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A control system for preventing cavitation of centrifugal pumps

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Abstract

Cavitation is a well-known phenomenon that may occur, among other turbo-machines, in centrifugal pumps and can result in severe damage of both the pump and the whole hydraulic system. There are situations in which, in principle, the cavitation could be avoided by detecting the condition of incipient cavitation, and changing slightly the working point of the whole system in order to move away from that condition. In the present paper two simple closed-loop control strategies are implemented, acting on the pump's rotational speed and fed by the measurements of a set of inertial sensors. In particular, the research is focused on a centrifugal pump normally employed in hydraulic systems. The pump operates in a dedicated test rig, where cavitation can be induced by acting on a reservoir's pressure. Three accelerometers are installed in the pump body along three orthogonal axes. An extensive set of experiments has been carried out at different flow rates and a number of signals' features both in the time domain and in the frequency domain have been considered as indicators of incipient cavitation. The amount of energy of the signal captured by the accelerometer in the component orthogonal to the flow direction, in the band from 10 to 12.8 kHz, demonstrated to be effective in detecting the incipient cavitation, by selecting a proper (condition-dependent) threshold. Therefore, two simple controllers have been designed: the first regulates the speed of the pump, to recover from cavitation, bringing the indicator back to the nominal value, while the second allows to reduce the pump's rotational speed when the cavitation detector indicates the incipient cavitation and restoring the nominal speed when possible. The latter approach is rather general, because the threshold-based detector can be substituted by any detector providing binary output. Experimental results are reported that demonstrate the effectiveness of the approach.

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1. Introduction

Cavitation is an unwanted phenomenon that affects the operating functions of centrifugal machines with a liquid working fluid. The cavitation phenomenon takes place due to local evaporation of the fluid caused by a lowering of the pressure. If the pressure falls below the vapor pressure of the fluid, steam bubbles are created. When the bubbles reach regions of higher pressure, they implode in contact with the surfaces of the machine, generating pressure waves that cause erosion [1]. If the phenomenon of cavitation persists for a long time, it may cause severe mechanical consequences. Furthermore, the onset of cavitation has a negative influence on the performance of the machine. In pumps it causes a decrease in the flow rate and the total head generated, while in turbines a decrease in power and efficiency. Therefore it is necessary to detect and avoid the development of cavitation in centrifugal machines. In abnormal operating conditions of centrifugal pumps, especially in cavitation conditions, vibrations and noise are present; many studies use acoustic noise and vibrations to detect cavitation formation. Čudina [2] presents a method to identify, through acoustic noise, the formation of cavitation and its complete development. Zhang [3] uses the pump vibrations, analyzing the energy of the accelerometers' signals, in the frequency range between 10 and 25 kHz, to identify the critical cavitation point. Baldassarre [4] presents a method to detect the incipient cavitation through image analysis: the aim is to identify in real time the presence of cavitation (analyzing images of the impeller blade) and to alert with an acoustic signal, in case of incipient cavitation. Other methods use statistics of the accelerometers' signals to identify the operating status of the centrifugal pump. Nasiri [5] identifies a set of indicators that allow, when fed to a neural network, the detection of the operating states of the pump. The author divides the pump working condition into three classes: normal condition, developed cavitation and fully developed cavitation. Mohammad [6], instead, develops a system for detecting the phenomenon, based on five different cavitation conditions, through a multi-class Support Vector Machine (SVM) classifier [7]. The indicators used for the classification of cavitation were obtained from the statistical analysis of vibrations in the time domain and in the frequency domain. Muralidharan [8] has developed a fault detection method for centrifugal pumps using SVM. To derive the features, used in SVM, the Continuous Wavelet Transform (CWT) of the vibration signals was carried out. In that study, several good and defective conditions have been identified on the operation of the pump. In the present work, two control schemes are presented for regulating the pump with the aim to keep its working condition away from the fully developed cavitation phenomenon. The first controller acts based on a real valued index computed from the sensors' measures. A second strategy is based on a discrete (binary) index, corresponding to the output of a generic "cavitation detector". The paper is organized as follows: in Section 2, the test rig and the instrumentation necessary for carrying out the tests on the pump are presented, Section 3 is dedicated to the methods for detecting cavitation and for regulating the pump accordingly. In Section 4 the results of two kind of experiments are reported and finally, in Section 5, conclusions are drawn and some possible developments are mentioned.

2. Materials

The experiments were carried out in a specific test rig (see Fig. 1), opportunely designed to measure and collect the most significant parameters indicating cavitation [9]. The test rig has been designed according to the International Standard 9906:2012 [10], and it allows to draw the characteristic curves of the pumps and the Net Positive Suction Head (NPSH).

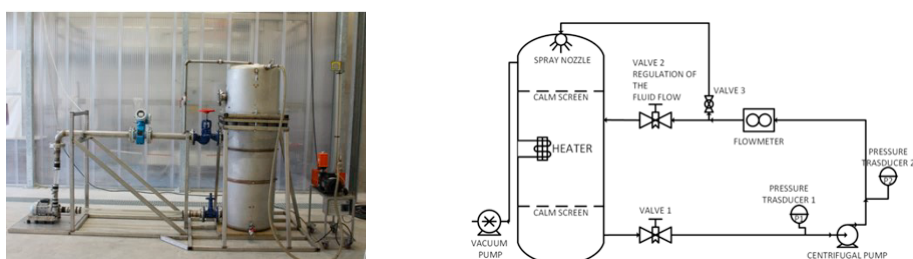


Fig. 1. Test Rig

The pump in the test rig is installed in a closed circuit where is possible to change the barometric load of the free surface level of the tank and the temperature of the fluid. The three-phase centrifugal pump in use has the electrical and hydraulic characteristics shown in Table 1.

Table 1. Centrifugal pump characteristics

Electrical quantities	
Power supply	400 V
Power rate	2.2 kW
Current	5.4 A
Speed	2800 rpm
Frequency	50 Hz
Hydraulic quantities	
Flow rate	0 m ³ /s to 0.0158 m ³ /s
Total head	0 m to 16 m

The tank is designed to avoid the gas inclusion in the aspiration of the pump. Inside the tank are present: two calm screens, two electric heaters (one of 17 kW and the other of 9 kW), a spray nozzle device and a vacuum inlet for controlling the pressure in the free surface level inside the tank. There are two manually regulated valves, one in the bottom side of the tank and the other in the upper part. Various sensors have been installed to detect hydraulic, mechanical and electrical quantities. The hydraulic quantities include: the upstream and downstream pressure of the pump, the tank pressure, the flow rate and the fluid temperature. The pressure measurement sections are positioned at a distance of 2 diameters from the suction and from the outlet section of the pump. The measuring range is between -1 and 1 bar for the pressure transducers in the suction side, and between -1 and 3 bar in the delivery side. These instruments are provided by Trafag, need a power supply of 24 Vdc and provide a signal output 4-20 mA. The precision output on full scale is 0.15%. The flow meter is positioned after the outlet section of the pump at a distance of 10 diameters from the pipe curve. The outlet section of the flow meter is positioned 5 diameters from the branch connecting the spray nozzle used for deaeration purposes. Such distances are needed for having an accurate measure of the fluid flow. The flow meter is provided by Endress Hauser, it requires a power supply of 230 Vac, delivers an output signal between 4-20 mA and has a fluid flow measurement range between 0 m³/s and 0.0158 m³/s. Its error is 0.5% on the read value. For reaching a uniform velocity and pressure distribution at the suction of the pump, 12 diameters are guaranteed in length from the pump suction. The tank pressure is measured through a pressure transducer. The transducer has the following characteristics: measurement range from 0 to -1 bar, voltage output between 1 and 5 Vdc, error at full scale of 2%. To detect the temperature of the fluid, necessary to obtain the vapor pressure, a thermal-resistance was installed in the tank. The Pt100 used has an accuracy of 0.01% and a measuring range between -50 and 600 °C.

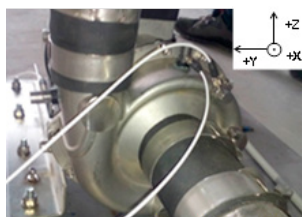


Fig. 2. Accelerometer position

The mechanical quantities measured include: pump vibrations along orthogonal directions and pump's rotational speed. The vibrations were acquired by three piezoelectric ICB accelerometers, installed on the pump volute (see Fig. 2) in the following position: X axis in the direction of the rotation axis of the pump, Y and Z axes in the radial directions of the volute. In a previous work by some of the authors [9], three accelerometers were used with a range from -50 to 50 g and sensitivity of 100 mV/g, not enough to detect the vibrations during fully developed cavitation. Therefore, they have been replaced with three accelerometers having the following characteristics: sensitivity of 10 mV/g and a range of -500 to 500 g. In the system has been also installed an inverter used to regulate the pump's rotational speed. The use of this device increases the cost of the system by an amount that corresponds roughly to the cost of the pump alone. The inverter model is the Combivert F5 Basic by KEB, with the following characteristics: maximum power of 4 kW, maximum current of 15 A and frequency range between 0 and 400 Hz. Through the inverter feedback is possible to acquire the number of revolutions per time unit. The analogue output of the inverter in voltage, 0-10 V, is converted first in frequency and then in the rpm of the centrifugal pump. Finally, to measure the electrical quantities

in all the different conditions a power meter was used, to get the current value, voltage value and the power absorbed by the pump (Yokogawa digital power meter with accuracy of 0.1% of reading).

3. Methods

3.1. Cavitation detection

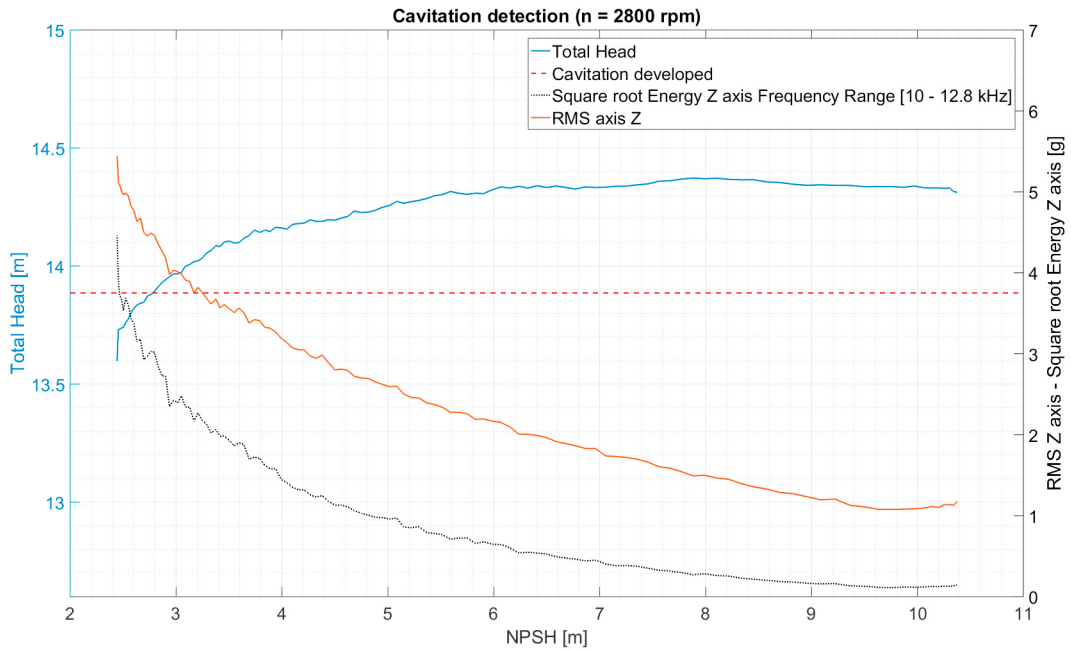


Fig. 3. Cavitation detection

In order to characterize the pump, many tests were carried out under both nominal conditions, varying the pump flow rate (from 0 m³/s to 0.0158 m³/s), and cavitation condition, varying the tank pressure load. Through the analysis of the tests' results the most significant curves have been drawn: characteristic curve, which shows the relationship between flow rate (Q) and total head (H), and NPSH curve dependency of total head (H), used to identify cavitation. The test rig allows to test various pump configurations in different operating conditions, obtained by varying the fluid temperature and its properties, adding detergent and additives [11]. According to standards [10], cavitation occurs in the pump when the total head decreases more than 3% compared to analogous conditions in the absence of cavitation. In the test rig, to induce cavitation, the tank pressure is reduced by means of a vacuum pump. Vibration measurement allows to detect cavitation inception. The statistical indicators considered for the analysis of the vibrations, obtained from the three accelerometers (along the X, Y and Z axis) at the sample rate of 25.6 kHz, are shown in Table 2, where α represents the acceleration, μ_α represents the mean and σ_α the standard deviation of the sequence α_i , $i = 0, \dots, N - 1$. Another parameter analyzed, in different frequency spectra, is the energy of the signal, defined as the integral of the Power Spectral Density (PSD) [12]:

$$\text{Energy} = \int_{f_1}^{f_2} \text{PSD}(f) df. \quad (1)$$

The frequencies considered for computing the signal energy are $f_1 = 10$ kHz and $f_2 = 12.8$ kHz, because they demonstrated to be effective in detecting cavitation. These frequencies have been selected based on the investigation presented in [13], where the author analyses different frequency bands in order to find the most sensible to cavitation

Table 2. Statistical indicators (μ_α and σ_α represent the mean and the standard deviation of the sequence α_i , $i = 0, \dots, N - 1$)

Indicator	Formula
Root mean square (RMS)	$\sqrt{\frac{1}{N} \sum_{i=0}^{N-1} \alpha_i^2}$
Max value (MAX)	$\max_i \alpha_i $
Crest factor (CF)	$\frac{\text{MAX}}{\text{RMS}}$
Kurtosis (K)	$\frac{\sum_{i=0}^{N-1} (\alpha_i - \mu_\alpha)^4}{N\sigma_\alpha^4}$

inception. The selected frequencies are in good agreement with other theoretical analyses [3],[14],[15],[16],[17],[18] where is reported that the noise excited during the collapse of cavitation bubbles, has a particular effect on the vibration energy in high frequency bands. Furthermore, high frequency components of the signals are firstly affected by cavitation inception [3],[13],[14],[15]. The authors of [14] divide the vibration signal into 4 frequency bands. The range in which the effect of cavitation is more evident is between 10 kHz and 51.2 kHz. In [15] the author identifies the frequency intervals from 10 kHz to 15 kHz, and between 15 kHz and 20 kHz, as frequency bands influenced by cavitation inception. In [13], for the same test rig used in the present work, the frequency range 10 - 12.8 kHz has been shown to be effective for detecting cavitation inception. We report an example, chosen from several experiments performed in different operating conditions. Figure 3 shows the total head and the energy of the Z-axis accelerometer in the frequency range 10 kHz-12.8 kHz as a function of the NPSH (at the nominal flow rate of 0.0083 m³/s). From right (beginning of the test) to left (end of the test), is possible to observe a decrease of the total head, due to the action of the vacuum pump. According to [10], cavitation occurs when the total head falls below the threshold depicted in dashed line. Notice that the decrease of the total head is accompanied by an increase of the energy. Figure 3 shows also the RMS of the Z axis accelerometer signal, computed using a sliding window of 1 s. The energy along the Z axis is employed in all the experiments reported below.

3.2. Control schemes

In the following, experiments performed with two different controllers (shown in Fig. 4) are reported. Both the controllers act on the pump speed, precisely they reduce the speed when cavitation occurs. Indeed, by decreasing the pump's rotational speed, the kinetic component of the total pressure decreases and the static component increases above the vapor pressure. The first controller (Fig. 4, left) is a classical servo that simply tracks a constant reference \bar{w} . It is based on proportional and integrative (PI) actions and allows to keep the indicator value w (the energy of the signal of axis Z) at a desired level, by acting on the pump rotational speed. The desired level can be chosen as the indicator value measured in a cavitation-free working condition (step 3 of the procedure reported below). It is assumed therefore that such indicator value, corresponds to a cavitation-free condition, even for a (small) variation of the pump speed. A formal stability analysis of the control system is out of the scope of the present work. However, under the assumption that a monotonic relationship holds between the rotational speed, the energy (1) and the cavitation indices, and by choosing moderate values of the proportional and integral actions¹, a stable control system is obtained. Such a control scheme has been employed in a test carried out according to the following procedure:

1. Activation of the pump.
2. Waiting for the rest time (T_s).
3. Computation of the initial conditions H_{init} and $EnergyZ_{init}$ at time T_1 .

¹ with the proper sign

4. Activation of the vacuum pump.
5. Switching off the vacuum pump when cavitation conditions are reached.
6. Waiting for the rest time (T_s).
7. Activation of the control with $EnergyZ_{init}$ as set point.
8. Switch off the control and the pump.

The idea is to find the proper reference value for the indicator (the energy value for the Z axis) during a first phase, where the control is off and the pump is assumed to operate in cavitation-free condition. More precisely, the set point, used in the PI control, is calculated at step 3 of the previous procedure. At all times, the vibrations are acquired at the sampling rate of 25.6 kHz, from which the statistics are obtained at 1 Hz. The proportional gain (K_P) and the integral gain (K_I) of the PI controller have been selected manually by several trials. Satisfactory results have been obtained by choosing $K_P = 1.2$ and $K_I = 0.9$. The results of one of the many different experiments performed, are reported in the next section. The second control strategy (control 2, Fig. 4, right) is designed for exploiting the output of a generic binary classifier (the “detector”) whose output is 1 when cavitation is occurring and -1 otherwise. The detector may operate on some signals’ features or even on the raw signal/signals. However, the control scheme does not depend on the specific detector. For simplicity, in the experiments carried out and reported in the next section, a threshold-based detector was used, acting on the energy value for the Z axis already introduced. The controller is basically an integrator which outputs a variation δ_n of the rotational speed, followed by a saturation at zero (to avoid increase of speed with respect to the nominal speed \bar{n}). The integrator is equipped with a simple anti-windup scheme (not shown in the figure) that basically stops integration when the output of the integrator is negative. Again, under mild assumptions, the stability is guaranteed. When the incipient cavitation is detected, the speed of the pump is reduced, while upon exiting, it is increased toward \bar{n} .

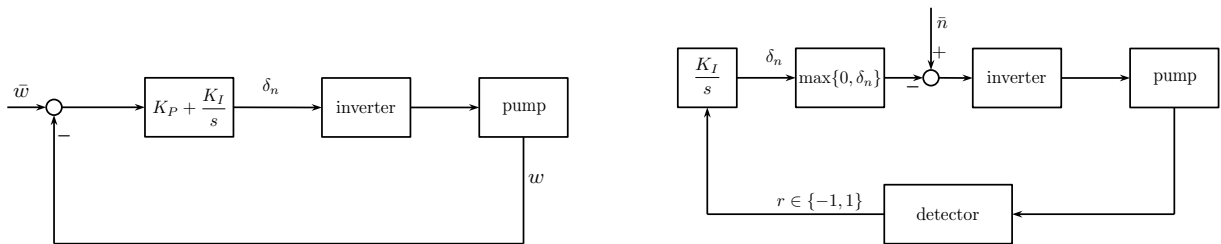


Fig. 4. Control 1 (left) and Control 2 (right)

4. Results

In the diagrams shown in Fig. 5, the results are reported, using the first control strategy. In particular, the considered indicator (energy on the Z axis) and the pump speed (RPM) are shown as a function of time. During the test, performed at the flow rate of $0.0083 \text{ m}^3/\text{s}$, a total head reduction of 3% has been obtained. The pump speed regulation is activated when the system reaches the selected head reduction (according to the procedure described above). When activated, the PI controller acts reducing the pump speed, bringing the indicator back to its reference value. The bottom panel of Fig. 5 shows the NPSH evaluated using the measures acquired during the test. As expected, the NPSH decreases when the vacuum pump is active and reaches a steady value when it is turned off (at 112s). Then, as soon as the control is activated (at 123s), an increase can be observed, corresponding to the new, cavitation-free operating condition. In the diagrams of Fig. 6a and Fig. 6b, the results of two tests carried out using the second control strategy (control 2) are reported. As can be seen by inspecting Fig. 4 (right), the controller can only reduce the speed of the pump, with respect to the nominal speed \bar{n} , in response to a positive output from the detector. The scheme is suitable for any binary classifier employed as detector but, for the sake of simplicity, a threshold-based detector was used, acting on the energy Z signal. Therefore, in the top panel of Fig. 6a and Fig. 6b the energy Z value is shown. The dashed line represents the threshold value. When the energy Z exceeds the threshold, the output of the detector is 1, otherwise is -1. To identify the threshold value, any other detector may be used, for instance based on some statistics of the

signal(s) such as those of Table 2, or on raw data (for instance a Neural Network or an SVM). In the tests shown in both Fig. 6a and Fig. 6b, the control system is kept active during the whole experiment. Some maneuvers such as turning on/off the vacuum pump and opening/closing a reservoir's valve are carried out for varying the reservoir's pressure. In Fig. 6a, the control starts reducing the speed as soon as the detector's output becomes positive (around 60 s). The speed decreases until the vacuum pump is turned off; then, oscillates around the value that corresponds, for the actual reservoir's pressure, to the detector's threshold. As shown in Fig. 6b, the controller is able to bring the speed back to its nominal value whenever possible, precisely when, due to the increased reservoir's pressure, the operating conditions change and the output of the detector becomes negative (corresponding to the Energy Z below the threshold, in the example). Precisely, the test consists of the following parts: the vacuum pump is turned on at time 14 s, and turned off at 108 s (14–108 s). Between (154–168 s) with the vacuum pump turned off the reservoir pressure increases toward ambient pressure due to the manual opening of a valve. Then the valve is closed and during the intervals (185–260 s) and (297–341 s) the vacuum pump is turned on again. Finally, starting from 370 s, the pressure increases toward ambient pressure, due to the manual opening of the valve.

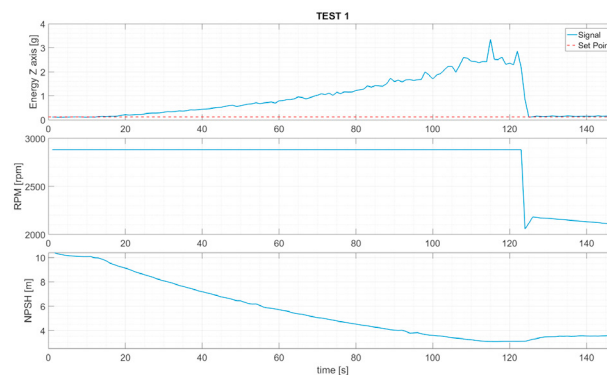
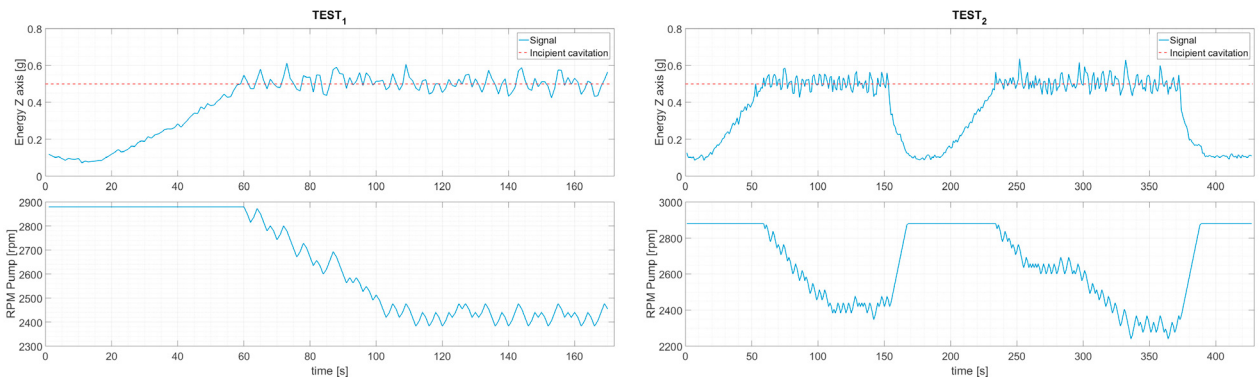


Fig. 5. Test 1 (control 1). A test carried out using control 1. The plant is brought to a decrease of total head of 3%.



(a) Energy of axis Z and RPM for a test carried out using control 2. (b) A test carried out with control 2 where the detector's response, may be observed.

Fig. 6.

5. Conclusion and further work

In the present paper simple closed-loop control strategies have been introduced, able to change slightly the working point of a centrifugal pump, with the aim to avoid cavitation. In particular, such control strategies have been implemented in a dedicated test rig, inducing cavitation by acting on the reservoir's pressure. The energy of the vibrations of the pump body can be computed, using the signals acquired by using three mono-axial accelerometers

(properly installed on the centrifugal pump body). In facts, the amount of energy of acceleration signal (captured by an accelerometer in the component orthogonal to the flow direction) in the band from 10 to 12.8 kHz, may be used effectively to detect the incipient cavitation, by selecting a proper (condition-dependent) threshold. The proposed control schemes rely on two different cavitation detectors, both based on the evaluation of the energy of the acquired vibration signals; in both the schemes the controller acts on the centrifugal pump rotational speed, reducing it when cavitation occurs. In particular, the first proposed control scheme regulates the pump rotational speed, based on the actual value of the energy-based cavitation indicator, bringing the indicator back to the nominal (cavitation-free) value, while the second control strategy allows to reduce the pump's speed when a binary detector indicates the incipient cavitation, restoring the nominal speed when possible. The latter approach is rather general, because it relies on any detector (based on the vibration signal energy) providing binary output (i.e. “-1” in the case of no cavitation, “+1” when cavitation occurs). The obtained results are promising and allow to further experiments, varying the pump size, and investigations, with the aim to develop an auto-tuning procedure for the proposed control schemes.

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