Real-time underwater abrasive water jet cutting process control

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Summary
The underwater cutting of large steel structures is a cumbersome process. There is no directly applicable method for the real-time control of abrasive water jet cutting quality. However, for some applications where structures have to be separated by means of underwater cutting, an adequate process monitoring strategy is indispensable. This paper describes how two related methods can be used for indirect cutting process monitoring. One method uses a real-time time and spectral analysis of the emitted sound of the abrasive water jet while the other method monitors the resonant behavior of the structure during the cutting operation.
The first section of this paper focusses on the main parameters of an abrasive water jet cutting process and their influence on the resulting sound spectrum of the jet. An overview of the currently applied monitoring methods and analysis techniques is given.
A second part relates the emitted sound spectrum of the abrasive water jet with its possible disruptions or irregularities during cutting. It is fully outlined how adequate lab experiments are used for this analysis.
The third section analyses the structural resonant behaviour of simple tubes during cutting. It is outlined how real-time vibration monitoring helps to estimate the degree of separation during a typical cutting operation and the remaining defects after a cutting process.
Finite elements models are applied to determine the optimal measurement configuration for this vibration monitoring. Simulations are validated by means of lab-scale experiments. Special attention is given to the spatial resolution that can be reached by this method and a discussion of its advantages and limitations.
Section four describes the planned validation of both methods during an industrial under water abrasive water jet cutting process. It summarizes with general conclusions on the application of both methods.

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1. Introduction

When metal plates or shells with a thickness of over 30 mm have to be cut, abrasive water jet cutting is a high-performance technique. In particular circumstances where cutting operations have to be performed under water there are very few alternative industrial cutting methods available.

The quality of such a cutting process is governed by several crucial parameters of which table I gives an overview.
The parameters in table I all influence to some extent the quality of the cutting process. The influences of the different cutting parameters is extensively discussed in [1 – 5].

Table I. Main parameters in an abrasive water jet cutting process.

Cutting process parameter
Water pressure
Type of abrasive
Abrasive mass flow rate
Cutting speed
Substrate material type (and properties)
Water orifice (nozzle) diameter
Substrate thickness
Standoff distance

It is however very difficult, and sometimes impossible, to monitor the cutting quality in a direct way. Due to the turbulences induced by the very high water pressure, visual inspection or monitoring of the cut zone is not feasible. The need for indirect monitoring methods clearly appears.
If the cutting quality is very poor it might even occur that during a cutting operation the material is not completely cut through. In underwater applications where structures have to be cut, e.g. for dismantling purposes, without the possibility for a visual check-up of the cutting result this may lead to inconveniences and even hazardous situations.
According to [6 – 10], an appropriate analysis of the emitted sound during an abrasive water jet cutting process can yield accurate information on the quality of the cutting process. It is concluded that from an enhanced analysis of the sound pressure spectrum even the fluctuation of the most dominant cutting parameters (abrasive mass flow, water pressure) can be deduced. This is possible because each of the cutting parameters contributes to the cutting sound at its own specific frequency interval. This first monitoring method is motivated and illustrated by sound measurements that are performed during the abrasive cutting of steel plates with a thickness of about 30 mm.
A second indirect monitoring method that is proposed is the analysis of structural vibrations of the parts during cutting. The test samples used to illustrate the method are thick plates. Structural vibrations are captured by means of a set of accelerometers with their measurement orientation perpendicular to the cutting plane.
It is concluded that both methods are very well suited for an adequate analysis of the cutting quality. However, more research is needed to relate the variation of a certain cutting parameter with the sound or vibration spectrum changes in a quantitative way. Furthermore, the reproducibility of the various measured spectra is not treated there. The research described here does not focus on analyzing the abrasive water jet cutting quality but the main interest is assuring that cut parts are fully disconnected after the cutting process is completed. The work presented here is the preparatory research in the development of a real-time detection system for cutting operations under circumstances that do not permit visual inspection. Moreover, this work focusses on the cutting of cylindrical shell structures.

2. Analysis of emitted sound

This part describes how elementary lab-scale tests illustrate that emitted sound spectra (and direct time signals) are very suitable to indicate interruptions in a cutting process.
A series of simple experiments is conducted using small metal plates of thicknesses 5, 3, and 1 mm. A jet of compressed air (0.9 MPa, nozzle diameter of 1.2 mm) is generated. During the test, one of the plate samples is mounted on an electrodynamic shaker and oscillated in front of the air jet. The distance between plate and nozzle is 10 mm. Figure 1 shows the recorded sound pressure in case the shaker oscillates with a frequency of 2 Hz.

Figure 1. Recorded sound pressure as a function of time (sample thickness: 5 mm).

Figure 1 clearly indicates the timespan in which the plate sample passes by the air jet. The measured sample thickness is determined with a caliper and is 5.05 mm. the average speed of the plate sample is measured with a lightweight accelerometer. Taking into account this average travelling speed, the mean

sample thickness is retrieved from the recorded sound pressure signal and is found to be 4.94 mm. this corresponds to an error of only 2.2 %. Increasing the frequency of oscillation to 4 Hz leads to an error increase to 3.5 %.
Repeatability is checked by each time performing a set of 12 identical measurements. The corresponding coefficient of variation (COP) is approximately 1.5 % in all cases (different sample thicknesses).
Although the conducted tests are elementary, they clearly indicate the potential of using recorded sound pressure signals to trace interruptions in a cutting process. Since cutting speed and structural dimensions are known, one can easily trace the location of the cutting fault after the cutting process is finished.

3. Analysis of structural vibrations

A second indirect monitoring technique is real – time analysis of structural vibrations. Since the aim of this work is to detect any chance of parts not being fully cut throughout, this approach comes down to monitoring the increasing degree of uncoupling of the considered cut parts.

3.1. Experimental tests

The dynamic energy from the abrasive water jet acts as a vibration excitation source. Here, the case of cutting cylindrical shell structures is considered. Two accelerometers, each positioned at one side of the cutting plane, capture the structural response. Performing a vibration analysis without measuring the excitation is known as operational modal analysis (OMA). References [11 – 14] outline the background of this analysis type in detail.
However, in this case an elaborate operational modal analysis is not desired. Instead, a simple but robust vibration monitoring method is preferred. Therefore the frequency response function (FRF) of two accelerometers (at opposite sides of the cutting plane) is considered and determined during shell cutting.
As in the previous paragraph basis lab - scale experiments are carried out to illustrate and validate the detection method. A number of experiments is carried out on PVC – tubes of diameters 250, 320 and 400 mm with wall thicknesses of 2, 3.5 and 4.5 mm respectively. These experiments provide insight in the reproducibility and spatial resolution of the detection (or monitoring) method.
A first test uses a simply vertically supported tube of diameter 300 mm and a height of 1 m. A (virtual) cutting plane is provided at a distance of 100 mm from the upper tube side. Two accelerometers, each positioned 1 cm off the (virtual) cutting plane, are used for the experiment. As with the sound test (see paragraph 2) a jet of compressed air is used to excite the cylindrical shell structure. During this excitation the FRF of the two accelerometer signals (lower accelerometer act as a reference) is measured. The frequency span is set at 1.6 kHz with a frequency resolution of 1 Hz, while the number of averages is fixed at 500 (maximum overlap is allowed).
During a repeatability test, a set of 10 virtually identical FRFs is obtained. Figure 2 illustrates the scatter of this set in a frequency range of 1.6 kHz. The variability of the FRF rms – value fits in a small interval of 2.5%.

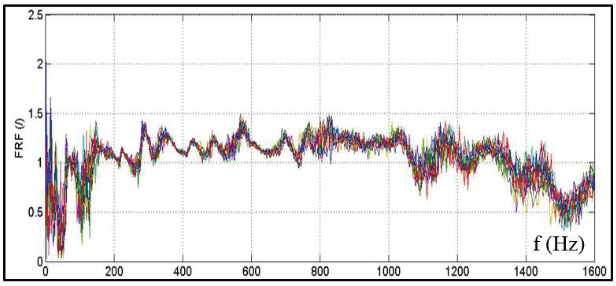

Figure 2. Set of 10 identical FRFs during repeatability test.

Now the shell structure is being cut along the cutting plane using a reciprocating saw. This is done stepwise, with an angular step of 30°.To simulate a ‘real’ cutting operation and vibration monitoring situation, the air jet excites the shell at the end point of a cutting step. From structural dynamics [15 - 17] it is known that a measured FRF changes with a change of excitation location while measurement locations are fixed. In this case the change in FRF is also characterized by shifting of resonance peaks due to the structural changes during cutting of the shell. Figure 3 shows the relative evolution of the measured FRF’s during the final 60° of the cutting operation. The first FRF of this series of 13 is taken as reference.

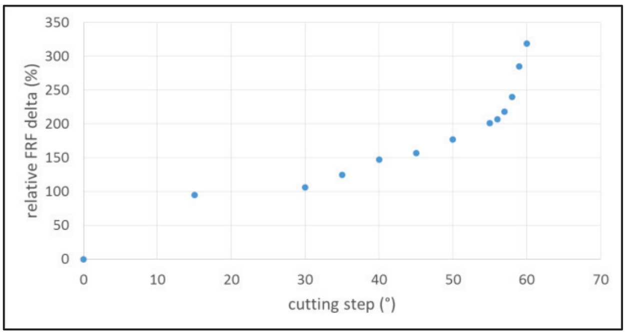

Figure 3. Evolution in measured FRF's during shell cutting (final 60°).

De plotted FRF evolution in figure 3 clearly shows that during the very last cutting steps the evolution rate increases drastically. This indicates that by simply monitoring this evolution enables a real – time estimation of the uncoupling of cut parts, which is the major goal of the work. Before the last cutting step, both shell parts are still joined by 1.1 mm material along the circumference of the shell (and along the full shell thickness).
It is evident from this 'cutting' test that the observed FRF evolution is much larger than the earlier stated repeatability uncertainty.

3.2. Numerical modelling

Finite element modelling is used to study the case of a PVC shell structure. The reason for this is to have a founded idea about the theoretical FRF change during cutting operations. In this study the numerical model thus acts as a reference. Figure 4 compares the relative FRF – changes for the experimental and numerical 'cutting' process. Although the experimental boundary conditions cannot be simulated exactly the simulation clearly confirms the conducted experiments.

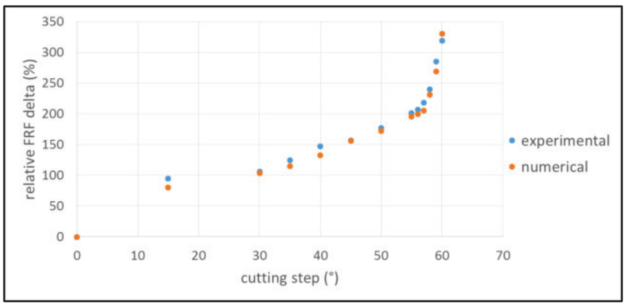

Figure 4. Evolution in measured FRF's during shell cutting (final 60°): comparison between numerical and experimental data.

4. Conclusions and research prospects

The research work done so far gives a good indication that both proposed techniques prove adequate to monitor the structural decoupling of two parts being cut.
However, there are some remaining issues that also have to be considered. Firstly, it might occur during real cutting operations that cut structures or parts remain slightly joined (after the cutting operation) at more than one location. This is being addressed in current research work.
Secondly, real underwater structures might be mounted or placed under complex boundary conditions. Currently, tests are conducted where shell structures are subjected to different boundary conditions. Some of these conditions induce severe damping of the structural vibrations. It is desired that even under these circumstances a monitoring of structural decoupling is still possible.

References

[1] Momber WA, Kovacevic R (1998) Principles of abrasive water jet machining. Springer, New York.
[2] Tonshoff HK, Jung M, Männel S, Reitz W (2000) Using acoustic emission signals for monitoring of production processes. Ultrasonics 37:681–686
[3] Valíček J, Hloch S (2010) Using Acoustic sound pressure level for quality prediction of surfaces created by abrasive waterjet. Int Journal of Advanced Manufacturing Technology 48(1–4):193–203.
[4] Asraf I, Hassan AI, Chen C, Kovacevic R (2004) On-line monitoring of depth of cut in AWJ cutting. International Journal of Machine Tool Manufacturing 44(6):595–605.
[5] Bostjan J, Brissaud D, Junkar M (2004) Monitoring of abrasive water jet (AWJ) cutting using sound detection. International Journal of Advanced Manufacturing Technology 24:733–737.
[6] Peržel V, Hreha P, Hloch S Vibration emission as a potential source of information for abrasive waterjet quality process control. International Journal of Advanced Manufacturing Technology (2012) 61:285–294.
[7] Hloch S, Peržel V, Hreha P Vibration as a source of information for abrasive waterjet monitoring. Journal of Naval Science and Engineering 2011, Vol.7 , No.1, pp. 71-85.
[8] Hreha P, Hloch S, Peržel V Analysis of acoustic emission recorded during monitoring of abrasive waterjet cutting of stainless steel AlSi309. Tehnički vjesnik 19, 2(2012) , 355-359.
[9] Mono M, Ravasio C (2005) The effect of cutting head vibrations on the surfaces generated by waterjet cutting, International Journal of Machine Tools & Manufacture, vol. 45.
[10] Bostjan J, Brissaud D, Junkar M (2004) Monitoring of abrasive water jet (AWJ) cutting using sound detection, International Journal of Advanced Manufacturing Technology 24:733-737.
[11] G.H. James, T.G. Carne, J.P. Lauffer, A.R. Nord, Modal testing using natural excitation, in: D.J. DeMichele (Ed.), International Modal Analysis Conference (IMAC X), San Diego, CA, February 3–7, 1992, Society for Engineering Mechanics, Bethel, CT, 1992.
[12] D.J. Ewins, Modal Testing Theory, Practice and Application, Research Studies Press, Somerset, England, 2000.
[13] L. Hermans, H. Van der Auweraer, Modal testing and analysis of structures under operational conditions: industrial applications, Mechanical System and Signal Processing 13 (2) (1999) 193–216.
[14] G.H. James, T.G. Carne, J.P. Lauffer, Sandia National Laboratories, The natural excitation technique (NExT) for modal parameter extraction from operating structures, Journal of Analytical and Experimental Modal Analysis 10 (4) (1995) 260–277.
[15] W. Heylen, S. Lammens, P. Sas, Modal analysis: Theory and testing, KU Leuven, 2003.
[16] A.Schenk, G.I. Schuëller, Uncertainty assessment of large finite element systems, Springer, Innsbruck, 2005.
[17] B. Cauberghe, Applied frequency-domain system identification in the field of experimental and operational modal analysis, doctoraatproefschrift Vrije Universiteit Brussel, 2004.