortex shedding. The numerical flow simulation was therefore repeated with the option of cavitation switched on. It should be noticed that all the boundary layers within the thread of the bluff body were resolved, giving an indication of the high quality of the computational grid.

The simulation program Fluent is actually not directly simulating the cavitation bubbles but the vapor content in the flow field. As expected, at the upper surface of the bluff body, where the highest velocity is found, is the highest concentration of the water vapor. The resulting view of the volume fraction of vapor as predicted by the numerical simulation can be seen in Fig. 6 for the highest velocity of 6 m/s.

The numerical flow simulation demonstrated the possibility of cavitational effects on the threaded bluff body. The question that remained was: how should these effects be reduced or possibly eliminated? As the local increase in velocity was the reason for the low static pressure, it seems imperative reduce the height of the thread and thus decrease the local velocity. Therefore, the experiments were repeated with the threaded rods having their thread heights turned flatter.

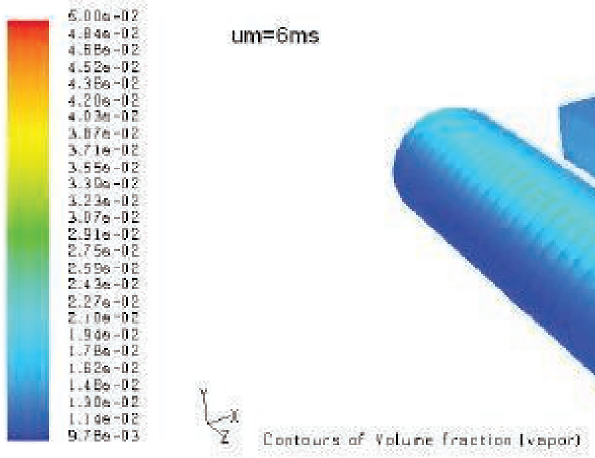

Figure 6: Volume fraction of water vapor as numerically simulated.

Experimental Work with Modified Threaded Rods

As described above, the thread height was reduced by turning in order to possibly reduce the influence of cavitation on the vortex shedding frequencies. In the previous work, it has been found that the optimum size of the rod for the DN50 meter was M14. Consequently, a stainless steel threaded rod was turned by 0.5 mm and 1 mm, resulting in outside diameters D of 13.5 mm and 13 mm. The distance to the paddle was adjusted to between 3.7 mm and 4.2 mm. The corresponding dependency of Strouhal number on the Reynolds number is shown in Fig. 7.

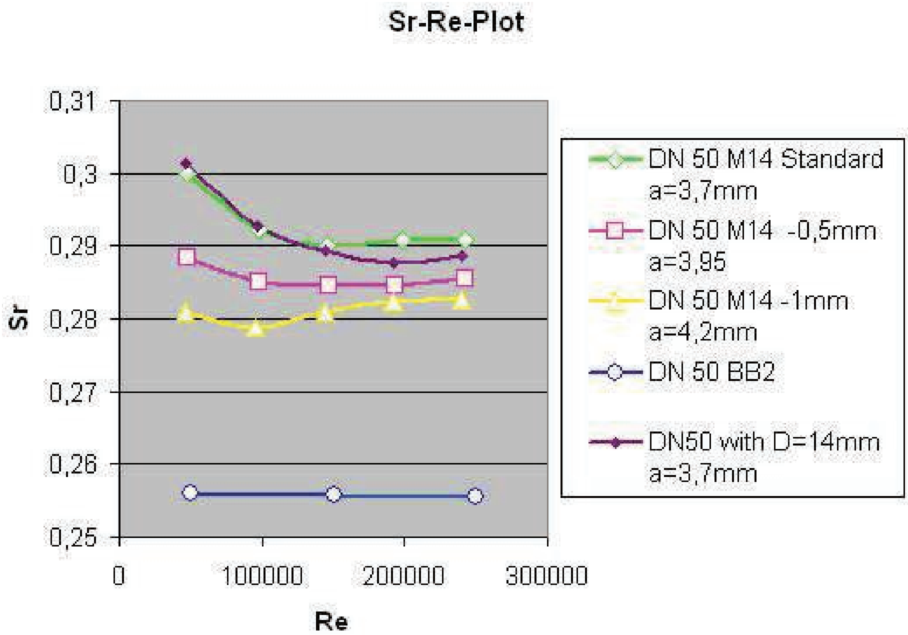

Figure 7: Strouhal number vs. Reynolds number for the modified threaded rods.

The relative vertical shift of the curves is mainly to to the different scaling factor D due to the modification of the thread. As thread height is reduced, the Strouhal number approaches that for the original bluff body BB2. The unmodified threaded rod results in low vortex shedding frequencies for higher bulk velocities. The intermmediate case of a rod turned down by 0.5 mm seems to represent an optimum solution, as it results in the best linearity if the lowest velocity is omited. The heavily modified case turned down by 1 mm approaches in its behavior a smooth cylinder with all its disadvantages (frequency rise for higher velocities).

Conclusions

In the present investigation, the feasibility of implementing a threaded rod as a bluff body in a small size vortex shedding flow meter was studied experimentally and numerically. To this end, several geometries including the M12, M14 and M16 at different distances from the detection paddle were tested in an experimental rig using water as working fluid. At low velocities, the threaded rod displayed favorable properties making it an plausible candidate for a bluff body. However, at higher velocities, the signal quality deteriorated and the linearity became unacceptable. Subsequent numerical flow simulation in similar configuration revealed that the most probable cause of the reduced signal quality was onset of local cavitation in the thread. The problem was eluded by reducing the thread height. The optimum combination of thread diameter (M14), turning and distance between the bluff body and the paddle provided a feasible replacement for the original bluff body.

References

[1] C. Fureby, „Large-eddy simulation of turbulent anisochoric flows“, AIAA Journal, Vol. 33, No. 7, pp. 1263-1272, 1995.

[2] Hans, V., Poppen, G., Lavante, E. v., Perpeet, S., „Interaction between vortices and ultrasonic waves in vortex-shedding flow meters“, FLUCOME '97, Hayama, 1997.

[3] Hans, V., Poppen, G., Lavante, E. v., Perpeet, S., „Vortex-shedding flow meters and ultrasound detection: signal processing and bluff body geometry“, Flow Measurement and Instrumentation 9, pp. 79-82, 1998.

[4] Johnson, M.W., „Computation of flow in a vortex-shedding flow meter“, Flow Measurement and Instrumentation, pp. 201-208, 1990 .

[5] Madabhushi, R.K., Choi, D., Barber, T.J., „Unsteady simulations of turbulent flow behind a triangular bluff body“, AIAA Paper, pp. 97-3182, 1997.

[6] von Lavante, E., Yao, J. and Perpeet, S., „Effects of Disturbed Inflow on Vortex-Shedding from a Bluff Body“, AIAA paper 2000-2220, 2000.

[7] von Lavante, E., Nath, B. and Färber, J., "Effects of Manufacturing Tolerances on the Accuracy of Vortex-Shedding Flow Meters", XVII IMEKO World Congress on Metrology, Dubrovnik, 2003.

[8] E. von Lavante, U. Banaszak, M. G. Yilmaz, O. Ricken and R. Höcker,”Effects of Shape Change due to Wear on the Accuracy of Vortex-Shedding Flow Meters”, Proceedings of the 14th Int. Conf. on Flow Measurement Flomeko 2007, Johannesburg, RSA, September 2007.

[9] E. von Lavante, U. Banaszak, T. Jubin, S. Tournillon, H. Krisch, „Numerical and Experimental Investigation of Small Size Vortex-Shedding Flow Meter”, Proceedings of the 7th Int. Symposium “Metrologia 2008”, Havana, Cuba, May 2008.

[10] von Lavante, E., Cambier, P., Vandermarliere, S., Banaszak, U., Krisch, H. and Tournillon, ., “Numerical and Experimental Study of Effects of Upstream Disturbance on Accuracy of Vortex-Shedding Flow Meter”, Proceedings of the XIX IMEKO World Congress on Metrology, Lisbon, September 2009.

[11] von Lavante, E., Gedikli, A., Thibaut, A., Tournillon, S. and Krisch, H., “Effects of Upstream Butterfly Valve on the Accuracy of a Vortex Flow Meter”, Proceedings of the 15th Flow Measurement Conference Flomeko 2010, Taipei, Taiwan, September 2010.