An application of LD and photon counting techniques for fluid flow measurement

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Abstract. The paper presents a new approach to signal detection in vortex flow meters. The vorticity structure is measured by detecting light scattered on particles (contamination or water fog) in flowing medium. Some unique features of optical approach are shown and discussed. The comparison of the results obtained with two media: water and air is given. A conversion characteristic shows signal below well-known limit of the vortex flowmeters at Reynolds number Re=4000. The paper is the continuation of research previously published in [1] and [2].

1. Introduction
In all vortex flow meters, the measuring signal contains the information about frequency of coherent vorticity structure directly proportional to the discharge velocity. At present the signal is detected mostly by pressure sensors using thin metal membrane with pressure actuator or piezoelectric actuator. Recently [3] the application of ultrasonic detector was reported; it demands weaker vortices and probably is less sensitive on hydraulic shocks. However the above technologies generate electric signal within the flow leading to electric hazardous (especially with explosive or flammable fluids) and have reported lower limit of measuring range of Reynolds number Re=4000. In the paper the new method of obtaining measuring signal is presented and discussed. It is based on light detection scattered on contamination contained I flowing medium. The results were obtained with two media: water and air.

2. Setup description
For experiments the air and water flow measurement stands, approved by Polish Central Office of Measures were used. The stands are characterized by following features: wide range of flow (0.5÷5500m³/h), total uncertainty 0.25% and flow in range 0.1÷5.0m³/h, total uncertainty 0.15% for the air and the water flow measurements, respectively. Both stands are described in details in [1] and [2], respectively. As the reference the coordinates x, z, y are introduced (Fig.1): 0x - axes of the flow, 0z - axis of the optical set-up (perpendicular to 0x), 0y - geometric symmetry axis of the vortex generator (gray trapezoid at the bottom of the scheme). D – indicates the diameter of the measuring segment of conduit. The segment is equipped with two specular windows. The input window in on the IOS (Input Optical set-up), it transmits the light to the measurement volume.

IOS consists of low power laser diode as a light source and photomultiplier tube as a reference detector. The light scattered on seeding incorporated into flowing medium is collected by objective Ob onto second multiplier PMT. In case of water flow measurement, the water contamination was treated...
as seeding, and in case of air flow measurement a specially generated water aerosol was acted as seeding.

![Measurement setup](image)

**Figure 1. Measurement setup.**

### 3. Results

Figure 2 presents the power spectrum of signals at reference PMT (grey colored line) and signal PMT. The frequency on the abscissa is normalized by Nyquist frequency and the power on the ordinate is normalized by the maximum value of each spectrum and expressed in dB. The input signal has wide and plane spectrum of white noise. It has a distribution similar to Poissonian distribution as one can expect from coherent light source. The spectrum of the output signal is strongly modified compared to the input one. There are narrow fringes of harmonics dominate over the wideband noise. Typically only the first harmonic appears but quite often the signal seems to be deteriorated and second harmonic (as in an example) exists. In certain cases the power of the second harmonic was greater than at the first one. It will be touched on latter. The Figure 3 presents exemplary power spectrum of water (same as in the Figure 2) and air flow (grey colored line). Dimensions along both axes are normalized as previously. The air spectrum power shows why the gas is much more difficult to measure compared to liquid.

(1) The possible vortex frequencies are much higher [4].
(2) The signal fringe is much wider (measured at half of the maximum value).
(3) Noise spectrum is completely different.

However 1/f noise limits definitely the applicability of the “vortex” method. The slower flow the smaller value of the fist harmonic in signal and the signal gradually decays into the noise. In addition, the power of the noise relatively increases with decrease of the flow velocity. The authors consider this noise as integral part of the flow phenomenon and, unfortunately, just as in other disciplines have

![Power spectrum](image)

**Figure 2. The input and output power spectrum.**

![Power spectrum](image)

**Figure 3. The power spectrum of water and air.**
no clear interpretation. We haven’t seen notice any information about this type of the noise occurring in similar experiments.

It is popular in literature that vortex flowmeter has low band limit at Reynolds number $Re=4000$. The Table 1 contains results of measurements of the flow down to approximately $Re=2200$. The flow velocity $w$ was recalculated based on volumetric discharge in normal conditions (273,15$K$ and 101,325kPa). Figure 4 presents conversion characteristic based on data from the table. The abscissa is in logarithmic scale. Two additional lines are drawn arbitrarily but express the function $f=f(Re)$ character. There is well known kink [5] in characteristic at $Re=5000$ where the slope of the line changes.

The next figures present moving variance (Fig. 5) and moving average (Fig. 6) of the signal. The values are calculated based on following equation [1]:

$$
\sigma_{n+1} = \frac{n}{n+1} \left[ \sigma_n + \frac{1}{n+1} \left( x_{n+1} - \langle x_n \rangle \right)^2 \right]
$$

$$
\langle x_n \rangle = \frac{n-1}{n} \cdot \langle x_{n-1} \rangle + \frac{1}{n} x_n
$$

(1)

where $n$ denotes number of points in signal course, $x_n$ is a value of the signal at point $n$, $\langle \rangle$ denotes mean value and $\sigma_n$ denotes variance of $n$ points. Finally the values are normalized by the last calculated values that seem to be variance and expected value, respectively. There are four curves of exemplary flows: two of each medium in both figures. The grey line curves (air) converge slower then “water” curves. The Figure 5 shows that power stabilizes with growing $n$. It is obvious since while

| Frequency f [Hz] | Norm. flow $q_N$ [m3/h] | Flow veloc. $w$ [m/s] | $Re$ |
|-----------------|-------------------------|--------------------------|------|
| 78,1            | 85,4                    | 70,8                     | 2,42 | 1,37 | 2210 |
| 87,9            | 95,2                    | 80,6                     | 2,98 | 1,68 | 2717 |
| 97,7            | 105,0                   | 90,3                     | 3,20 | 1,81 | 2919 |
| 107,4           | 114,7                   | 100,1                    | 3,75 | 2,12 | 3426 |
| 170,9           | 178,2                   | 163,6                    | 6,22 | 3,52 | 5678 |
| 463,9           | 473,6                   | 454,1                    | 18,26 | 10,33 | 16666 |
| 556,6           | 566,4                   | 546,9                    | 22,57 | 12,77 | 20599 |
then \( n \rightarrow \infty \) then \( \sigma_{n+1} \rightarrow \sigma_n \) because the latter constituent in square brackets tends to null. This is the most significant difference between water and air that the variance stabilizes within first 1000 points (arbitrary units at abscissa) in case of water. But the air fluctuates within 5% through the entire signal course. The slope of mean value convergence is much gentle (see the scale on coordinates in Fig. 6). Therefore the signal is assumed to be ergodic at considered time period.

The last important difference between results recorded with air and water is presented in the Figure 7. The distance \( x_f \) is between laser beam axis and vortex generator surface at downstream side and is normalized by the inner diameter of the pipe. The curve with squares (■) depicts data obtained with water flow and the curve with circles (●) depicts data of air flow. The value zero means that half of the laser beam was reflected by the vortex generator and half passed through entire measurement volume.

![Figure 7. The distance \( x_f \) at both media.](image)

The ordinate shows SNR normalized by its maximum value. SNR reaches local maximum at distance \( x_f \) of approximately half of the pipe diameter and then it remains at the same level in case of water. The signal for longer \( x_f \), however still readable, becomes deteriorated. The second harmonic appears and its amplitude grows with \( x_f \). In case of the air flow the maximum is much sharper; the SNR decreases rapidly at both sides of the peak. It shows how transitory is Kármán street in gas.

4. Conclusion

The presented characteristics shown unique features of photonic approach in a conventional vortex flow meter. The conversion characteristics proved the applicability of optical method to discharges below Re=4000. The method is relatively fast: the average value of the signal stabilized within 1s to the level of ±2% of expected value for both media. However to stabilize the power at level of ±5% it takes 20s in case of gaseous discharge. The optimum distance \( x_f \) is suggested for the best SNR – this parameter seems to be very important in case of gaseous flows.

The weakness of the method is same as mainly all other optical flow measurements: it requires the seeding. However there are some significant advantages like: very fast detection, electromagnetic immunity and intrinsically safe, capacity to built a net of flowmeters based on fiber coupling and only one laser diode and one detector with multiplexer. The further investigation including especially optimalization of the geometrical parameters is necessary and scheduled.

References

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