A torsional vibrating mass flowmeter suited for large pipe diameters and high pressure

Dag Wang[1], Bjørn Erik Seeberg[1] & Christopher Grinde[1]

[1]Baker Hughes a GE Company

Summary

A novel flowmeter is presented. The flowmeter is directly measuring the mass flow as well as the density of the flowing media. The flowmeter extends the operational area of conventional coriolis flowmeters into the large diameter and/or high pressure range. This is achieved through decoupling of the structure used for pressure containment and the structure used for vibrating the fluid. Furthermore, the outer tube of the flowmeter is not moving, therefore the flowmeter is well suited for submerged operation.

Background

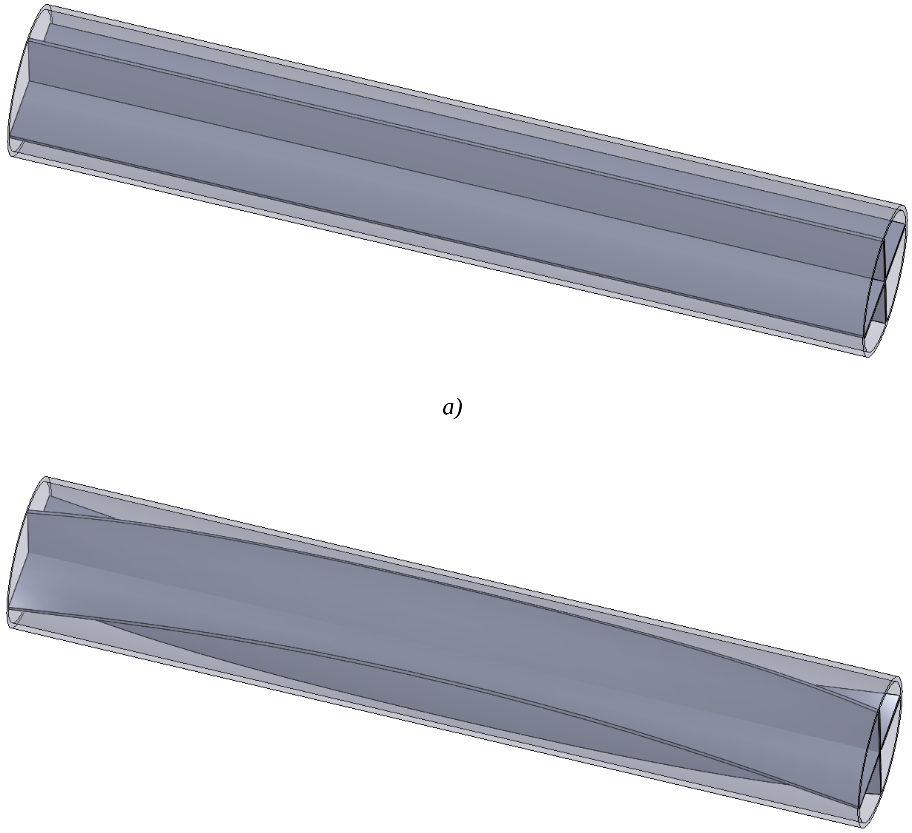
Coriolis flowmeters are utilized across multiple industries as they provide accurate measurements over a wide flow range. The coriolis flowmeters are user friendly and output the actual mass flow as well as the density directly. In contrast, venturi or orifice based flowmeters require knowledge of the density to calculate the mass- or volume flow.

Nevertheless, Coriolis flowmeters have not found widespread use subsea. We believe this is due to the facts that subsea flowmeters are submerged and that they typically operate at high line pressure. The first calls for an extra encapsulation layer carrying the full hydrostatic pressure, and the second requires long pipe sections to reduce the operating frequency.

Here, we present a flowmeter which has the same practical advantages as a coriolis flowmeter, but with a design which can be adapted to any pressure range and to large diameter pipes.

Construction

In the torsional flowmeter, the fluid is manipulated by two members, the outer pipe and the twister, as shown in Figure 1.



a)

b)

Figure 1. The pipe and the twister. a) twister in its straight position. b) deflected twister.

The twister is fixed to the tube in each end but is otherwise free to move. When torque is applied to the twister it can deform as shown Figure 1 b). Fluid flowing through the structure will follow the shape of the twister, thus there will be induced a swirl in the fluid.

The twister acts as a torsional spring with a certain torsional stiffness and a polar moment of inertia. The eigenfrequency of the fluid loaded twister is determined by the torsional stiffness and the polar moment of inertia for the combination of twister and fluid. Thus, the eigenfrequency can be used to find the density of the fluid. The thickness of the twister vanes can be adapted to achieve a suitable eigenfrequency range for the system.

The purpose of the tube is simply to retain the pressure and to restrict fluid movement in the radial direction. The thickness of the tube walls does not affect the eigenfrequency of the twister. It could be noted however, that a rigid tube is beneficial for reducing anchor losses.

As shown in Figure 2, a drive is positioned around the tube at the center of the twister. When current runs through the drive, a torque will be applied to the twister, rotating it. In operation, an AC signal is applied to the drive so that the twister is oscillating at its eigenfrequency.

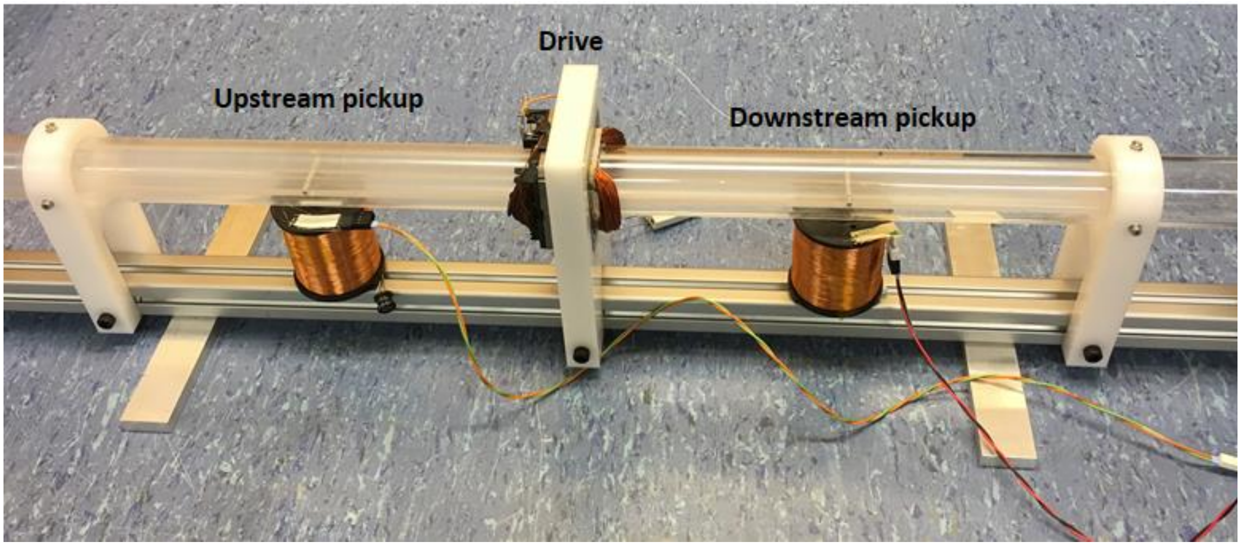


Figure 2. Picture of a demonstrator unit showing the positon of the drive and the two pickups.

Two pickups are placed along the tube, one upstream of the drive, and one downstream. The pickups generate a signal roughly proportional to the angular velocity of the twister at the respective positions.

When a fluid flow runs through the tube, there will be a time delay between the downstream and the upstream signal. This time delay is proportional to the mass flow running through the tube.

Theory of operation

In a conventional coriolis flowmeter a transversal wave in the tube couples to a transversal wave in the flowing fluid. In the torsional flowmeter a torsional wave in the twister couples to a torsional wave in the flowing fluid. For a torsional mass flowmeter, the torsional spring stiffness plays the role of the bending stiffness and the polar moment of inertia plays the role of the mass per unit length. The equations of motion can be derived in a way analogous to that of Raszillier [1]. Since the wave equation for a torsional wave is a second order wave equation and not a forth order equation as the Euler beam equation, the solution can be found on a closed analytical form and without the need for series expansion.

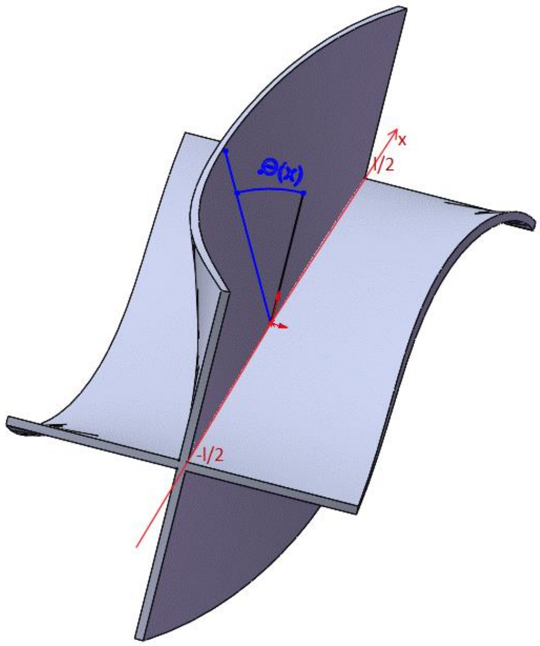


Figure 3. The angular rotation of the twister, θ, varies along the length.

Equations of motion

We consider a twister, denoted with subscripts *T*, as illustrated in Figure 3, fixed at both ends and with a centerline that is assumed to stay fixed. The angular displacement along the length is denoted by θ_T.which is a function of time and position.

Along the twister, and confined by the tube, the fluid, denoted with subscripts *F*, is flowing. In a similar fashion the fluid is rotated by an angle θ_F, in order to use the lagrangian multiplier method, the two angles are first treated as independent in order to write the lagrangian:

Equation 1

$$L = \frac{1}{2}\left(\rho_T J_T \left(\frac{\delta\theta_T}{\delta t}\right)^2 - K\left(\frac{\delta\theta_T}{\delta x}\right)^2\right) + \frac{1}{2}\left(\rho_F J_F \left(\frac{\delta\theta_F}{\delta t} + v\frac{\delta\theta_F}{\delta x}\right)^2\right) + \lambda(x,t)(\theta_F - \theta_T)$$

Here the first term is the lagrangian of the twister, the second term is the lagrangian of the fluid, and the third term is the lagrangian multiplier which represents the coupling of the two. *K* is the torsional stiffness of the twister as defined in [2]. ρ is density and *J* is the polar moment of inertia.

Setting up the Lagrangian equations of motion and eliminating the lagrangian multiplier and requiering that the fluid follows the twister, one arrives at the equation of motion:

Equation 2

$$(\rho_F J_F + \rho_T J_T)\frac{\delta^2\theta}{\delta t^2} + 2\,v\,\rho_F J_F\frac{\delta^2\theta}{\delta t\delta x} - (K - \rho_F J_F v^2)\frac{\delta^2\theta}{\delta x^2} = 0$$

Here the first term is the angular acceleration expected in a torsional wave equation. The second term is the coupling term, often called the coriolis term which is fundamental for the operation of the flowmeter. The last term is the spring stiffness. Here there is an extra term proportional to the square of the fluid velocity. This is often called the centrifugal term, it results in an effective spring softening. As a consequence of the spring softening, there is a critical velocity at which the effective spring stiffness vanishes and the wave velocity is zero.

Solution

It can be proven by direct insertion that

Equation 3

$$\theta(x,t) = cos(k\,x)\,e^{j\omega(t-ax)}$$

is a solution of the equation of motion and the boundary conditions, provided that:

$$k = \frac{\pi}{l}\ , \quad a = -\frac{v\,\rho_F J_F}{(K-\rho_F J_F v^2)}$$

and

Equation 4

$$\omega = \mp \frac{(K-\rho_F J_F v^2)}{\sqrt{(v\,\rho_F J_F)^2 + (\rho_F J_F + \rho_S J_S)(K-\rho_F J_F v^2)}}k$$

The last expression can be rewritten in terms of frequency. At low flow rates (omitting second order terms in *v*) one obtains:

Equation 5

$$f_0 = \frac{1}{2\,l}\sqrt{\frac{K}{(\rho_F J_F + \rho_S J_S)}}$$

Hence the fluid density, ρ_F, can be found directly from the eigenfrequency.

From Equation 3, we see that if two points are situated a distance Δx apart and we consider the time difference between the time at which the two points reach a certain phase (zero crossing or maximum amplitude), this time is given by $a \cdot \Delta x$, or in terms of the mass flow, q_m and cross sectional area of the fluid, A_F:

Equation 6

$$\Delta t(q_m) = -q_m \frac{J_F\,\Delta x}{A_F\left(K - \frac{J_F}{\rho_F}\left(\frac{q_m}{A_F}\right)^2\right)}$$

The time difference is negative, this means that the phase is first achieved at the downstream position and then at the upstream positon. This is because the fluid is transferring rotational inertia from the upstream part of the twister to the downstream part.

Equation 6 can be used to find the mass flow from the measured time delay and vice versa.

Dimensioning example

A 16 inch flowmeter fitted with a twister which is 1 meter long and 20 mm thick will have characteristics as shown in Figure 4 and Figure 5.

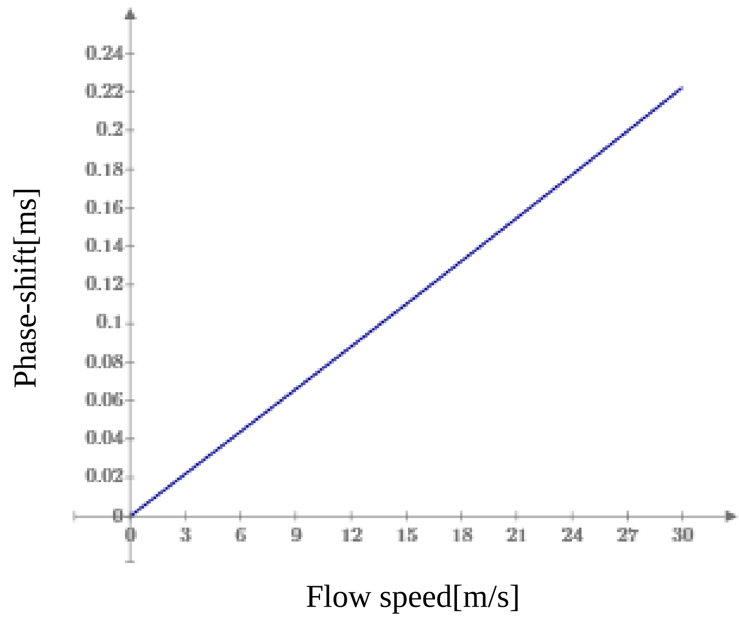


Figure 4 Phase shift between upstream and downstram vanes ¼ m from the fixed ends as a function of flow speed.

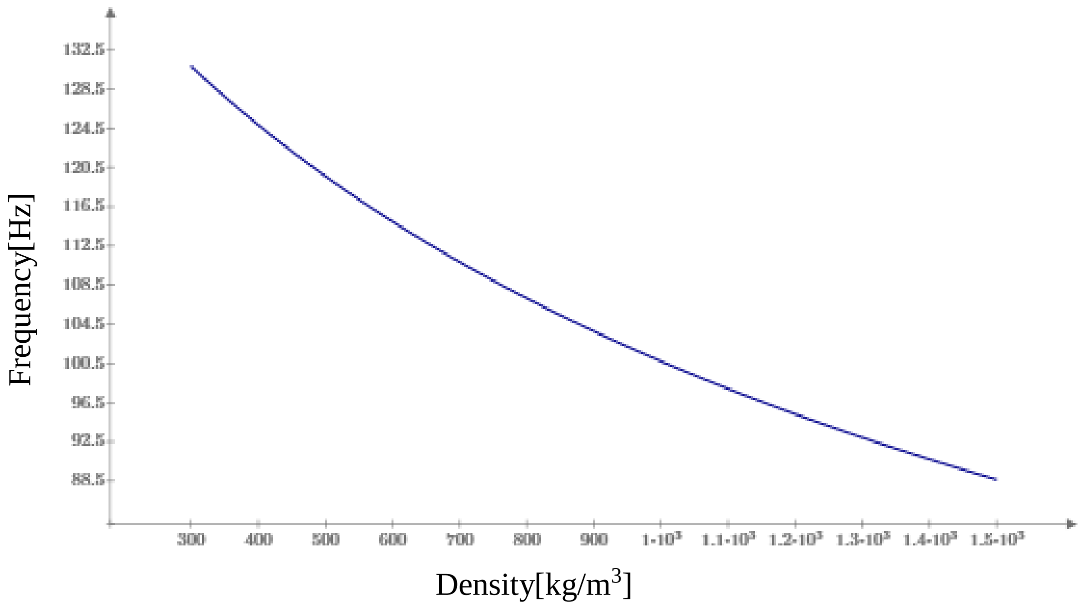


Figure 5 Frequency as a function of density of the flowing media.

Demonstrator and results

Figure 2 shows a demonstrator that has been built and tested to prove the concept. All parts were made from plastic. Neodymium magnets were pressed into the twister at the center and ¼ of the length from each end. The twister was fixed in place at each and using screws in all four vanes. The motor unit was extracted and adapted from a vacuum cleaner. Tube diameter was 34 mm and a simple single-speed garden pump with estimated capacity of 14.5 m^3/hour was used to pump spring water through a simple flow loop. See Figure 6

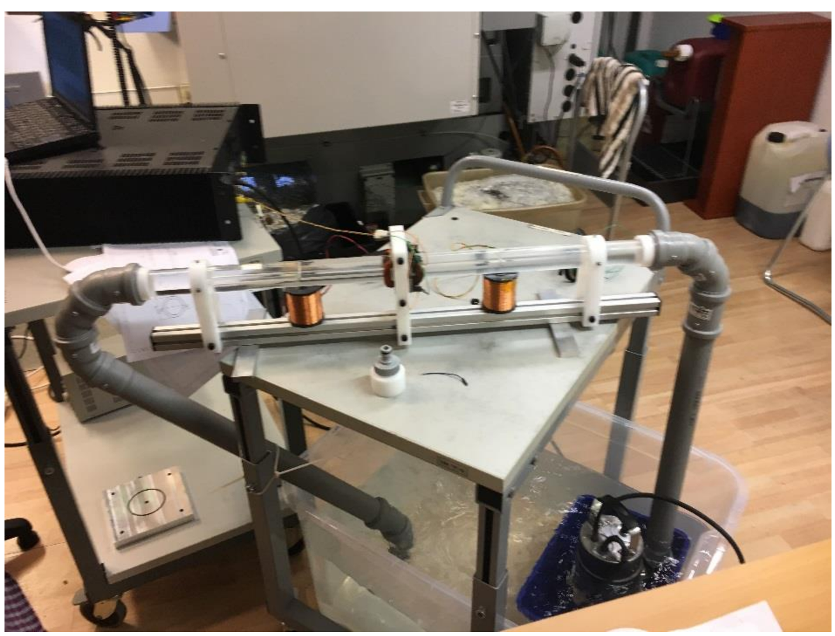


Figure 6 Demonstrator mounted in flowloop.

The unit was driven manually with a sinus signal from a Analog Discovery USB Oscilloscope and waveform generator. The signal was amplified with an audio amplifier. Tuning to resonant frequency was done manually. The signals from the pickup coils were monitored and recorded with a software based oscilloscope. Upon applying flow, a phase shift between the upstream- and downstream signals was observed. The observed shift was approximately 50 ms when comparing zero flow and maximum flow. This is consistent with calculated values.

Postprocessing of the recorded results indicates sensitivity comparable to traditional Coriolis flowmeters, but because of the limitations of the test setup, further work and testing in a more controlled environment and with a feedback system for the drive frequency must be performed to confirm this.

Conclusion

A novel concept for a true mass flowmeter has been presented along with the governing equations and results from a test of a proof-of-principle demonstrator in a rudimentary flow loop. The test results show that the principle of the presented mass flowmeter works as expected. Hence, a principle for a mass flowmeter in which the pressure integrity member is separated from the sensing principle has been proven. It is suitable for applications where high line pressure and/or large pipe size makes Coriolis meters unfavorable. The concept is therefore suitable for large volume fiscal metering, both top-side/on-shore applications as well as subsea.

References

[1] H. Raszillier and F. Durst, "Coriolis-effect in mass flow metering," *Archives of Appled Mechanics,* vol. 61, no. 3, 1991.

[2] K. F. Graff, Wave Motion in Elastic Solids, Oxford University Press, 1991.