METROLOGICAL ANALYSIS OF THE FLOW RATE MONITORING OF A WATER COOLING SYSTEM IN HYDROELECTRIC POWER PLANTS

Orlando, Alcir F., afo@mec.puc-rio.br
PUC-Rio,R. Marquês S. Vicente 225, Rio de Janeiro, RJ, 22453-900, Brazil

Farias, Maria Helena, mhfarias@inmetro.gov.br
INMETRO, Av. N.S. das Graças 50, Xerém, Duque de Caxias, RJ, Brazil

Accioly, Carla Cito, carla.accioly@light.com.br
Light, R. Marechal Floriano 168, Rio de Janeiro, Rj, Brazil

Callegario, Evêmero, callegario@mec.puc-rio.br
PUC-Rio,R. Marquês S. Vicente 225, Rio de Janeiro, RJ, 22453-900, Brazil

Abstract. *The monitoring of the cooling water flow rate in power producing equipments of hydroelectric plants has been an issue of concern due to the possibility of clogging up measurement instruments by the used non treated flowing water. Furthermore, for economic reasons, a cheap and reliable instrument must be chosen for each of the many monitoring points. In this work, a non-intrusive device was developed and its performance analized for measuring water flow rate in the 0,7 to 7 m3/h range. The basic operating principle is the variation of the vortex shedding frequency with flow rate. An accelerometer placed outside the pipe wall measures the vortex induced vibration frequency. Several tests showed that the instrument is noise sensitive, which must be filtered to reduce the uncertainty of measurement. The Strouhal number was plotted as a function of the pipe Reynolds number, showing an asymptotic trend towards an approximately constant value at high Reynolds numbers. The instrument sharply differenciates between flow and non-flow situations. Presently, a signal conditioning effort is being conducted to reduce the uncertainty of measurement of the flow rate, which is estimated in this work.*

Keywords*: Non intrusive flow rate measurement,Vortex shedding meter, Cooling water flow rate,Struhal number*

1. INTRODUCTION

The remote operation of hydroelectric power plants requires that the information about the performance of different system components be supplied to the system controller, that will check if the minimum operating conditions have been achieved. In case of the component is not working properly, it must be subjected to a maintenance procedure. In case of failure, the system must be shut down.

Presently, in hydroelectric power plants that have been operated by the electric energy utility company LIGHT, there exists a great difficulty in monitoring the water flow rate of the refrigerating circuits of the electric energy producing equipments, preventing its remote operation, and requiring frequently equipment maintenance. The cooling water quality is variable with a high concentration of sediments, even after having passed through a self cleaning filter. Thus, frequently, the measurement instruments are clogged up by those sediments, and prevented from properly functioning.

Three (3) types of instruments have been used by LIGHT to monitor the cooling water flow rate. A flow switch requires frequent maintenance schedules because of deposit of sediments on it. Turbines and ultra-sonic meters do not measure accurately flow rate because of fouling and sediment blockage.

The motivation for this project is to develop a new non intrusive, low cost and low maintenance flow measuring equipment, to operate in different power plant cooling water circuits, besides shutting off the electric energy generators when needed. Uncertainty level is not the main objective of this study, although it has been determined. The instrument was designed to operate in the 0,7 m^3/h to 7 m^3/h flow rate range, and 4 to 7 bar pressure range.

Two systems have been studied. In the first one, a strain gage is attached to the outer surface of a water pipeline elbow, to measure the force exerted on the wall when the flow changes direction. In the second one, an accelerometer is attached to the outer surface of a water pipeline to measure the induced frequency of vibration due to vortex formation after a flow obstruction. The output from both sensors are related to flow rate in this study.

2. THEORETICAL BACKGROUND

2.1 Flow rate measurement with a strain gauge

When a fluid is flowing (volumetric flow rate Q) through a pipeline (diameter D, length L, cross section A), that has a fixed support in a wall in one end, and a bend in the other end, a force F is exerted in such a way to stretch the pipeline by ΔL. The strain (ε) can thus be expressed by :

$$\varepsilon = \frac{\Delta L}{L} = \frac{F}{A.E} \tag{1}$$

where E is the Young modulus of elasticity. The momentum theorem shows that the following expression can be written :

$$F = \rho.Q.U = \rho.\frac{4.Q^2}{\pi.D^2} \tag{2}$$

where ρ is the fluid specific mass, and U is the mean fluid velocity. Also, if a strain gage has a constant C(≈2) and a resistance R (≈120 Ω), its change ΔR can be related to the strain by the following expression :

$$\varepsilon = \frac{\Delta L}{L} = \frac{1}{C}.\frac{\Delta R}{R} \tag{3}$$

Therefore, a relationship between strain gauge resistance and flow rate can be obtained.

A measurement system was designed for a maximum volumetric flow rate of 7 m^3/h, using a 1½ in diameter pipe. Table 1 shows the design parameters. Using these values and Eq. (1), (2) and (3), the following parameters can be calculated, as indicated in Table 2.

Table 1 : Design parameters for a flow measurement system with a strain gauge

Parameter	Symbol	Unit	Value
Design Flow rate	Q	m^3/h	7
Internal pipe diameter	D	in	1,610
Wall thickness	t	in	0,145
Strain Gage constant	C		2,1
Young's modulus	E	psi	30 x 10^6
Stain Gauge Resistance	R	Ω	120

Table 2 : Estimated performance parameters

Parameter	Symbol	Unit	Value
Flow cross section	A_{cross}	m^2	0,001313
Fluid mean velocity	U	m/s	1,48
Wall area	A	m^2	0,000473
Exerted Force	F	N	2,880
Strain	ε	µs	0,0294
Resistance variation	ΔR	µΩ	7,42

Available commercial equipments are designed to measure strain values from 1 µs and on, which results in resistance variation of 240 µΩ, that is, about 34 times larger than what is required. In order to overcome this difficulty, a Wheatstone bridge was built, consisting of three 120 Ω resistance and a 120 Ω strain gauge resistance to measure. The bridge is fed by a constant current source (I). The voltage difference (ΔV) between output ports of the bridge can be related to resistance difference (ΔR) by :

$$\Delta V = \frac{\Delta R.I}{4} \tag{4}$$

Strain can thus be calculated by Eq. (3).

2.2 Flow rate measurement with an accelerometer

The physical phenomenon to be used for measuring the flow rate is the boundary layer separation and the vortex formation that occur when an obstacle is placed in a fluid flow (Schlichting, 1968). When a flow is started up the motion in the first instant is nearly frictionless, and remains so as long as the boundary layer remains thin. Outside the boundary layer there is a transformation of pressure into kinetic energy. A fluid particle which moves in the immediate vicinity of the wall in the boundary layer remains under the influence of the same pressure field as that existing outside, because the external pressure is impressed on the boundary layer. Owing to the large friction forces in the thin boundary layer such a particle consumes so much of its kinetic energy on its path that the remainder is too small to surmount the pressure elevation when the flow is decelerated. Such particle cannot move far into the region of increasing pressure, and its motion is eventually arrested. The external pressure causes then it to move in the opposite direction, and a reverse motion starts, giving rise to a vortex, which becomes separated shortly afterwards and moves downstream in the fluid. At a larger distance from the obstacle it is possible to discern a regular pattern of vortices which move alternately clockwise and counterclockwise, and which is known as a Kármán vortex street.

The frequency with which vortices are shed in a Kármán vortex street behind a cylinder has been extensively studied by many researchers. It has been observed that two dimensionless parameters are sufficient to describe the phenomenon, and the Strouhal number (S) is only a function of Reynolds number (Re), which are defined in terms of cylinder diameter (D), mean flow velocity (V), viscosity (υ) and frequency (n), according to Eq. (5) and (6), and shown in Fig. 1.

$$S = \frac{n.D}{V} \tag{5}$$

$$\mathrm{Re} = \frac{V.D}{\upsilon} \tag{6}$$

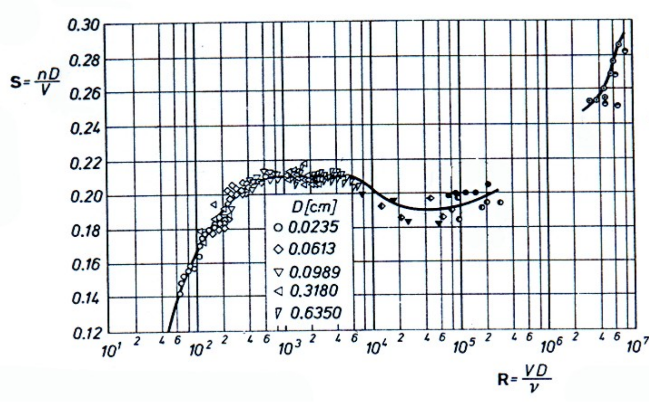

Figure 1 : Strouhal number as a function of Reynolds number for cylinders (Schlichting, 1979).

The Strouhal number (S) increases when Reynolds number varies from a small value up to approximately Re= 1200, where it reaches a constant value of S = 0,21; then it decreases down to S = 0,18, for approximately Re = 400000. In the vicinity of Re = 1000000, it does not seem to exist a regular pattern of vortices.

Commercial vortex meters use this principle to estimate flow rate from the measured vortex frequency, inserting a cylinder into the pipeline. However, if a non intrusive instrument is desired, the vortex frequency must be measured downstream of an existing obstacle in the pipeline, a valve for example. The induced pipewall vibration due to the vortex motion is measured with an accelerometer. This study deals with relating flow rate with the vortex frequency in situations where the obstacle is not a cylinder.

3. EXPERIMENTAL PROCEDURE

3.1 Flow rate measurement with a strain gage

Water from a pressure vessel flows through the test section with a specified flow rate, which is adjusted by a valve placed at its entrance. The vessel has a volume of 160 L and is placed on a weighter. At a maximum flow rate of 7 m^3/h, it is emptied in about 1,37 min, which allows the uncertainty of flow rate measurement to be estimated within less than 1%. Furthermore, the water in the vessel can be pressurized up to 10 bar, thus covering the required pressure range (4 to 7 bar). Measurement system, instruments and uncertainties are described in Fig. 2, following (Orlando et al, 1997).

A test section was designed to measure flow rate as a function of vortex frequency. It consists of two 1½ in diameter steel pipes connected by a 90° plastic (PVC) pipe bend, where the strain gauges are glued to measure strain, according to Fig. 3. Each pipeline is 15 in long.

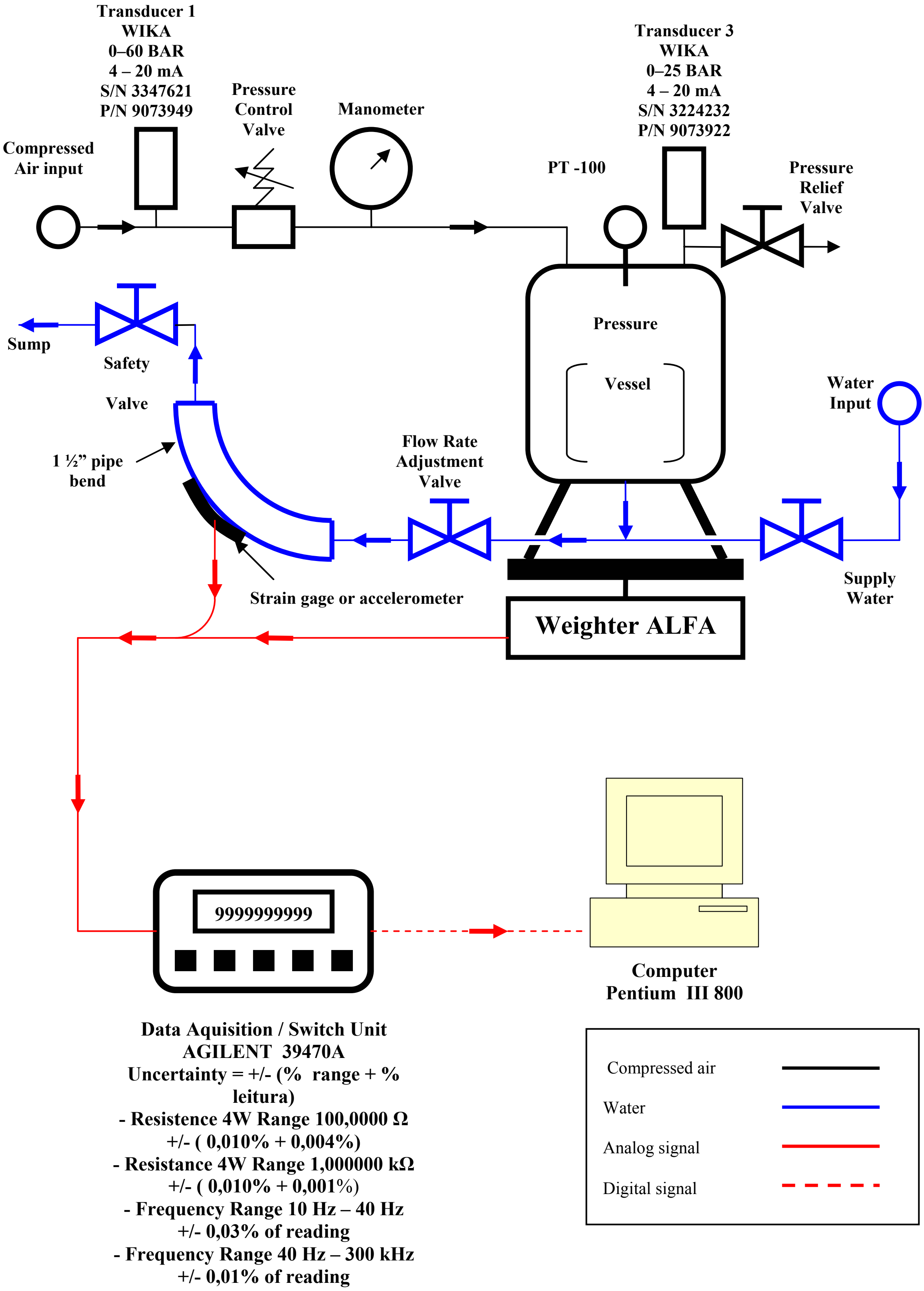

Figure 2 : Flow rate measurement system

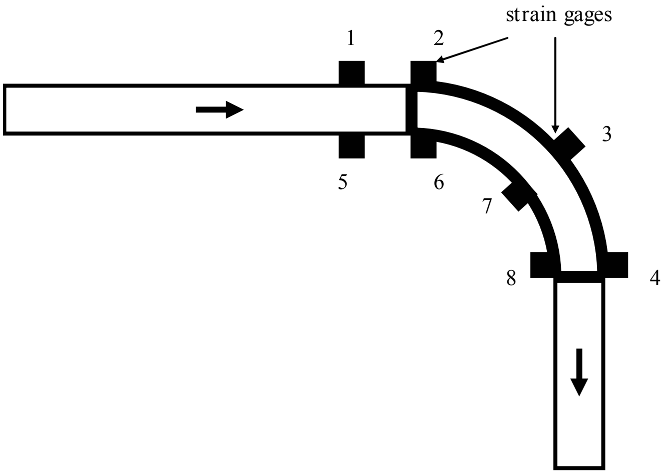

Figure 3 : Strain gages in the test section

The mean flow rate during a run ($\dot{m}$), in kg/s, was determined by measuring the water mass in the vessel (M), to within of ± 0,020 kg (95,45%), as a function of time (t), as registered by the computer clock, to within ± 0,01 s. Then, a straight line was fitted to the experimental data by the least square method, according to Eq. (7), following (ISOGUM, 1995)

$$M = A + B.t \tag{7}$$

The mean flow rate during the run ($\dot{m}$) was determined as coefficient B of Eq. (7). The root mean square deviation (s) was calculated by first defining a variable Z_i, in terms of the measured values M_i and t_i .

$$Z_i = \frac{M_i - A}{t_i} - B \tag{8}$$

$$s = \sqrt{\frac{1}{N-2} . \sum_{i=1}^{N} (Z_i - \overline{Z})^2} \tag{9}$$

$$\overline{Z} = \frac{1}{N} \sum_{i=1}^{N} Z_i \tag{10}$$

It was found that the contribution of water mass and time uncertainties to flow rate measurement is very small. Therefore, they can be neglected. The expanded uncertainty of the mean flow rate measurement U_{flow} is :

$$U_{flow} = \frac{t_{student} . s}{\sqrt{N}} \tag{11}$$

The mean flow velocity (V) can be calculated from the knowledge of the pipe diameter (D) and flow rate measurement.

$$V = \frac{\dot{m}}{\rho . \frac{\pi}{4} . D^2} \tag{12}$$

Several exploratory tests were carried out to determine the most sensitive test section position to strain, so that to maximize the strain gage output signal. A KYOWA strain gage, model KFG-5-120-C1-11, was glued in each of the eight (8) positions of the test section, as shown in Fig. 3. An Agilent 34970A multimeter was used to measure strain gage resistance for each flow rate in the 0 to 14 m^3/h range, with an estimated accuracy of ± 11 mΩ for only one measurement. Table 3 shows the mean value and the spread (2.σ) of 357 measured data points. It can be seen that SG-1 and SG-5 strain gages are the most sensitive ones. Therefore, the SG-5 strain gage position of the test section was chosen for calibrating the developed flow rate measuring instrument.

Table 3 : Determination of the most sensitive position of the test section

Strain gage	Mean value	Spread (2.σ)
	mΩ	mΩ
SG-1	120101	27
SG-2	120150	1
SG-3	120303	1
SG-4	120186	1
SG-5	120545	34
SG-6	120121	1
SG-7	120020	3
SG-8	120050	1

In order to increase the sensitivity of the system with respect to the SG-5 strain gage resistance variation, a Wheatstone bridge was built with three more resistance arms, respectively SG-2, SG-3 and SG-6 strain gages, already glued on the pipe outer surface. They were chosen because their resistance variation was not sensitive to flow rate variation (Table 3).

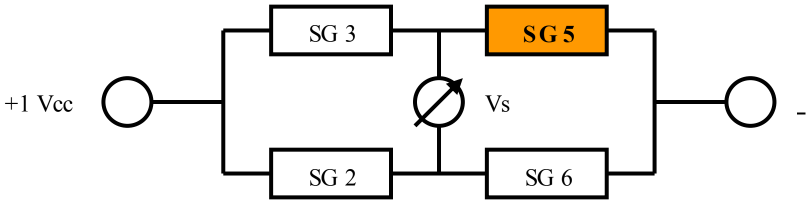

Figure 4 : Wheatstone bridge for measuring SG-5 strain gage resistance

During measurement, a + 1 V was applied to the bridge, and the V_s is measured in µV.

3.2 Flow rate measurement with an accelerometer

A two axis ANALOG DEVICES accelerometer, model ADXL203, was specified to measure frequency as a function of flow rate, in the same test section position as SG-5 strain gage. An Agilent 34970A multimeter was used to measure frequency with an estimated accuracy of ± 0,01% of the reading, which can be neglected when compared to the spread of the data, indicating that the experiment is not completely under control. Its mean value ($\bar{n}$), Eq. (13), and spread (u_n), Eq. (14), gather the influence of all unknown causes. The last one can be interpreted as the uncertainty of frequency measurement in the experiment, including all unknown causes for the spread of data (maybe, pipe vibration).

$$\bar{n} = \frac{1}{N}.\sum_{i=1}^{N} n_i \tag{13}$$

$$u_n = \sqrt{\frac{1}{N-1}.\sum_{i=1}^{N} (n_i - \bar{n})^2} \tag{14}$$

The uncertainty of the average value (U_n) can be expressed as :

$$U_n = \frac{t_{student}.u_n}{\sqrt{N}} \tag{15}$$

4. RESULTS AND ANALYSIS

4.1 Flow rate measurement with a strain gage

Measuring the output voltage from the Wheatstone bridge, several data points were collected for different flow rates, as shown in Fig. 5.

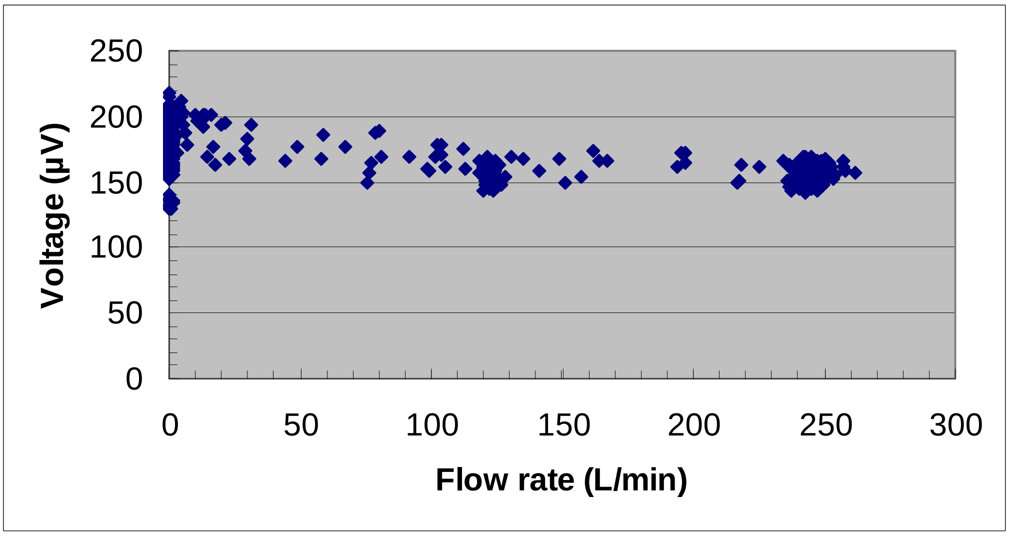

Figure 5 : Instrument performance

It can be observed that that the output voltage from the bridge does not vary much with flow rate. In fact, for low flow rates (up to 70 L/min) it varies in the (190 ± 29) µV range. It then stabilizes in (158 ± 14) µV for higher flow rates.

The analysis of the experimental data for different pressure values shows that the pipe deformation due to pressure is much larger than those due to hydrodynamic forces.

As a conclusion, the instrument can be used for identifying if the pipe is pressurized or not. Its sensitivity for flow rate measurement is small.

4.2 Flow rate measurement with an accelerometer

The test section of Fig. 3 was rigidly coupled to the pressure vessel and the mean flow rate and frequency were measured, as shown in Fig. 6. It can be seen that the flow rate is smaller for higher frequencies.

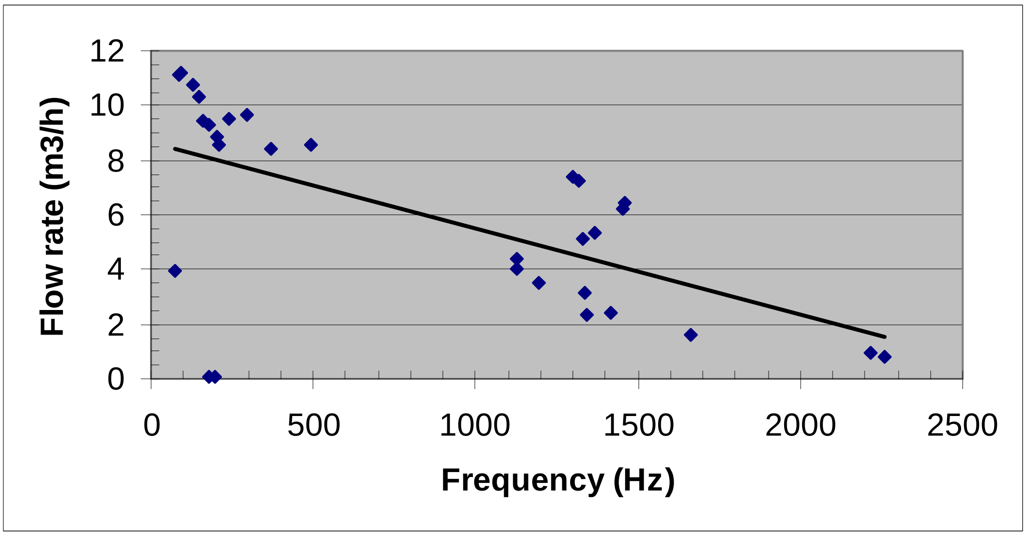

Figure 6 : Flow rate versus Frequency. Rigid coupling with pressure vessel

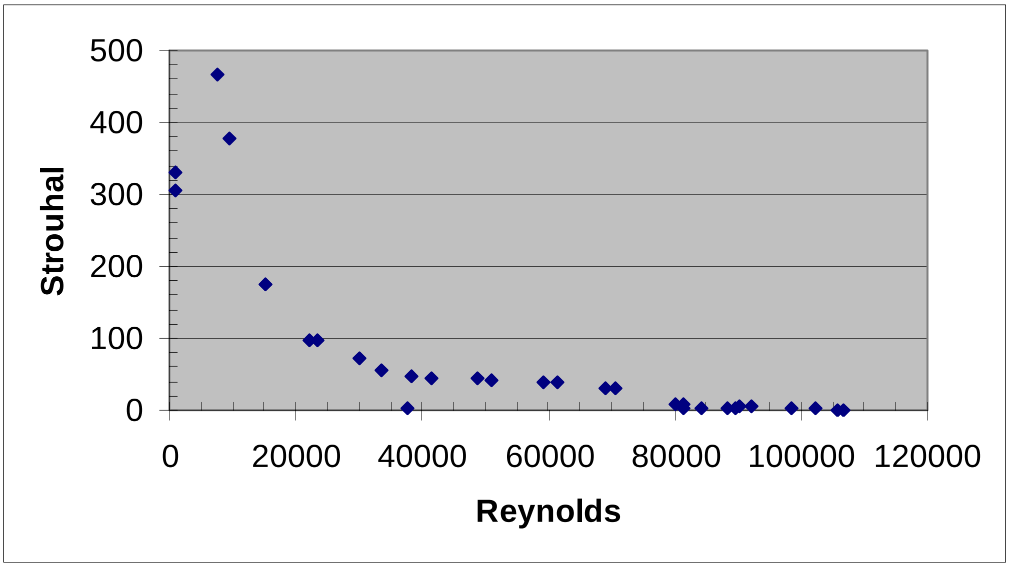

Figure 7: Strouhal number as a function of Reynolds number. Rigid coupling with pressure vessel

Table 4 : Measured, calculated parameters and uncertainties. Rigid coupling with pressure vessel.

Flow rate (m^3/h)		Frequency (Hz)		Strouhal	Reynolds
Q	U_{flow}	n	U_n	S	Re
Eq. (10)	Eq. (11)	Eq. (13)	Eq.(15)	Eq. (5)	Eq. (6)
11,21	0,43	92	12	1,38	106625
10,34	0,43	146	17	2,36	98368
9,42	0,22	157	13	2,80	89580
9,28	0,37	181	24	3,27	88257
8,87	0,09	203	45	3,83	84343
8,56	0,22	493	76	9,66	81393
7,41	0,15	1300	108	29,42	70500
6,46	0,27	1457	47	37,82	61439
5,37	0,06	1370	51	42,74	51119
4,37	0,07	1125	55	43,15	41587
3,52	0,15	1195	33	56,86	33518
2,45	0,01	1418	79	97,20	23272
3,95	0,02	72	6	3,04	37617
0,81	0,00	2259	128	465,70	7734
0,10	0,00	178	41	306,88	927
0,10	0,00	196	42	331,61	944
0,98	0,01	2220	141	378,77	9345
1,60	0,02	1665	90	174,39	15227
2,33	0,02	1341	53	96,51	22159
3,17	0,03	1339	89	70,92	30112
4,04	0,13	1124	36	46,67	38401
5,12	0,11	1332	80	43,60	48723
6,24	0,05	1453	64	39,04	59348
7,27	0,08	1318	92	30,39	69173
8,41	0,31	369	23	7,35	80005
8,54	0,12	212	22	4,15	81275
9,49	0,11	237	46	4,19	90239
9,68	0,12	295	85	5,11	92111
10,74	0,12	127	18	1,98	102144
11,10	0,14	83	11	1,26	105608

It can be observed from Fig. 7 that the measurements were taken in the decreasing part of Fig. 1 (Re > 4000). Table 4 shows the measured and calculated parameters of Fig. 6 and 7, and their uncertainties.

The experimental data can be fitted to a straight line to represent average volumetric flow rate (Q) as a function of average frequency. It can be seen that the uncertainty is high, and that the data must be better interpreted and processed to improve the repeatability of results. However, when Strouhal number is plotted as a function of Reynolds number (Fig. 7), the scatter is much smaller.

$$Q = 8{,}6482 - 0{,}031\ n \qquad (16)$$

As a first attempt to better understand the phenomenon, a flexible coupling between the test section and the pressure vessel was used in place of the rigid coupling. Fig. 8 shows the results.

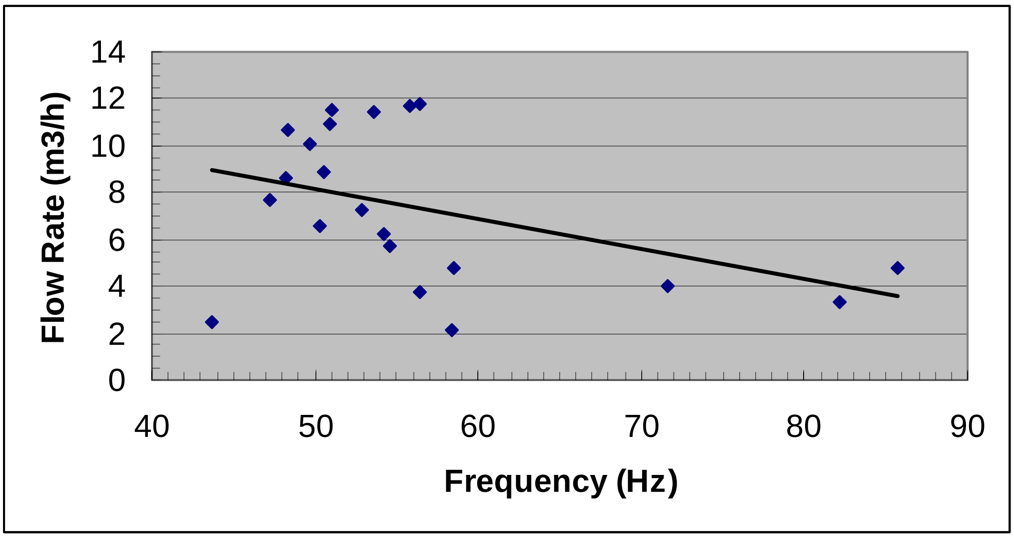

Figure 8 : Flow rate versus Frequency. Flexible coupling with pressure vessel

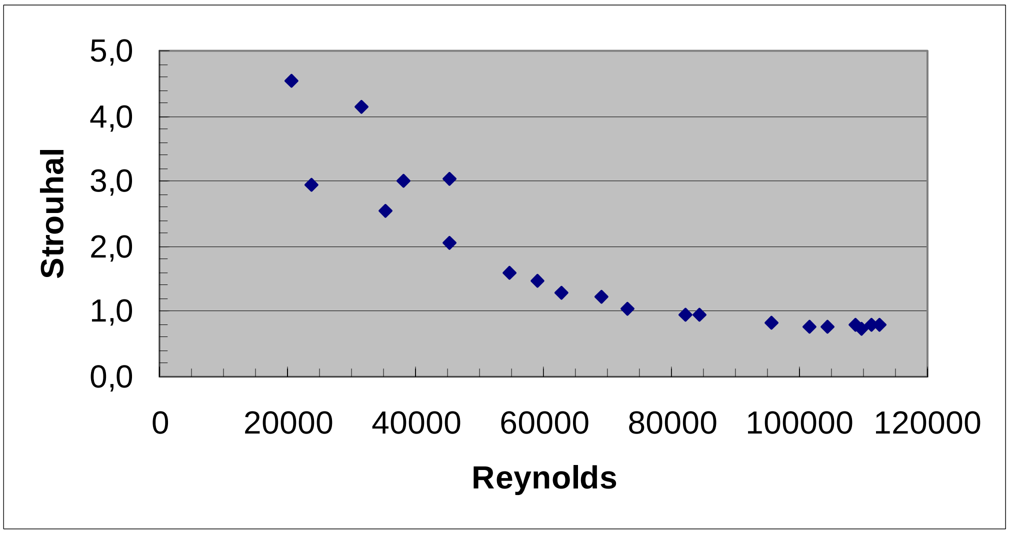

Figure 9 : Strouhal number as a function of Reynolds number. Flexible coupling with pressure vessel

It was observed that the frequency is much smaller, and, therefore, the coupling has an important effect on the instrument performance, because it propagates the structure vibration. Again, when Strouhal number is plotted as a function of Reynolds number (Fig. 9), the scatter is much smaller. Table 5 shows the measured and calculated parameters of Fig. 8 and 9, and their uncertainties.

The experimental data can be fitted to a straight line to represent average volumetric flow rate as a function of average frequency.

$$Q = 14{,}481 - 0{,}1269\, n \quad (17)$$

Table 5 : Measured, calculated parameters and uncertainties. Flexible coupling with pressure vessel.

Flow rate (m^3/h)		Frequency (Hz)		Strouhal	Reynolds
Q	U_{flow}	n	U_n	S	Re
Eq. (10)	Eq. (11)	Eq. (13)	Eq.(15)	Eq. (5)	Eq. (6)
11,81	0,33	56	7,4	0,80	112364
11,44	0,44	54	3,6	0,79	108772
10,97	0,23	51	2,9	0,78	104299
10,04	0,14	50	1,7	0,83	95511
8,87	0,11	51	2,3	0,96	84371
7,25	0,02	53	2,2	1,22	68921
6,20	0,04	54	2,4	1,47	58960
4,77	0,10	59	3,8	2,06	45363
3,73	0,09	56	2,6	2,54	35445
2,50	0,02	44	1,2	2,93	23737
2,16	0,01	58	4,0	4,53	20548
3,33	0,05	82	10,0	4,14	31649
4,00	0,08	72	5,0	3,00	38047
4,75	0,02	86	3,0	3,02	45184
5,75	0,04	55	1,8	1,59	54663
6,61	0,02	50	2,4	1,27	62841
7,69	0,14	47	1,9	1,03	73117
8,63	0,18	48	1,6	0,94	82052
10,67	0,10	48	2,9	0,76	101498
11,53	0,44	51	5,4	0,74	109686
11,70	0,12	56	8,2	0,80	111243

In order to continue the development of the system, a Fourier analysis of the frequency signal will be carried out, so that the unknown causes for the spread of data can be identified, thus better controlling the experiment.

The main conclusion of this exploratory study is that the measurement of the vibration frequency of the pipe outer surface can be used to measure flow rate, provide that the contributions of different parameters to signal output be identified and eliminated, thus smoothing out the results. Today, the instrument can be used to measure flow rate with a high uncertainty value, if it is calibrated at the installation. Finally, because of the fact that the vibration frequency is zero at no flow condition, the instrument is able to identify if there is flow or not.

5. CONCLUSIONS

This paper presents the preliminary results of the development of a non intrusive instrument for monitoring the cooling water flow rate in hydroelectric power plants. It uses an accelerometer to measure the vibration frequency of the pipe outer surface, induced by vortex formation as a function of flow rate. The system is very sensitive to coupling of the test section with the structure. In the continuation of the development, the contribution of each parameter on the frequency output must be identified, thus keeping only the vortex frequency. Today, the system can be used to measure flow rate, provide it is calibrated where it is going to be used. However it can be clearly identify if there is flow or not.

6. AKNOWLEDGMENTS

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