

Laboratory and field tests on photo-electric probes and ultrasonic Doppler flow switch for remote control of turbidity and flowrate of a water-sand mixture flow

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Abstract. The paper describes the experimental apparatus and field tests carried on to remotely control through non-invasive and non-intrusive instruments turbidity and flowrate of a water-sand mixture flow conveyed by a pipeline. The mixture flow was produced by an innovative plant for seabed management. The turbidity was monitored by thru-beam infra-red photo-electric sensors, while flowrate was monitored by an ultrasonic Doppler flow switch. In a first phase, a couple of photo-electric sensors and a mechanical flow switch were preliminary tested in laboratory to verify installations concerns and measurement repeatability and precision. After preliminary test completion, photo-electric sensors and mechanical flow switch were installed in the real scale plant. Since the mechanical flow switch did not reach high reliability, an ultrasonic Doppler flow switch was identified and tested as alternative. Then, two couple of photo-electric sensors and ultrasonic Doppler flow switch were installed and tested on two pipelines of the plant. Turbidity and minimum flow signals produced by the instruments were integrated in the PLC logic for the automatic management of the plant. The paper also shows how ultrasonic Doppler flow switch measurement repeatability was negatively affected by the presence of the other ultrasonic Doppler flow switch working in a close pipeline and installed inside a steel casing.

1. Introduction

In the last decade an innovative technology for seabed plant management has been developed, designed and tested with the contribute of the University of Bologna [1,2]. The main element of the plant, called “ejector” (figure 1), is an open jet pump (i.e. without closed suction chamber and mixing throat) with a converging section instead of a diffuser. The ejector transfers momentum from a high speed primary jet flow to a secondary flow. The primary jet flow contacts the suction fluid at the nozzle exit and drags it into the sea bottom, thus starting up and sustaining the secondary flow of suction fluid from surrounding water mass. If present, solid particles are entrained in the secondary flow, where jet stream and suction fluid are further mixed, exchanging momentum and recovering pressure. The water-sediment slurry then passes through a converging and into a discharge pipe for delivery to a discharge point (or into a booster). The ejector can be used as a fixed or mobile device [3]: when used as a fixed device, one ejector works on a limited area whose diameter depends on the sediment characteristic as, for example, the angle of repose. The water for ejectors feeding is pumped from a pumping station placed near the ejectors



installation area. The plant works 24 hours a day, 7 days a week, and by ejectors integration in series and in parallel it is possible to create and maintain over the time a seaway (figure 2).

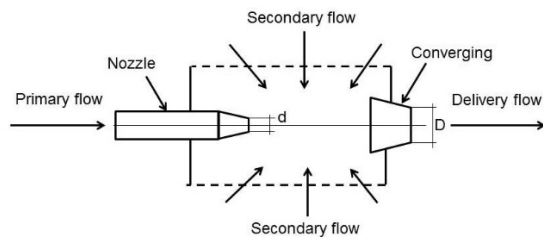


Figure 1. Schematic of the “ejector” developed by DIN.

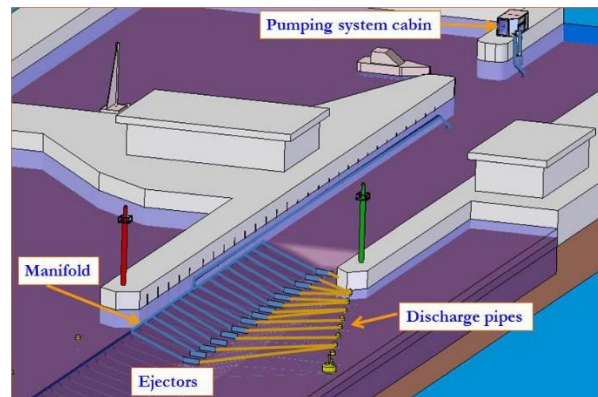


Figure 2. 3D image of seabed maintenance plant lay-out.

In 2005 [1] the first full-scale experimental plant was designed and carried out in the port of Riccione (Italy). The results of the experimental campaigns demonstrated the functionality of the system itself, the cost-effectiveness and low environmental impact if compared to the use of the dredge. In 2011 [2] a small scale industrial plant has been realized in the Portoverde Marina (Italy). This plant is characterized by better performances in automation and control higher than the first experimental plant. The monitoring of discharge pipelines was one of the critical issues to be further developed. In particular, two parameters need to be monitored: sediment content in the discharge pipelines and discharge flowrate. Both parameters can be used to regulate ejector water feeding: when discharge flowrate is too low and/or solid content is too high, the water flowrate that feeds the ejector must be increased up to a maximum level to avoid clogging risk, while if discharge flowrate and solid content are about nominal values, the ejector can work at a reduced load (i.e. less water feeding flowrate). The instruments to be applied for such measurements should have the characteristics described in table 1. After a market survey, two different instruments were identified as best suitable for the specific application: thru-beam infra-red photo-electric sensors for the measure of the solid content, ultrasonic Doppler flow meter for flowrate monitoring. Nevertheless, also a mechanical flow switch was taken into consideration to evaluate a low cost solution for flowrate monitoring, despite the fact that the instrument is both intrusive and invasive.

Table 1. Characteristics requested by the instrumentation to be used.

Characteristic	Reason
Continue monitoring	Avoid risk of clogging between two consecutive measurements.
On-off electric signal	Only need a command to bringing ejector water feeding to the maximum level from the nominal value.
High durability	Limit maintenance activities (and related costs).
High resistance	Work in aggressive environment (seawater and sand).
Low energy consumption	No access to the electric grid (use of electric batteries).
Non-intrusive and non-invasive	Avoid risk of clogging and limit pressure losses.
Good repeatability	More than precision, high repeatability is requested since the objective is not to continuously measure turbidity and flowrate, but to detect the exceeding of a critical point.

An infra-red photoelectric sensor emits a light beam from its light-emitting element. In the thru-beam configuration the light emitting element and the light receiving element are separated (figure 3). When a target passes between the emitter and the receiver it may interrupt the light transmission.

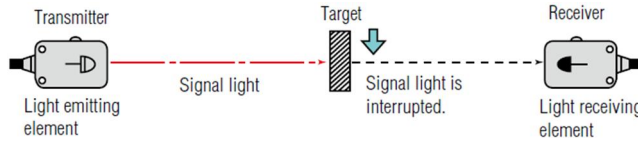


Figure 3. Example of thru-beam infra-red photo-electric sensor configuration, where signal light is interrupted by the presence of a target between light emitter and receiver.

Photo-electric sensors are widely used for different purposes in several industrial and non-industrial fields and so they represent a reliable technology [4,5,6]. The application of photo-electric sensors in solid content measurement (called “turbidity sensors”) has been already applied [7,8] and many products are available, but they are quite expensive since sensors need a complex set up to result functional for the specific application. Moreover, turbidity sensors are usually quite large in size, since they are often installed for the turbidity monitoring of river, lake or sea. So, they cannot be easily adapted for a measure on a close and small duct (diameter size DN80 in the application described in the paper). On the other hand, it is possible to use commercial photo-electric sensors to measure turbidity, thus reducing cost and size, but the calibration must be realized by the user [9].

In the ultrasonic Doppler flowmeters (figure 4) an emitter sends ultrasonic waves at frequency f_1 (approximately between 1-5 MHz) at angle α in a flowing fluid. The ultrasonic waves strike particles or air bubbles moving through the sound field at velocity v_p . The wavelength λ_1 of the emitted wave at frequency f_1 amounts to c/f_1 . Due to its rate of motion v_p , the particle moving away from the emitter sees the wavelength λ_p as in equation (1):

$$\lambda_p = (c - v_p \cdot \cos\alpha) / f_1 \quad (1)$$

In turn, the receiver sees the reflected frequency f_2 (which is equal to c/λ_2) out of line because the reflecting particle is moving further away all the time, and the wavelength λ_2 changes as follows in equation (2):

$$\lambda_2 = (c - 2 v_p \cdot \cos\alpha) / f_1 \quad (2)$$

The difference in frequency is therefore a linear measure of the rate of motion of the particles as in equation (3), where the term v_p can be neglected if compared with c .

$$f_2 - f_1 = (2 v_p \cdot f_1 \cdot \cos\alpha) / (c - 2 v_p \cdot f_1 \cdot \cos\alpha) \approx (2 v_p \cdot f_1 \cdot \cos\alpha) / c \quad (3)$$

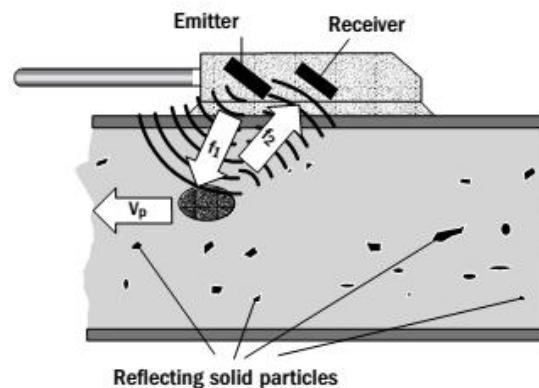


Figure 4. Principle of the Doppler flowmeter.

So, ultrasonic Doppler flowmeter needs “reflectors” like solid particles and air bubbles in the process fluid to properly work. That’s why, in particular, ultrasonic Doppler flowmeters are applied in the

monitoring of flowrate discharge in wastewater plants and natural or artificial canals and channels [10,11]. Due to the complexity of the physical process, which is influenced by many factors, this kind of instrument has been perceived as un-reliable and uncertainty: in particular, wrong installation (i.e. sensor positioning) [12,13], acoustic interference [14] and variability of reflectors content [15] are the typical issues affecting the reliability of measurements made by ultrasonic Doppler sensors. So, ultrasonic flow measurement has been applied only in few and limited applications.

The paper shows the results of preliminary laboratory tests and the following test realized on field in the real scale plant on photo-electric sensors, ultrasonic Doppler flow switch and a mechanical flow switch, which was tested in the very beginning as an alternative to the ultrasonic Doppler sensor.

2. Laboratory tests

2.1 Photo-electric sensors

The thru-beam infra-red photo electric sensor Osiris XU2 produced by Schneider Electric has been identified as a potential solution for turbidity monitoring. Characteristics of the sensor are reported in table 2. A testing plant was designed and realized to verify if the degree of opacity measured by the sensor (figure 5) is compatible with sediment content level suitable for the application described in the paper. The final objective was to identify the potentiometer regulation, if any, which corresponds to a certain sediment content in the discharge pipe of the ejector.

Table 2. Schneider Electric's Osiris XU2 characteristics.

Characteristic	Value
Weight (kg)	0.155
Length (mm)	95
Diameter (mm)	M18x1
Nominal sensing distance (m)	50
Degree of protection	IP67
Rated supply voltage (V)	12-24
Current consumption (mA)	< 55
Delay time (ms)	< 15
Price, wiring included (€)	110

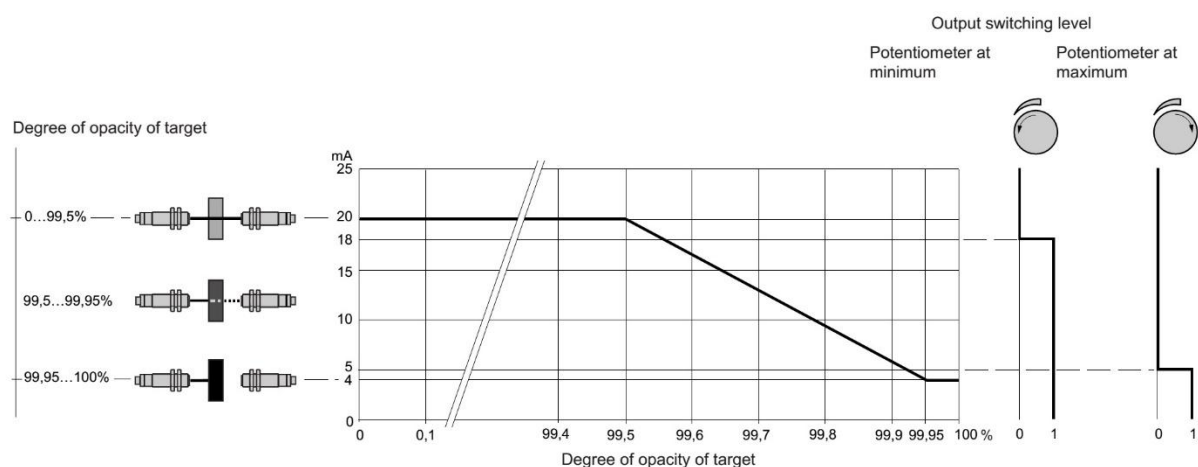


Figure 5. Degree of opacity measured by the Schneider Electric's Osiris XU2 and output signal 4-20 mA as a function of potentiometer regulation.

The testing plant was made by a centrifugal water pump, a manual regulating valve, a transparent tank wherein water and sand can be mixed, piping and a measuring pipe (figure 6). The measuring pipe is composed by a DN80 PVC duct connected with a plexiglass tube. Photo-electric sensors are installed on the plexiglass pipe. Firstly, the manual regulating valve position has been adjusted to guarantee a volumetric flowrate of about 25 m³/h. Then, each test was characterized by the following procedure: after filling the tank up to a certain level, the pump was turned on, working only with water. Then, a certain mass of sand was introduced in the tank. The circulation guaranteed by the pump produced in few minutes a good mixing of water and sand, and so the test can start: the discharge pipe of the pump was manually connected with the aspiration duct of the pump, so the pump work in a closed ring. After observing photo-electric sensors response (green or red light, the latter being the condition of minimum opacity reached, see figure 5), the solid content in the mixture was measured by putting the discharge flow of the pump in another tank and by measuring relative water and sand level after sedimentation. The tests were carried on at different level of potentiometer regulation. It was found that the minimum opacity set with the potentiometer in the lower position corresponds to a 10% of sand in mass per kg of discharge flow (that is, more or less equal to a 5% of sand in volume per liter of discharge flow). This value is compatible with the working characteristic of ejector [2]. So, photo-electric sensors were set at the minimum value of the potentiometer and several tests were conducted with three different pairs of sensors in the same working conditions (i.e. constant increasing of sand content in the circuit). The results show a good repeatability of the instruments, since 95% of the measures follow in a variation range from the mean value of each measuring series that is ± 20 g of sand per kg of discharge flow.

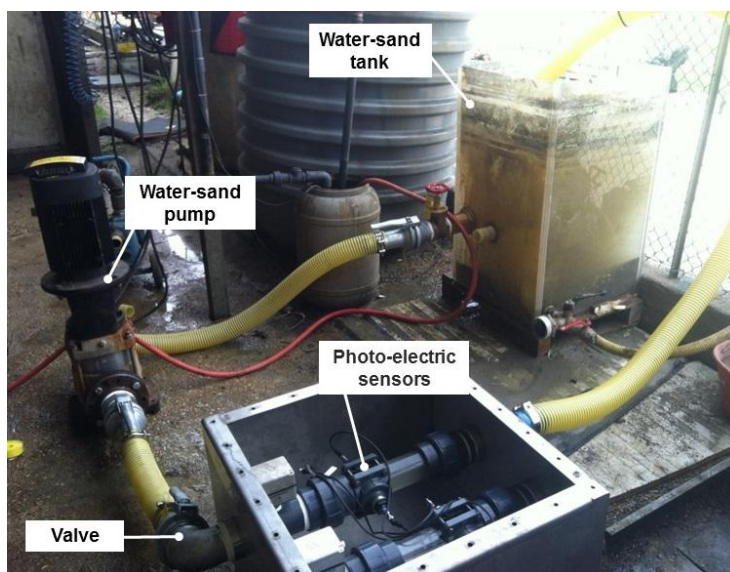


Figure 6. Testing plant.



Figure 7. Measuring pipe.

2.2 Mechanical flow switch

The mechanical flow switch (figure 8) FLU25 was taken into consideration for the discharge flowrate monitoring as an economic alternative to ultrasonic Doppler sensors (FLU25 cost is about 60€). This kind of instrument is usually applied in thermal energy plant and it is used to switch off methane burner when water circulating pump suddenly stops working. The sensitive element is made by a metallic lamina that is pushed by water flow. Lamina movement is contrasted by a spring. Through spring regulation, it is possible to set the opening of the electric switch at a certain flowrate. Since fluid is characterized by the presence of sand and, more in general, solid particles, to avoid clogging the lamella was modified as in figure 9 with the aim of reducing its intrusion within the pipe. Obviously, also the spring was substituted as well. Due to the modification of the sensitive element, tests were needed to identify the correct position of the calibration screw. The mechanical flow switch was tested in the same plant shown in figure 6. After several test, it was found the new calibration screw position corresponding to a volumetric flowrate of 15 m³/h. This value was chosen because it corresponds to a velocity in the

ejector discharge duct that is lower than 1 m/s, which is the limit under which sand sedimentation in the pipeline can occur with a high grade of probability [1,2]. After being set, the mechanical flow switch was tested to verify its repeatability: several tests were carried on with the same procedure (flowrate decreasing from 25 m³/h down to 10 m³/h in a certain time), and the mechanical flow switch show a good repeatability, since 95% of the measures follow in a variation range from the mean value of each measuring series that is ± 1 m³/h.

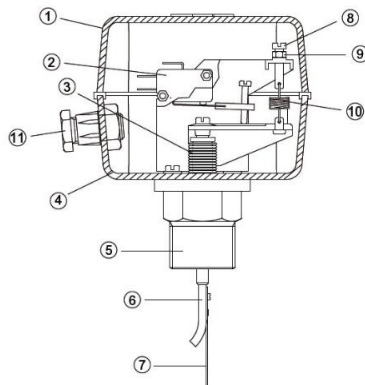


Figure 8. Mechanical flow switch FLU25, which is composed by: cover (1), micro switch (2), bronze bellow (3), body (4), threaded fitting (5), actuator (6), lamina (7), calibration screw (8), locknut (9), return spring (10) and fairlead (11).



Figure 9. The lamella of the mechanical flow switch, respectively, after and before length modification made to avoid clogging risk.

2.3 Ultrasonic Doppler flow switch

The ultrasonic Doppler flow switch DFS-II produced by Greyline Instruments has been identified as a potential solution for flowrate monitoring. Characteristics of the sensor are reported in table 3. The instrument was installed and tested in the water pumping cabin of the Portoverde Marina plant (figure 10): in the cabin two flowrate meters were already present (two orifice plates plus differential pressure transmitters) to measure the water flowrate feeding each ejector.

Table 3. Greyline Instruments's DFS-II characteristics.

Characteristic	Value
Sensor frequency (MHz)	0.64
Degree of protection	IP67
Rated supply voltage (V)	24
Current consumption (mA)	< 150
Measuring diameter range (m)	0.0125-4.5
Measuring velocity range (m/s)	0.08-3.0
Price (€)	900

Installation and calibration are two important phases and may have strong impact on measurement precision [12-15]. Installation on vertical pipes has no particular needs, while installation in horizontal pipe is preferred at hour 3 or 9 to avoid the risk of presence of air (at hour 12) or solid (at hour 6). Generally speaking, the sensor must be installed away from devices able to disturb the flow like pump, valves, orifice plate, curves, section increasing or decreasing: a number of diameters D of straight tube before (10D) and after (6D) the sensors should be respected to guarantee the performance of the instrument. Very important is also the contact between the sensor and the duct. Before the installation

the duct surface should be cleaned and degreased, by eliminating in particular paint, scale and rust. Silicon made compounds should be used to fill the gaps between sensor and duct, where contact is not possible due to pipe curvature. The sensor is fixed to the duct through a metallic clamp. DFS-II requires solids or bubbles minimum size of 100 microns with a minimum concentration of 75 ppm to ensure a precision of $\pm 2\%$. So, if the installation is realized in accordance to previous suggestions and the characteristics (size and concentration) of reflectors in the fluid are over certain values, the linear calibration curve of figure 11 can be used to set the instrument.



Figure 10. Ultrasonic Doppler sensor installed in the water cabin pumping in Portoverde Marina.

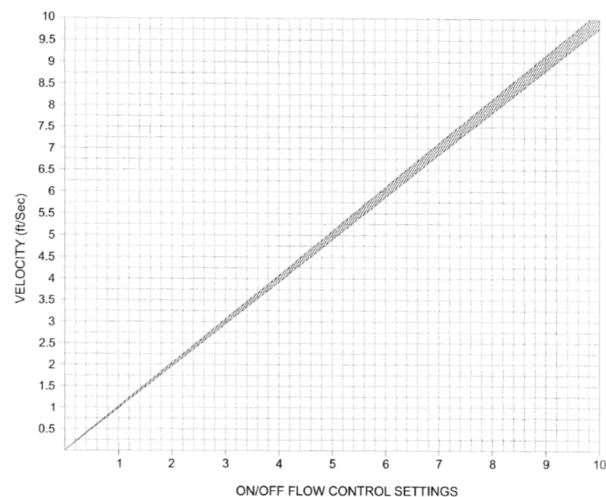


Figure 11. Calibration curve of DFS-II.

Two set-points can be defined on the instrument panel: one for the off-trip, and one for the on-trip. So, for example, if the ON set point is fixed at value 5, while the OFF set point is fixed at 3, it means that the switch is closed (position on) at a velocity of about 1,5 m/s (5 ft/s) and then is opened (position off) at a velocity of about 0,9 m/s (3 ft/s). Delay time (from 0 to 60 seconds) and sensitivity can be adjusted too.

The DFS-II was tested by simulating a cyclic increasing-decreasing of water flowrate. The pump was regulated by an inverter and the flowrate was measured by differential pressure drop on an orifice plate, working as a reference system. The test values were set at 25 m³/h and 15 m³/h, which means ON set point regulated at 5 (1,5 m/s of velocity) and OFF set point regulated at 3 (0,9 m/s of velocity). With these values no correspondence was found between control setting and flowrate measured by the reference measuring system. It was found that, if set with ON at 7 and OFF at 5, the DFS-II works well (switch on at 25 m³/h, switch off at 15 m³/h). Then, the system was tested to verify measure repeatability: several tests were carried on, also varying flowrate variation gradient, and an acceptable repeatability was observed since 95% of the measures follow in a variation range from the mean value of each measuring series that is ± 2 m³/h. So, probably due to a not perfect installation and/or insufficient reflectors characteristics, DFS-II does not work coherently with calibration curve showed in figure 11, but, after an on-site calibration, shows satisfying performances.

3. Field tests

After preliminary test results the three instruments were installed at the Portoverde Marina seabed maintenance plant. The instruments were placed in two measuring pipes (similar to the one shown in figure 7) and closed in a metallic box (figure 12), that was installed near the dock (figure 13) and connected to the discharge lines of the ejectors. The on-off signals are communicated to the PLC of seabed maintenance plant through a wireless LAN bridge (distance about 150 meters) and are used to determine the value of the water feeding flowrate of the ejectors. In a first phase, two thru-beam infrared photo electric sensors and two mechanical flow switches (thus, a couple for ejector discharge

pipeline) were installed. Both mechanical switches and photo-electric sensors demonstrated to work well, in particular by confirming good repeatability and the absence of false positive: checks were made both through on-site measurement on discharge flowrate and solid content, as well as through rapid verification of correspondence of critical condition after the generation of high turbidity and/or low flowrate signals. On the other hand, the mechanical flow switch showed, after 2 working months, a problem related to clogging. Figure 14 and figure 15 show, respectively, a picture of the lamella inside the discharge duct and a picture of the duct clogged due to shells presence.



Figure 12. Instruments installed in the metallic box.



Figure 13. Metallic box installed near the dock and connected with discharge pipes of the ejectors.

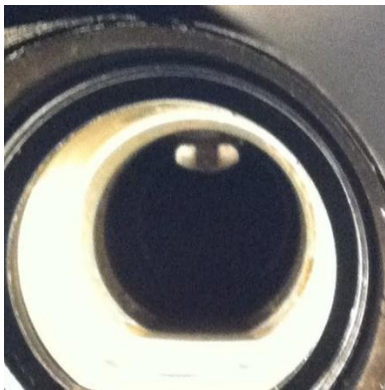


Figure 14. Lamella profile of the mechanical flow switch within the discharge duct.



Figure 15. Discharge duct clogging produced by shells.

So, despite the good performances, the mechanical flow switch was substituted by the ultrasonic Doppler flow switch. In a first period (about eight month) there was only one ultrasonic Doppler installed. The ultrasonic flow switch works for several weeks with good results, which means absence of false positive (i.e. when discharge flowrate actually reaches critical values, the Doppler switch always signalled them). After one month, a false negative event occurs, which means that the discharge flowrate of one ejector was zero, but the instrument did not recognize it. So, the instrument was re-installed and re-calibrated on-site. In particular, the new installation focused on a more well distributed and abundant application of silicon compound. Then, the ultrasonic Doppler flow switch worked well up to about seven months. A second ultrasonic Doppler flow switch was then installed (figure 11). The calibration of the two ultrasonic Doppler flow switches was unsatisfying, since it was not possible to reach previous performance in terms of measurement repeatability. In particular, a dramatic decreasing in sensor repeatability was observed, since only 25% of measures follow in the range $\pm 2 \text{ m}^3/\text{h}$ (while the percentage was over 95% in previous tests). The following were checked: right installation, number of diameters of straight tube before and after the sensor (measured), electric power supply, switch functioning, silicon compound characteristics. Number of diameters D of straight tube before (10 D) and after (6 D) the sensors were found to be lower than the one recommended by the manufacturer (5 D and

3D, respectively); there also some little diameter variation in the pipeline (in the order of some millimetres), but the whole effects should be negligible in terms of repeatability, thus affecting only measurements precision. The others items were found to be correct. So, the sensors were re-calibrated and tested separately, and then together. It was found that the two sensors, by working separately, worked well (i.e. acceptable repeatability, 95% in the range $\pm 2 \text{ m}^3/\text{h}$). So, the hypothesis is that the two sensors influenced and disturbed each other.

The manufacturer confirmed (even if not mentioned in the instrument manual) that acoustic interference can be observed, but usually when two instruments work on the same pipeline, since the echo of the signals produced by one ultrasonic Doppler sensor can be detected also by the other one. The mutual interference of ultrasonic Doppler sensors on different pipelines needs further analysis, since the both literature and normative reference (ISO 15679:2010) do not face this kind of problem. Test will be carried on at laboratory scale to investigate the phenomenon.

4. Conclusions

Different solutions were tested both in laboratory and in real environment for the monitoring of turbidity and flowrate of a sand-water mixture inside a pipeline. The technological solutions were applied in an innovative plant for seabed maintenance. It was found that:

- i. thru-beam infra-red photo electric sensors can be effectively applied for turbidity monitoring;
- ii. mechanical flow switches were tested and demonstrated to work with good repeatability, but they dramatically increased the risk of pipe clogging;
- iii. ultrasonic Doppler flow switch were tested and demonstrated to work with sufficient repeatability (in relation to the application), but some malfunctioning (i.e. acoustic interference) were observed when two instruments are installed on nearby pipes.

A new seabed maintenance plant is under realization in Cervia (Italy), the project being financed by the European LIFE program. So, further investigations are needed and will be carried on to verify if mutual interference is the main source of the problems revealed by ultrasonic Doppler flow switch when installed on nearby pipes.

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