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Phase Modulation of the Ultrasonic Wave in Von Karman Street

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Abstract

It is known that under certain conditions (in certain Reynolds number region) we get double row of staggered vortices in fluid flow behind the bluff body.
Frequency of generated vortices is directly proportional to the average velocity of fluid and that dependence is linear.
Flowmeters based on this phenomenon are known as vortex flowmeters. Origination of vortices causes changes some other parameters such as: pressure, perpendicular forces on fluid flow, etc. Frequency of vortices can be detected by detecting changes of these parameters. Great majority of the vortex flow meters are functioning using this principle.
Mathematical model of the phase modulation of ultrasonic wave that is transmitted normally on the fluid flow behind the bluff body in the region of stable flow will be given in this paper. Phase modulation is directly caused by appearance of vortices in the fluid flow.
We have developed the prototype of ultrasonic vortex flow meter (PVMP 100) DN 100 based on phase ultrasonic modulation, for liquid flow measurement fig.1.
Experimental results of testing this prototype vortex meter will be presented in this paper.

Introduction

In order to analyze propagation of ultrasonic wave trough the Von Karman street vertically on the fluid flow, a few conditions will be assumed.

1. Liquid flow is two-dimensional (flow in x-y plane),
2. Separated vortices are circular in flow plane,
3. Flow is potential in vortices and turbulent outside of vortices,
4. Shape and largeness of vortices do not change in stable flow region,
5. Von Karman street is unlimited,
6. Vortices generated from deferent side of bluff body have some circulation, but its direction is opposite.

Phase modulation of the ultrasonic wave is before all a result of interaction between two mechanical fields: ultrasonic field and fluid velocity field in the flow behind the bluff body. Schematic model is represented in fig.2. Analysis will be considered in x-y plane which lies perpendicular on the bluff body and which contents ultrasonic transceivers.

Equation of ultrasonic wave propagation which frequency is ? $_0$ for velocity potential ? is:

$$\Delta\Psi - \frac{1}{c^2}\cdot\frac{\partial^2\Psi}{\partial t^2} = 0\ .$$

Wave-equation could be written for every parameter of ultrasonic wave.
Since ultrasonic waves are propagating only in y direction we can write:

$$\frac{\partial^2\Psi}{\partial y^2} - \frac{1}{c^2}\frac{\partial^2\Psi}{\partial t^2} = 0\ .$$

Solution of this equation is harmonic function that can be written:
$\Psi(y,t) = A\cdot\cos(w_0 t - \mathbf{k}y + j_0)$, where $\mathbf{k}$ is wave number given (according to wave theory) with:

$$|\mathbf{k}| = \frac{2p}{l} = \frac{2pf_0}{c}\ .$$

We can consider that f $_0$=0 (without any decrease in generality), so the phase of wave is given with:

$$\Phi(t) = w_0 t - \frac{2pf_0}{c}\cdot y\ .$$

As shown in figure 1. for homogeneous liquid fluid $y = \pm\frac{D}{c}V_{\Theta y}$, i.e.

$y = \pm\frac{D}{c}V_{\Theta}\ cos\,wt$ where:

? – angular frequency,
V_{Ty} – y component of tangential velocity.

Sign $\pm$ indicates opposite direction of velocity circulation of generated vortices on different side of the vortex shedder.

Finally, signal on the receiving side, after conversion to electrical signal, can be written as follows:

$$U(D,t) = [U_0\,(1 + m_a\ \cos wt)]\cdot\cos(w_0 t + m_p\ \cos wt)$$

where are:

m_a: coefficient of amplitude modulation, $m_a \sim \frac{\mathrm{m}\cdot\mathrm{D}\cdot\mathrm{V}_q}{c}$,

m: coefficient of absorption, $m \sim \frac{f_0^{\ 2}}{c^3}$,

m_p : coefficient of phase modulation, $m_p \sim \frac{4pf_0 DV_0}{c^2}$,

c : velocity of ultrasound in liquid,

f_0: frequency of ultrasonic signal, $f_0 = \frac{w_0}{2p}$

Simulation ultrasonic signal, modulated in phase and amplitude is represented in fig.3.
For experimental affirmation these analysis, only phase modulation has been used.
Electronic structure based on PLL (Phase locked Loop), represented inf.fig.4.and ultrasonic sensors have been developed [5]. Housing and vortex shedder fig.5. (bottle type) were developed in „IRCA Energoinvest" as a part of the project of development vortex flow meter with thermistor as a detector of vortices [4].

Advantages of this vortex detection method are coming from the phase modulation advantage (among other modulation schemes) concerning the problem of noise.
Pipe vibrations do not affect the flow meter, but fluctuation components of fluid velocity affect on the propagation of ultrasonic wave. On the receiving side, this influence is manifested as noise of ultrasonic signal. Amplitude of noise signal is more less than the amplitude of ultrasonic signal, and frequency is much more for liquid fluid.

Experimental results

Testing and calibration of prototype (PVMP 100) were carried out in Laboratory for calibration of flow (volume) meters flow in company „Delta Petrol" BiH. Working fluid was petroleum (T= 15 [^{0}C], r =796 [kg/m^3], m =1,89 $\cdot 10^{-3}$ [Pas]). Etalon meter that was used in testing PD volume meter F4.S1 Smith Meter GmbH, range from 250[l/min] up to 2500[l/min], and linearity $\pm$ 0,15 %.
Testing procedure consist of measurement of volume, that passed trough the etalon meter during a time period of three minutes and of counting a number of pulses on prototype (PVMP 100).
Reference meters that were used in calibration method described above belong to A1 group (ISO/FDIS 11631:1998[E]). Results of these testing are shown in table 1.

time t [s]	etalon counter initijal status V1 [dm^3]	etalon counter finally status V2 [dm^3]	volume flow trough the etalon ΔV [dm^3]	flow Q [dm^3/s]/ [dm^3/min]	velocity v [m/s]	Reynolds number Re	number of inpulses N (PVMP 100)	$k = \frac{N}{DV \cdot k_p}$
180 s	51835	54550	2715	15,08 / 905	1,92	$8,1\cdot10^4$	5158	1,055
	54705	56840	2135	11,86 / 711,7	1,51	$6,36\cdot10^4$	4054	1,054
	59225	60764	1539	8,55 / 513	1,09	$4,59\cdot10^4$	2926	1,056
	61349	62593	1244	6,91 / 414,7	0,88	$3,71\cdot10^4$	2365	1,056
	62976	63942	966	5,37 / 322	0,68	$2,86\cdot10^4$	1837	1,057
	64262	65031	769	4,27 / 256,3	0,54	$2,27\cdot10^4$	1472	1,063
	65476	66121	645	3,58 / 215	0,46	$1,94\cdot10^4$	1234	1,063
	66427	66923	496	2,76 / 165,3	0,35	$1,47\cdot10^4$	954	1,068
	67128	67422	294	1,63 / 98	0,21	$0,88\cdot10^4$	566	1,069

Tabel.1.Testing results of prototype (PVMP 100) based on phase modulation of ultrasonic signal

Relation between a number of pulses read a pulse counter, which is integrated part of a prototype vortex meter (PVMP 100), and a volume of fluid which flowed by, and which was registered an a etalon flow meter (PD), in every point of examination, presents calibration constant K, where K is: $K = \frac{U}{\Delta V \cdot K_p}$.

K_p is programmable constant of Contrec (202) integrator, which was used as a counter of pulses on a prototype vortex meter (PVMP 100).
Calibration constant shows a number of pulses per liter of fluid that flowed by. Calibration curve is presented on a fig.6. Linearity of a calibration curve can be expressed using relation $L = \frac{K_p - K_i}{K_i} \cdot 100$ where: $K_s = \frac{K_{max} - K_{min}}{2} \cdot 100$ (K_{max} is maximum volume of calibration constant and K_{min} is minimum volume calibration constant)
K_i (I=1,2…) values of calibration constant in the points of calibration.

Diagram of linearity of calibration curve is presented on a fig.7.
Quantity of fluid in a calibration station tank limits a maximum flow on 900 [l/min]. This restriction doesn't influence on a generality of conclusions that can be made for vortex prototype meter, having in mind that in case of huge flows detection of vortices is easier because a level of modulation is higher.

Conclusion

1. It is analytically shown and experimentally confirmed that due to propagation of ultrasonic signal though Von Karman vortex street, we get a phase modulation of signal that is primarily affected by tangentional velocity of vortex.
2. Testing and calibration of prototype vortex meter (PVMP 100) DN 100 mm developed on this phenomenon, chaw a good results.
3. Linearity of curve is better than ±0,75% in full range of calibration.
4. Minimal registrated flow was 98[l/min].
5. Minimal registrated velocity was 0,2[m/s], and corresponding Reynolds number was $\sim 1 \cdot 10^4$.

Results present good base for testing and calibration other, different size vortex meter from 25 up to 400 mm for liquid and gas.

fig.1. prototype (PVMP 100)

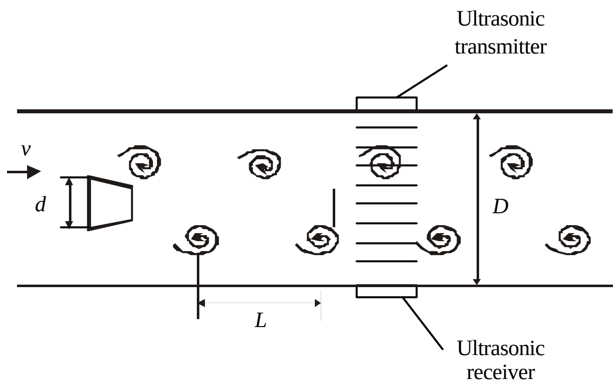

fig.2.

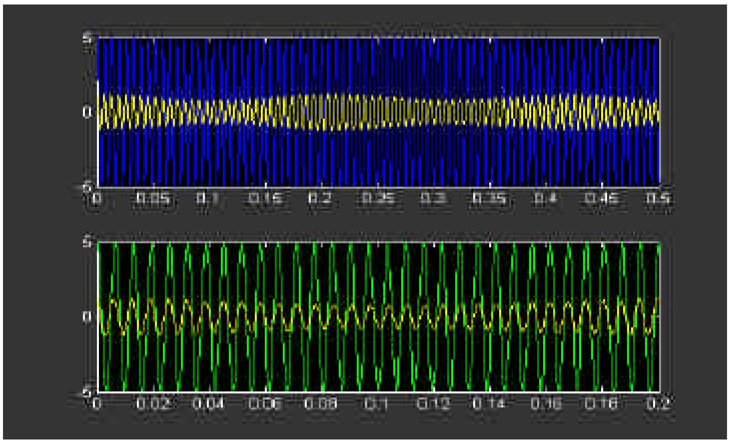

fig.3.

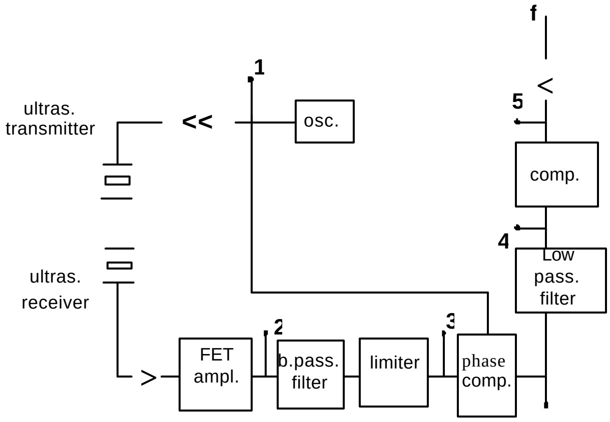

fig.4

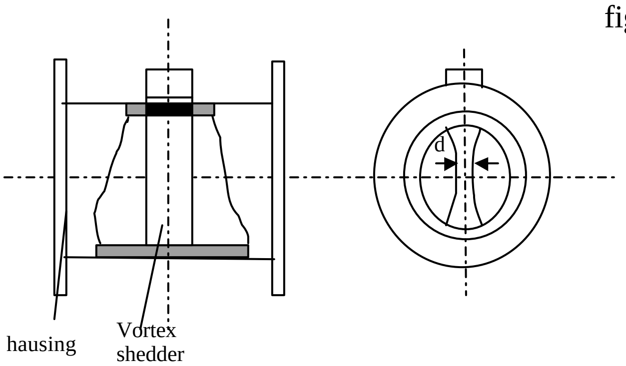

fig.5.

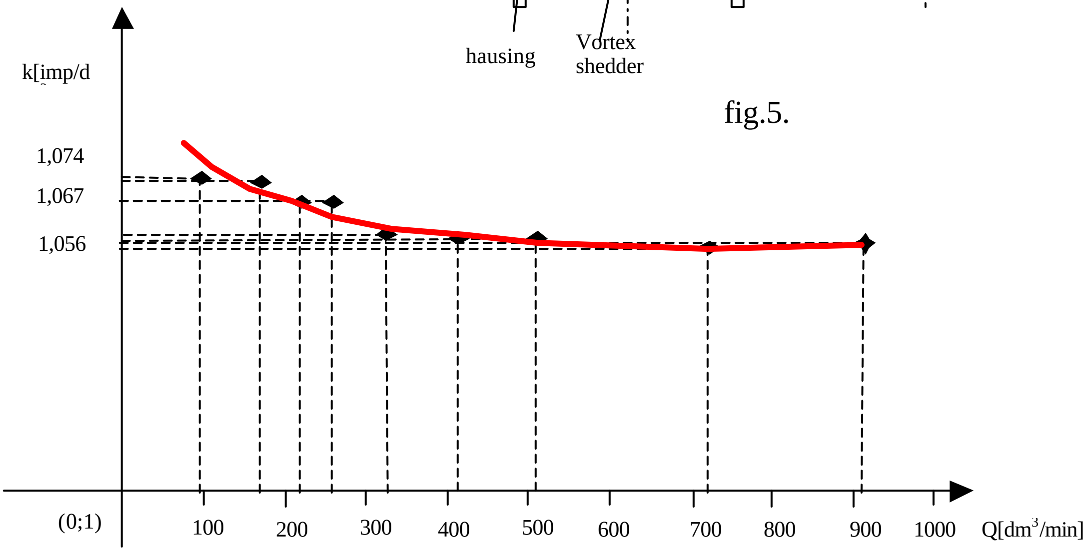

fig.6.

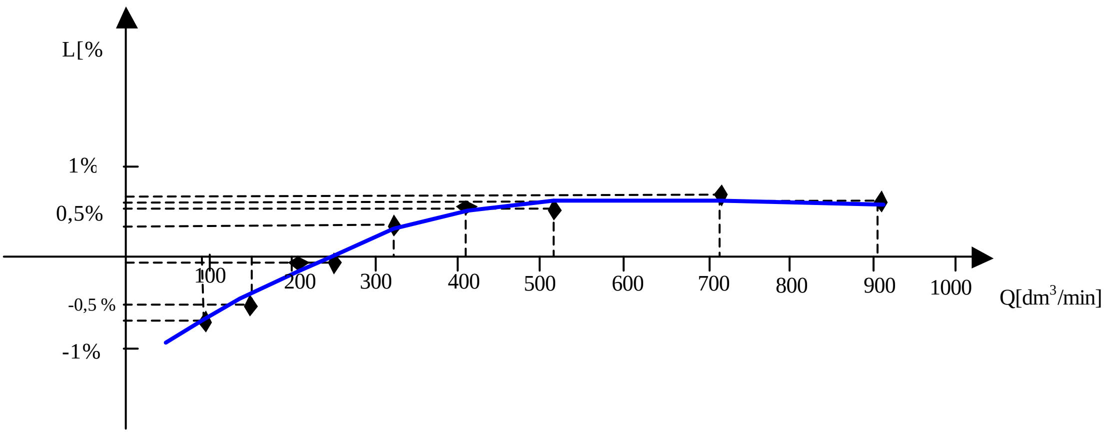

fig.7.

References:

[1] P.G. Saffman: **Vortex Dynamics**, Cambridge University Press 2001.
[2] H. Windorfer ,V.Hans : **Propagation of Ultrasound in Vortex Shedding Flow-Meter,** Flow Measurement 2001-International Conference.
[3] M.Takamoto; Y.Terao: **Standardization of Vortex Shedding Flow Meter** 4th. International Symposium on Fluid Flow Measurement, Denver Colorado USA 1999.
[4] Đuho H.;Kesic P.;Maksimovic J: **Influence of same Geometric Parameters on the Performance of Vortex Flow Meter,** Yurema 1988. Zagreb.
[5] M.Music: **Application of Ultrasound for Detection Vortices in Vortex Flow Meter.** M.Sc.Thesis 2002.year.