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Vpliv spreminjanja tlaka na rezalno zmožnost vodnega curka

The Effect of Pressure Fluctuations on the Cutting Ability of Pure Water Jet

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Tehnologija obdelave z vodnim in abrazivno vodnim curkom je predmet obsežnih raziskav. To področje raziskav je usmerjeno k boljšemu razumevanju mehanizmov odnašanja materiala in optimizaciji postopkovnih parametrov (hidravličnih in tehnoloških) v primeru različnih uporab. Optimizacija postopkovnih parametrov je posebej težavna zaradi njihove nestabilnosti med samim postopkom. Številne raziskave so usmerjene v fizikalno-mehansko interakcijo med curkom in mehanskimi lastnostmi materiala, iz česar so se razvili modeli z različnimi razlagami. Kljub temu pa sedanji modeli popisujejo večinoma rezalne mehanizme pri rezanju z abrazivnim vodnim curkom (AVC). Razlaga nastanka strij pri rezanju z AVC ne pojasnjuje podobnega pojava pri rezanju z VC. V resnici se pokaže, da se pojavijo nepravilnosti (raze), kadar režemo s čistim vodnim curkom po vsej odrezani površini, med tem ko se pri rezanju z AVC pojavijo raze le v spodnjem delu rezalne cone. Predhodne študije so pokazale, da je površina nastala pri rezu samo z vodo odvisna le od endogenih in eksogenih vibracij in ne od sprememb tlaka v curku ali pa od oblike tlačnega signala. Pri zmanjšanju teh vibracij lahko zaznamo občutno izboljšanje na odrezani površini, še posebej v smislu zmanjšanja strijavosti.

Kljub temu, da spreminjanje tlaka pri rezanju z VC nima vpliva na kakovost površine, bi morala imeti vpliv na globino reza. V tem prispevku je bila raziskana prav slednja teza. Da bi prišli do naslednjih rezultatov, smo morali preučiti usmeritev potiska vodnega curka na ravno površino. Cilj tega preizkusa je bil analizirati zmožnost prodiranja vodnega curka pri izhodnem rezu. Za tem je bila preučena povezava med signalom potiska in obliko profila v spodnjem delu reza.

(Ključne besede: rezanje s curkom, curek vodni, spreminjanje tlaka)

Water jets and abrasive water-jet technology are the focus of concentrated research. This research area is oriented to understand the material-removal mechanisms and to optimise the process parameters (fluid dynamical and technological) of various applications. The optimisation of the process parameters is especially difficult because of their instability during the process. Many authors have inquired into the physical-mechanical aspects of the interaction between the jet and the mechanical properties of the material and they have developed models and different interpretations. However, the existing models, mostly try to describe the cutting mechanism only for abrasive water-jet (AWJ) technology. The interpretation of the mechanism of striation formation in AWJ cutting does not explain the striation formation in the pure WJ process. In fact, whereas in the cutting surface realised by a pure WJ cutting along the whole surface there are irregularities (striations); the surface generated by AWJ cutting is characterized by a streaked morphology in the bottom zone of the cutting surface. Previous studies have demonstrated that the cutting surface realised by WJ is not influenced either by the pressure fluctuations or the pressure signal form, but depends strongly on the exogenous and endogenous vibrations. In fact, a considerable reduction of these vibrations makes it possible to obtain remarkable improvements in the surface quality, especially as regards the striation morphology.

Although the pressure fluctuation does not have substantial effects on the WJ surface quality, it should have an influence on the depth of cut. In this work the effect of the pressure fluctuation on the depth of cut in no-passing WJ cuts has been analysed. In order to do this, the thrust trend of the water jet on a plane surface has been analyzed. The aim of this experiment has been to analyze the penetration ability trend of the jet at the exit of a passing cut; afterwards, the correlation between the thrust signal and the bottom profile generated by a no-passing cut on polycarbonate slabs has been analyzed.

(Keywords: water jet cutting, pressure fluctuation)

0 INTRODUCTION

The WJ/AWJ (water-jet/abrasive-water-jet) removal process is influenced by several technological and fluid dynamics parameters. The anticipatory models proposed in the literature usually set process parameters (stand-off distance, feed rate, pressure, mass flow rate and mesh of the abrasive, etc.) to an established value ([1] and [2]). However, the instability of some in-process parameters might prejudice the validity of such models. In particular, the water pressure is subjected to cyclical fluctuations mainly due to the intensification mechanism.

The control of cyclical pressure fluctuation is very important. In fact, the pressure fluctuation has many effects:

- it causes a periodic stress state in the whole system: every mechanical component of the high-pressure circuit is subjected to a fatigue stress that can be brought about by forced vibrations [3];
- the jet is pulsating, with possible effects on the cutting quality ([3] and [4]);
- it causes a reduction in the life of many WJ-system components [5], for example, the nozzle;
- it is often a constraining factor that limits the applications of the WJ technology [5].

Other causes of the variability of the parameters can be considered, directly or indirectly, connected to the pressure fluctuation. Examples among many are the mass-flow-rate fluctuation and the vibrations on the structure of the system [6] and [7].

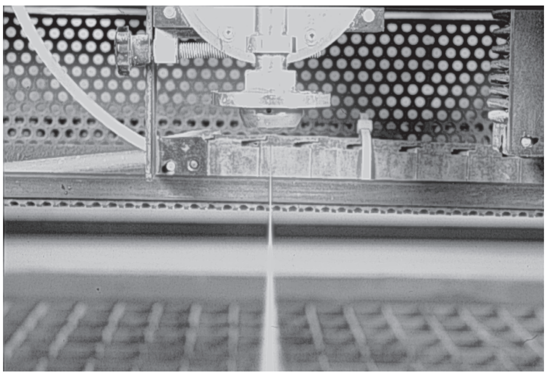
In order to investigate only the effects of pressure fluctuation on the cutting quality, leaving out the effects of the abrasive, only pure water-jet (WJ) has been considered. Therefore, the tests have been carried out on workable materials (polycarbonate, rubber, plasticine), even with high thicknesses, but without the abrasive injection. The effect of the pressure fluctuation on the penetration ability, measured in terms of the depth of cut, has been studied.

1 THE WJ/AWJ PROCESS

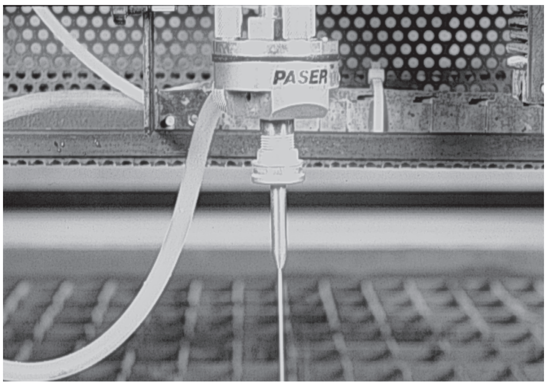
In WJ/AWJ technology, the high energy of the jet makes the cut. In pure WJ cutting, the material removal is due to the high speed of the jet; in AWJ cutting, in contrast, the jet only transfers its momentum to the abrasive particles, whose abrasive and erosive action causes the material removal.

The water pressure is increased up to the operating pressure through a pump system (intensifier). The usual pressure at present is 380-400 MPa, but the world trend is to increase the pressure: there are already proposed and realized systems that reach higher pressures [8]. Then, the high-pressure fluid is directed into the cutting head, where the pressure energy of the jet is converted into kinetic energy. The energetic conversion is obtained by means of an orifice in sapphire or synthetic ruby; at the exit of the orifice the jet reaches a rate of up to 900 m/s, depending on the selected pressure. The specific energy of the jet depends on the diameter of the orifice, which changes between 0.05 and 0.40 mm (Figure 1-a).

In AWJ systems the abrasive is added to the fluid in a mixing chamber (Figure 1-b), placed under the orifice.



(a)



(b)

Fig. 1. *WJ (a) and AWJ (b) cutting*

2 GENERATION OF HIGH PRESSURE

Intensifier systems operate on the principle of the conservation of hydraulic energy. A low-pressure, high-flow hydraulic region acts on a piston with a large area. A large force is generated, which in turn acts on a small plunger area, creating a much higher pressure. An exchange of energy is made where the low-pressure, high-flow hydraulic fluid is converted to high-pressure, low-flow water. The ratio of the low-pressure piston area to the high-pressure plunger area is called the intensification ratio.

The first intensifier for water-jet application was introduced in 1971, and the basic intensifier design did not change; that is, until the introduction of the phased intensification concept in 1991. Both types create an ultra-high pressure in essentially the same way, but they minimize the output pressure fluctuation differently.

The basic design of a standard intensifier consists of a double-acting, hydraulically actuated piston-plunger ram in which the two opposite-facing cylinders are mechanically coupled and the fluid compression and suction strokes alternate between the two cylinders (Figure 2-a).

As it strokes, creating pressure and output flow in a direction, the opposite side is in its suction stroke. When the piston reaches the end of its stroke, the directional valve is shifted. The output pressure decays due to the response time of the valve and the plunger stroke required to compress the water to the output pressure. When the water pressure in the high-pressure cylinder equals the pump's output pressure, the high-pressure check valve opens [9]. Because of the compressibility of water, the first 15% of the stroke of the piston is used to pressurise and compress the water in the cylinder without delivering water to the system [10]. This causes unacceptable pressure fluctuations that give rise to cutting inaccuracies and shortens the life of the system components. In order to reduce the pressure fluctuations, an accumulator of high-pressure water is installed. Its volume controls the range of fluctuations.

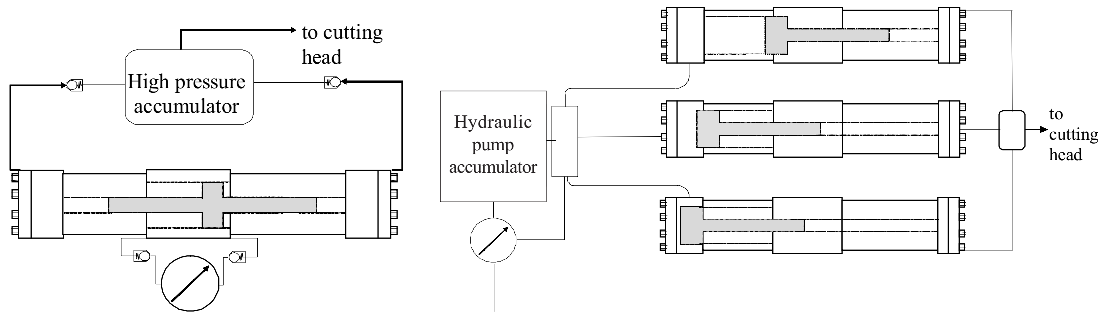
If the accumulator's volume increases, the fluctuation decreases, but the cost of the accumulator increases to more than a proportional extent. The choice of the volume results from a compromise solution between the benefits from a stable pressure signal and a sensible increase in costs ([11] and [12]).

In order to minimize the pressure fluctuation due to the intensifier, without resorting to the expensive solution of the accumulator, some constructors have opted for the use of a *phased pump* (Figure 2-b).

The phased concept is based on at least two (six in [13]) single-acting cylinders in parallel in which the plungers' motion can be arbitrarily phased through a combination of hydraulic and electronic circuitry. These systems are timed such that, at the end of the delivery stroke of a piston, there is already another piston in the phase of pressurization of the water. This implies the contributory presence of a peak of absorbed power. The concept offers several advantages in addition to the absence of a need for an accumulator, compact size, design flexibility, to name just a few [14].

3 CAUSES OF PRESSURE FLUCTUATIONS

The main cause of water-jet pressure fluctuation is intrinsic due to the architecture of the intensifier. The alternating motion of the piston brings about, in fact, an oscillating periodic trend in the pressure of the fluid. This phenomenon can be



(a) (b)

Fig. 2. *Double-acting intensifier (a) vs. phased pump (b)*

removed, only theoretically, by using an accumulator of infinite dimensions [11].

There are at least three factors [14] that have an effect on the stability of the pressure for both of the architectures mentioned above. The first one is the reversion time of the check valves which, in spite of their rapidity, have a finish time to respond. The second one concerns the speed of the return stroke of the intensifier piston: a high speed tends to reduce the pressure fluctuations because it reduces the time during which there is not a feed outflow [16]. Last, but not least, is the volume of the compression chamber: it has to be designed so as to balance these requirements:

- to obtain a higher flow rate than that of the outflow at every stroke;
- to have a short stroke in order to obtain high speed delivery.

In consideration of the compressibility of the water, which can reach up to 15% at 350 MPa [10], every piston covers a part of its working stroke in order to compress the water, without this there is water discharge while the jet is fed thanks to the accumulator and to the additional capacity supplied from the pipes.

In the single-acting system with phased pumping in parallel, the pressure fluctuation due to the compressible water is partly compensated for by the pre-compression of the piston at the end of the suction phase.

Moreover, in a double-acting intensifier the pressure developed by the pump in the forward stroke is different from the pressure developed in the backward stroke [5].

4 THE EFFECT OF PRESSURE FLUCTUATION: STATE OF THE ART

The surface morphology generated by WJ/AWJ is the subject of concentrated research.

Based on a flow visualization study of the water-jet cutting process, Hashish proposed that a water-jet cut surface consists of two cutting regions ([17] and [18]). The first region (the top cut of the surface) is dominated by the cutting wear mode, where penetration occurs at a small impact angle. The second region (the bottom part of the surface) is dominated by the deformation wear mode where penetration occurs at a large impact angle. The surface is smooth in the first region, but it is marked by striations in the second region.

In [19] and [20] it is concluded that a pressure fluctuation causes a cyclical fluctuation in the jet power density, which influences directly the diameter of the jet: the final effect is the periodic fluctuation of the dimension of the kerf.

Afterwards, Hashish proposed that in addition to jet-induced striations, which are due to the deformation wear mode of the waterjet cutting, traverse-induced striations also exist. These are due to the unsteadiness of the water-jet pressure or the motion of the AWJ traverse system and may appear in both the cutting and deformation wear zones [21].

In [4] it was found that the pressure fluctuations have a contribution to the striation formation mechanism in the lower part of the cuts generated by AWJ. In fact, using the two high-pressure generation systems, having a different amplitude fluctuation, at the same level of pressure, the streaked morphology is similar in frequency but not in amplitude. The amplitude of the striations is higher when using the pressure generation system with a higher fluctuation.

As regards pure water-jet cutting, no correlation has been found between the roughness profiles and the pressure signal [22]. Moreover, the pressure signal form does not have a substantial influence on the surface quality of waterjet cutting: in fact, for the process parameters used during the penetration time, the pressure can be considered continuous. The striations along the entire surface presuppose that there are other factors, the vibration of the cutting head and of the work piece [23], that directly influence the quality of the water-jet cutting.

Although the pressure fluctuation does not have substantial effects on the WJ surface quality, it should have an influence on the depth of cut. In fact, the water pressure determines the jet's power and is directly proportional to the energy transfer to the surface.

5 EXPERIMENTAL RESEARCH

5.1 The acquisition of the pressure signal

The trend of the pressure is a characteristic of the intensification system that generates it.

The intensification system that was used is a double-acting intensifier (30 kW).

The pressure was measured through a digital pressure transducer (Inter-Probes HP-48) that is placed in proximity to the cutting head and connected to an acquisition card (Figure 3).

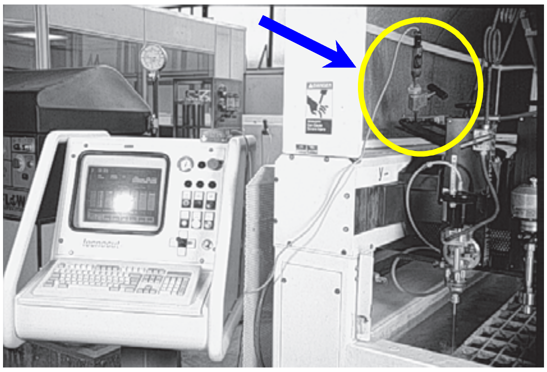


Fig. 3. *Arrangement of the pressure transducer*

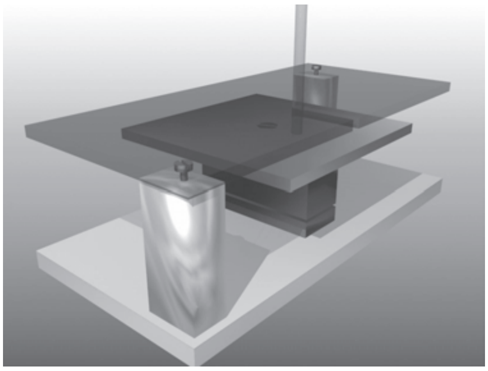


Fig. 4. *Plant description of the arrangement of the system used for the experiment with the load cell*

The pressure measured at the exit of the intensifier system differs from that acquired only by a constant. This constant represents the pressure losses' load inside the pipe lines.

For every measurement the acquired pressure signal was analyzed in the time and frequency domains.

5.2 The penetration ability

Using a mono-axial load cell (DS Europe 535-Q), the thrust trend of the water jet on a plane surface was analyzed either with a motionless cutting head or in motion (Figure 4)

The aim of this experiment was to analyze the penetration ability trend of the jet at the exit of a passing cut; afterwards, the correlation between the thrust signal and the bottom profile generated by a no-passing cut was analyzed.

The material used was polycarbonate, the chemical and mechanical characteristics of which are given in Table 1.

6 ANALYSIS OF THE EXPERIMENTAL RESULTS

Figures 5 and 6 show the pressure signal and the thrust signal with the cutting head not in movement in the time and frequency domains.

Table 1. *Chemical and mechanical characteristics of polycarbonate*

Density	1200 kg/m^3
Relative saturation humidity	0.3%
Thermal conductivity	0.18 W/(m K)
Failure resistance	68.6 MPa
Melting point	220 to 240 °C

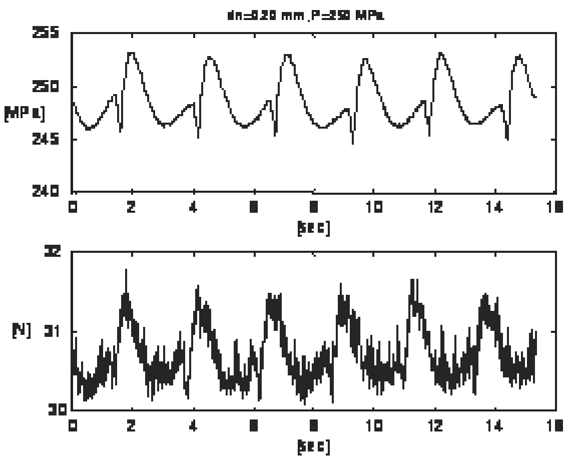


Fig. 5. *Pressure and thrust signals in the time domain*

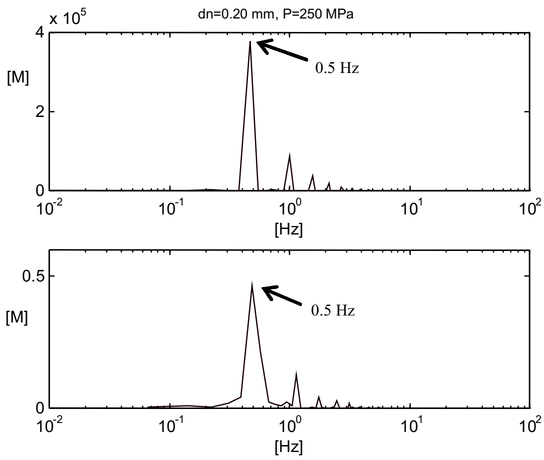


Fig. 6. *Pressure and thrust signals in the frequency domain*

It can be seen that the thrust signal, which represents the penetration ability, is comparable to the pressure signal: the main frequency of the force signal is the same of that of the pressure. Therefore, the fluctuation of the jet energy density causes cyclical areas in which the cut reaches greater depths.

Figures 7 and 8 show the thrust profile in the time and in the frequency domains, measured at the exit of a passing cut.

The main frequency of the thrust is the same as that of the pressure signal.

Figure 9 shows the profile of a no-passing cut on polycarbonate.

Figure 10 shows a frequency analysis of the no-passing profile.

The spatial frequency, which at 200 mm/min coincides with the pulsation of the pressure signal of 0.5 Hz, is 0.15 1/mm.

Figures 11 and 12 show the thrust signal in the time and in the frequency domains of the no-passing cut on polycarbonate.

It can be seen that there is a strong correlation between the dominant frequencies of the two signals and therefore with the pressure signal too.

7 CONCLUSION

This work has analysed the effect of the pressure on pure water-jet cutting.

As regards the effect on the surface quality, in a previous study [22] no correlation was found between the roughness profiles and the pressure signal. The striations along all of the surface presuppose that there are other factors, for example, the vibration of the cutting head and of the workpiece [23], that directly influence the quality of the pure water-jet cutting.

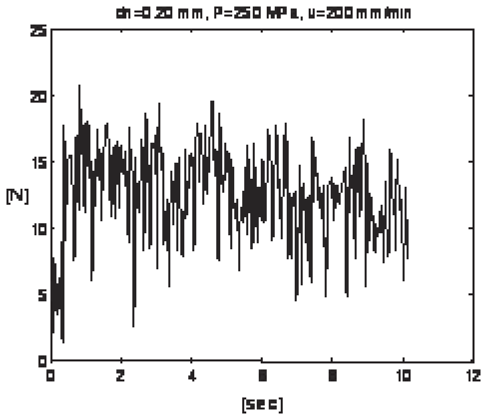


Fig. 7. *Thrust profile of the jet at the exit of a passing cut in the time domain*

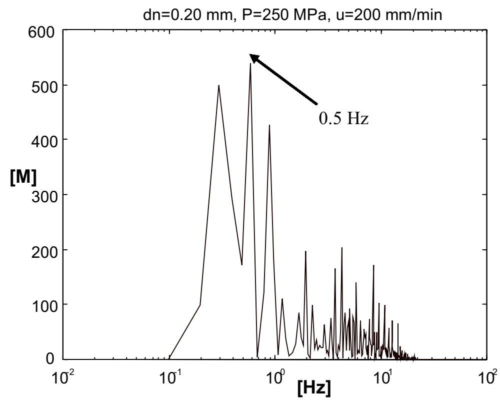


Fig. 8. *Thrust profile of the jet at the exit of a passing cut in the frequency domain*

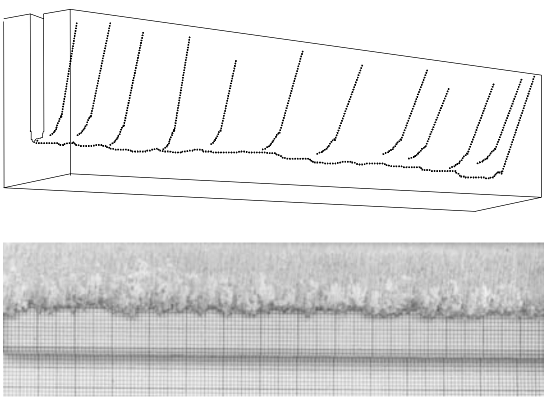


Fig. 9. *Bottom part of a profile of a no-passing cut on polycarbonate (P=250MPa, u=200mm/min, dn=0.2mm)*

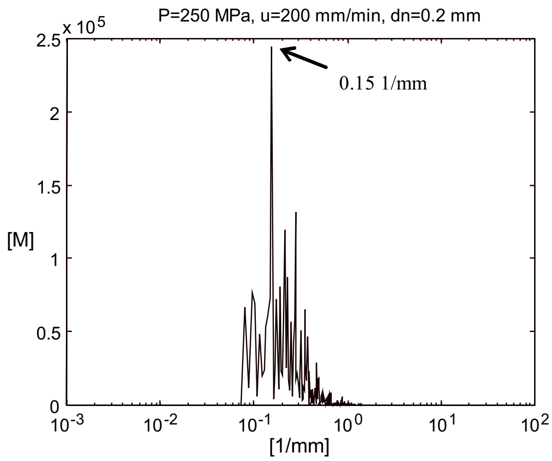


Fig. 10. *FFT of the bottom part of the profile of a no-passing cut on polycarbonate*

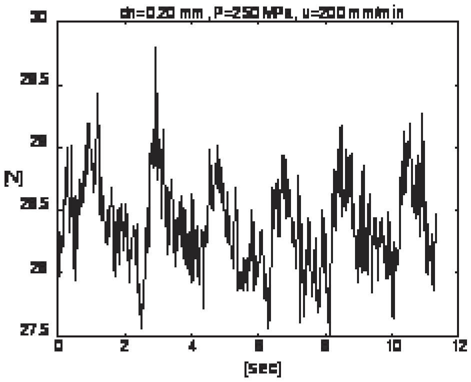


Fig. 11. *Thrust signal in the time domain of a no-passing cut on polycarbonate*

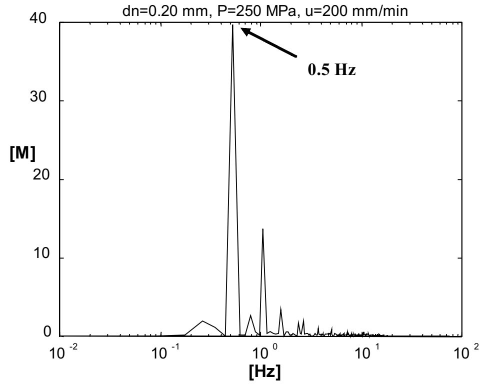


Fig. 12. *Thrust signal in the frequency domain of a no-passing cut on polycarbonate*

In contrast, in this work it was found that the pressure fluctuation causes a periodic trend in the water-jet specific energy and therefore a fluctuation in the cutting ability. In fact a strong correlation between the pressure signal and the bottom part of the profile of a no-passing cut realized on WJ suitable materials was found.

This result is very important for applications in which the jet does not pass all the way through the workpiece, rather it leaves a no-passing track (turning, milling, surface treatment).

It would be interesting to extend this research to abrasive water-jet cutting as well.

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8 NOMENCLATURE

P	Pressure [MPa]
u	Feed rate [mm/min]
dn	Nozzle diameter [mm]
sod	Stand-off distance [mm]
M	Power Spectrum Density Modulus
ρ	Density of the water at atmospheric pressure

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