

## Electric Power Signature Analysis for High Pressure Water Jet Pumps Fault Classification

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**Abstract** - Water jet and Abrasive Water Jet (WJ/AWJ) are manufacturing technologies suitable for particular operations (cutting, milling, turning, surface treatment, etc.) on different types of materials. The use of water (or water mixed to abrasive in AWJ technology) allows working both soft and hard materials without damaging the interested area of the workpiece. In previous studies the authors have just shown how it is possible to detect wrong operating conditions or to foresee them for an AWJ system analyzing the instantaneous electric power signal measured at the supply section of the system. Starting from this assumption, it is possible to define a monitoring procedure operating on the supply section of the plant, that performs a non intrusive continuous diagnostic activity during all the plant components' life. In particular in this work, a procedure based on the analysis and classification of the instantaneous power signal features is presented. The followed approach is based on the electric power signal signature analysis.

### I. Introduction

How it is well known, in modern industrial environment the “maintenance activity” represents an element of management strategy. In this scenario the possibility to improve maintenance efficiency procedure by means of diagnostic activity is demonstrated by the interest about this subject in the last decade. Diagnosis techniques and specific monitoring activities can be usefully used to reach the objective of early fault detection or early diagnosis of a developing fault. The aim of this paper is to verify if it is possible to apply this approach to a particular industrial manufacturing technology, called water jet, in order to improve the efficiency of the manufacturing process.

water jet and Abrasive Water Jet Technology (WJ/AWJ) are manufacturing technologies commonly used for cutting or treating special materials. The peculiarity of the WJ/AWJ technique is that the cut is not performed by thermal actions (like laser or plasma cutting processes) but by a water beam. In the WJ/AWJ cutting process, the mix of process parameters selection (water pressure, abrasive mass flow rate, abrasive granulometry, cutting head feed rate, standoff distance), fluid-dynamic parameters and cutting head characteristics (orifice and focuser diameters and mixing chamber geometry) determine the cutting quality: every fluctuation of the aforementioned parameters can determine a loss of quality of the workpiece. For this reason, the components involved in the cutting process are generally monitored using different types of sensors and ad hoc designed measuring systems.

In previous works [1], [2], [3], [4] and [5] the authors have already shown how it is possible to detect wrong operating conditions or to foresee them for an WJ/AWJ system. In fact, analyzing only the instantaneous electric power measured at the supply section of the electric motor, it is possible to get information about the machine status. The electric power signal can be considered as a “magnifying glass” of the phenomena taking place in the high pressure pumping system and of the status of the fluid-dynamic part of the plant [4]. Therefore, its analysis allows to detect wrong operating conditions or to foresee them for different sections of the plant (e.g. the oil pump, the valves operating on the water circuit and, last but not least, the orifices [1]).

Starting from the previous considerations, this paper proposes a new diagnostic procedure based on the analysis of the signatures extracted by the electric power signal and their classification by means of a statistical classifier.

## II. The water jet system

In Fig. 1 the main components of a typical water jet system have been depicted. The cut is produced by means of a jet formed by the water that reaches the cutting head and flows through the water orifice: the capability of water to perform the cut is given by the transformation of pressure energy into kinetic energy.

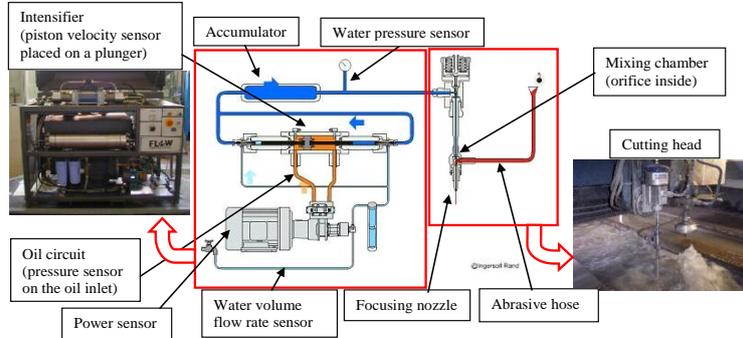


Fig. 1: Main components of the water jet cutting system.

The energy flux into a water jet system is originated by a 380 V-50 Hz three-phase induction motor that drives a radial pistons oil pump; the pump produces hydraulic energy pressurizing the oil (in this step the oil can reach a pressure value of 19 MPa in the oil circuit). A double-effect intensifier providing hydraulic energy to water allows it to reach pressure values up to 400 MPa. In this condition, the compressibility of water has to be considered. In order to reduce water pressure fluctuations [2], [6], [7] and [8], an accumulator is installed in the water circuit (see Fig. 1). If abrasive water jet is considered, solid particles join the water jet inside the mixing chamber, being entrained by the air flow generated by the jet itself. The kinetic energy of abrasive particles is increased thanks to the exchange of momentum with water inside the mixing chamber and the focusing nozzle.

It is important to highlight that the cutting head is “the core” of the cutting system. As yet shown by the authors in [1] and as will be shown in a more detailed way by means of the signature techniques, orifices characterized by the same nominal diameter but with a different internal profile can present different performances.

## III. The theoretical background

In order to extract a minimal but exhaustive set of parameter able to monitor the status of the water jet system, it is important to analyze the physical relationships among electrical, mechanical and fluid-dynamic signals. In the following, it is discussed the energy flow from the main side of the motor to the radial pistons oil pump and then to the double-effect intensifier (see Fig. 1 and Fig. 2).

Starting from the power balance of the different system components, it is possible to highlight the relationship among the instantaneous electric power signal and some fluid-dynamic signals [5].

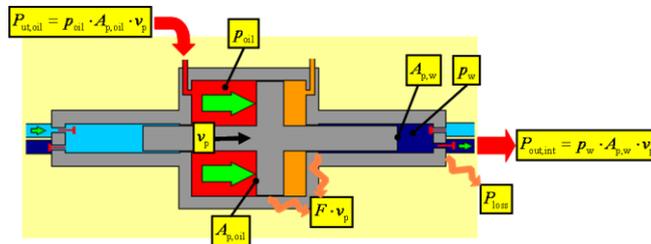


Fig. 2: Energy exchange into the intensifier.

The electric motor, driving the oil pump, performs the transformation of electric energy into pressure energy required by the double-effect intensifier. The power transmitted to the oil acting on the piston is (Fig. 2):

$$P_{ut, oil} = p_{oil} \cdot A_{p, oil} \cdot v_p \quad (1)$$

If the efficiency  $\eta_{lp}$  of the transformation is considered (this term can be seen as the efficiency of the low pressure oil circuit) the equation (1) can be written as:

$$P_{ut,oil} = \eta_{lp} \cdot P_{el} \quad (2)$$

where  $\eta_{lp}$  takes into account the losses along the low pressure circuit. Replacing (2) into (1) leads to:

$$P_{el} = \frac{P_{oil} \cdot A_{p,oil} \cdot v_p}{\eta_{lp}} \quad (3)$$

Equation (3) describes the relationship between the electric power  $P_{el}$  and three mechanical quantities (oil pressure  $p_{oil}$ , area on which the oil acts  $A_{p,oil}$  and piston velocity  $v_p$ ): a variation of these mechanical quantities determines a variation of the electric power  $P_{el}$ . It is noteworthy that it is possible to experimentally evaluate the efficiency of the low pressure oil circuit starting from the acquisition of piston velocity, oil pressure and electric power signals ( $A_{p,oil}$  is constant for each pump). The power balance at the double-acting intensifier (Fig. 2) can be also written defining with  $P_{in,int}$  and  $P_{out,int}$  respectively the total power entering the intensifier (equal to  $P_{ut,oil}$ ) and the total power provided to water and flowing out the intensifier [5]; the efficiency of the intensifier becomes:

$$\eta_{int} = \frac{P_{out,int}}{P_{in,int}} = \frac{p_w \cdot A_{p,w} \cdot v_p}{p_{oil} \cdot A_{p,oil} \cdot v_p} \quad (4)$$

therefore:

$$P_{el} = \frac{P_{out,int}}{\eta_{int} \cdot \eta_{lp}} = \frac{p_w \cdot A_{p,w} \cdot v_p}{\eta_{int} \cdot \eta_{lp}} \quad (5)$$

where:

$P_{el}$  = instantaneous electrical power;

$p_w$  = water pressure;

$A_{p,w}$  = piston area interested by the water;

$A_{p,oil}$  = piston area interested by the oil;

$v_p$  = piston velocity;

$\eta_{int}$  = efficiency of the intensifier;

$\eta_{lp}$  = efficiency of the oil low pressure circuit.

Equation (5) shows the relationship among electric power, water pressure and piston velocity. It is clear that, for every operating condition represented by different water pressure levels, a typical instantaneous power profile can be observed on the main side of the system. This assumption can be verified experimentally comparing  $P_{el}$  waveforms for different water pressure levels. Fig. 3 shows  $P_{el}$  and  $p_w$  for 200 MPa and 300 MPa using a 0.30 mm orifice (the waveforms have been treated with a moving average signal).

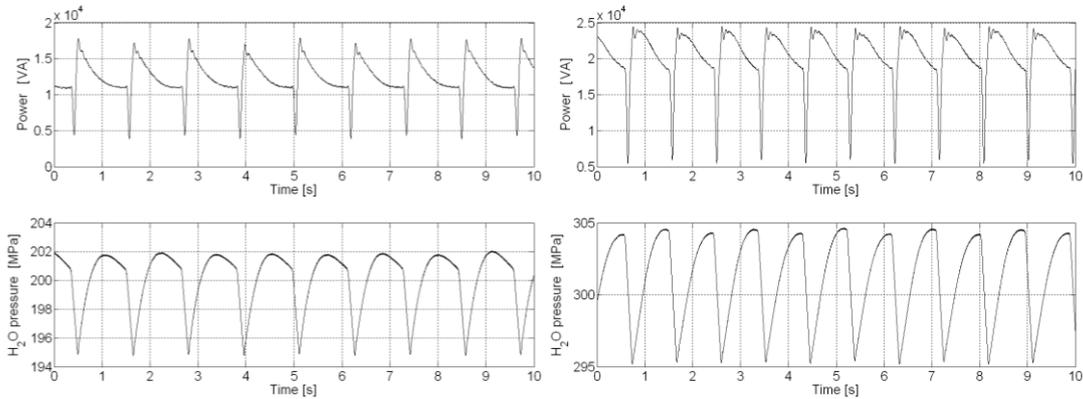


Fig. 3: Electric power  $P_{el}$  and water pressure  $p_w$  in different conditions:

$p_w = 200$  MPa (left) and  $p_w = 300$  MPa (right) with nominal orifice diameter = 0.30 mm.

A variation of the efficiency of the fluid-dynamic system is then reflected by the instantaneous power signal. Fig. 4 shows the same experimental conditions (same water pressures) presented in Fig. 3 but with a different orifice diameter (0.20 mm). It can be noticed that different power profiles are obtained.

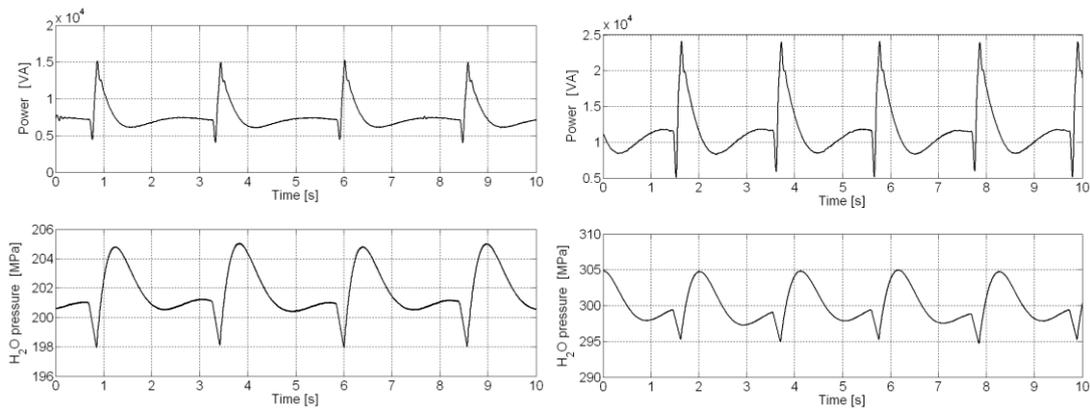


Fig. 4: Electric power  $P_{el}$  and water pressure  $p_w$  in different conditions:  $p_w = 200$  MPa (left) and  $p_w = 300$  MPa (right) with nominal orifice diameter = 0.20 mm.

It is a fact that instantaneous power signal profile is a sort of “mirror” of the water yet systems status [1]. The analysis of the variation of the instantaneous power profiles from reference conditions can be considered as a good support to monitor the efficiency of the system. It is important to highlight that the system status information extraction from the instantaneous power signal only requires the use of a power sensor placed at the supply section of the motor.

Moreover, the employment of a simple motion versus sensor allows to link the fault event or efficiency degradation to a specific machine working phase (left stroke or right stroke) Fig. 5.

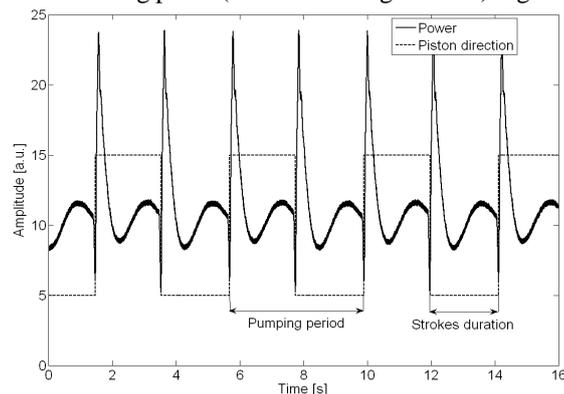


Fig. 5: Electric power signal and piston direction.

It can be noticed that the waveform of the instantaneous electric power is strictly related to the working conditions and settings of the system (Fig.3 and Fig. 4).

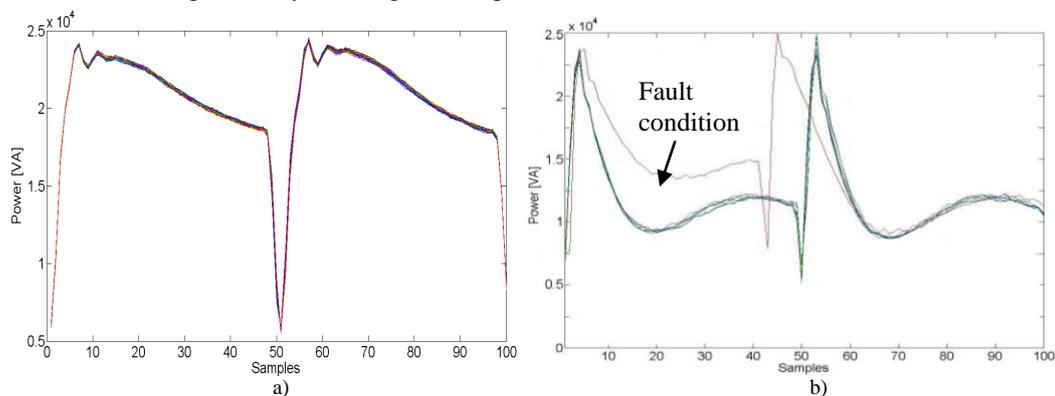


Fig. 6: Signature spread in healthy conditions (a) ( $p_w = 300$  MPa with nominal orifice diameter = 0.30 mm) and (b) comparison between signatures in healthy condition and a signature in failure condition ( $p_w = 300$  MPa with nominal orifice diameter = 0.20 mm).

The electric power waveform signals reported in Fig. 6 a) are representative of the repeatability of the water jet system behaviour (in this case a 0.30 mm nominal diameter orifice has been employed at 300 MPa). The signals have been acquired over the pumping period. The sensitivity of the instantaneous electric power is assured even in wrong operating conditions. In fact wrong operating conditions determines that the electric power signal moves away from the typical one. Fig. 6 b) reports a comparison between the electric power signal in a failure condition (a leakage on the valve intensifier is considered) and in healthy conditions; Signature spread in healthy conditions and signature in failure condition are related to 0.20 mm nominal orifice diameter with a water pressure of 300 MPa.

#### IV. Signature analysis

In a previous work, the authors have just singled out and extracted a set of synthetic indexes from the power signal able to discriminate between normal and wrong working conditions [3] [4]. In order to complete the set of proposed indexes, a quantitative analysis of the shape of the power signal is proposed employing a classification procedure based on signature analysis techniques.

As shown in the previous section, the electric power signal is strictly related to the piston motion versus. Therefore in order to synchronize the electric power signature acquisitions, the signal provided by a piston motion versus sensor has been used. The proposed signature has been extracted from the electric power signal over a pumping period (Fig. 5).

The classification procedure is based on the use of the statistical classifier proposed in [9]. The classifier analyzes a data vector containing the Euclidian distance between the acquired instantaneous power signal and the reference signal associated to each working condition. In this paper, it has been taken into account orifices provided by two different companies (type A and type B). In particular, the used orifices have a diameter of 0.20 mm and 0.30 mm and they have been employed with a water pressure of 200 MPa and 300 MPa. Considering all the possible combinations, eight classes have been defined. The electric power signature of the water jet machine working in a healthy status at the aforementioned conditions has been defined as shown in Fig. 7.

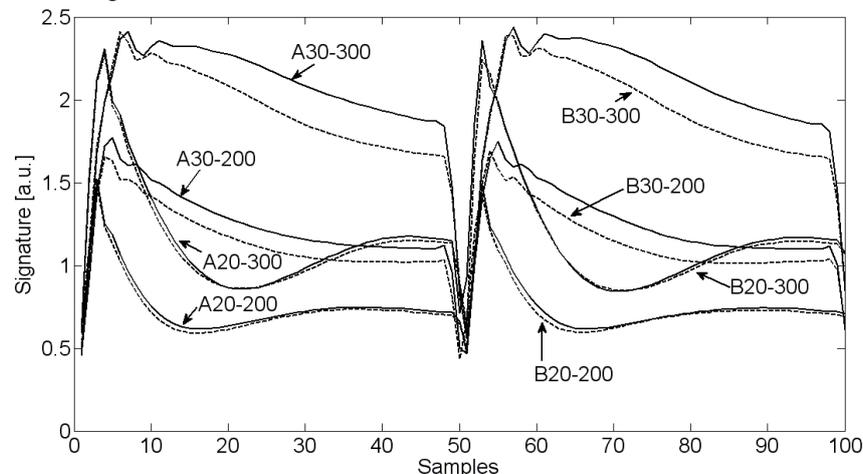


Fig. 7: Electric power signatures of 0.20 mm and 0.30 orifices at 200 MPa and 300 MPa.  
Orifice type A: continuous line. Orifice type B: dashed line.

Each one of the eight defined reference signal has been computed as mean of ten signatures. Even if, from a statistic point of view, ten samples are few for the statistical characterization of the signals, they are enough for a preliminary feasibility analysis.

#### V. Experimental results

Some tests have been performed in order to verify the effectiveness of the classification algorithm: the analysis has been performed classifying power signatures acquired when the water jet machine was working properly with different kinds of orifices. These orifices have been also tested for different pressures: 200 MPa and 300 MPa. Finally, the classifier has been tested using damaged orifices and a orifice with a nominal diameter (0.33 mm) not used during the classification procedure. The obtained results are reported in Table 1, where in the first column is reported a code identifying the test condition: type of orifice (A or B), orifice diameter (0.20 mm or 0.30 mm) and, finally, water pressure (200 MPa or 300 MPa).

Table 1: Classifier performances.

Test condition	# signature tested	Recognized	Not recognized	Wrong classification	% Recognized	% not recognized	% wrong classification
A_20_200	89	89	0	0	100.0	0.0	0.0
A_20_300	109	103	6	0	94.5	5.5	0.0
A_30_200	196	185	11	0	94.4	5.6	0.0
A_30_300	242	242	0	0	100.0	0.0	0.0
B_20_200	29	28	1	0	96.6	3.4	0.0
B_20_300	36	36	0	0	100.0	0.0	0.0
B_30_200	120	119	1	0	99.2	0.8	0.0
B_30_300	149	149	0	0	100.0	0.0	0.0
B_30_200 damaged	63	63	0	0	100.0	0.0	0.0
B_30_300 damaged	77	77	0	0	100.0	0.0	0.0
A_33_200	80	80	0	0	100.0	0.0	0.0
Total	1190	1171	19	0	98.4	1.6	0.0

It can be noticed that the developed tool properly recognizes the working condition in the 98 % of cases and no classification mistakes have been detected. It is important to highlight that the tool classifies in a correct way the test signals related to the condition 0.20 mm (fig. 7 shows that the reference signals for orifice type A and B are quite similar at 200 and 300 MPa).

The low number of non recognized signatures are probably due to the very few samples used in the data base definition. In any case, they could be further analyzed to improve the algorithm efficiency.

## VI. Conclusions

A classifier able to identify wrong operating conditions of a water jet pump has been proposed in this paper. The objective of the classifier is to define a database that allows the identification of wrong operating conditions. The sensitivity of the classification procedure has been successfully proved in different and significant working conditions. The presented classification procedure can be usefully employed as a support in maintenance policies based on "Condition-Based Maintenance" strategies.

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