1994-3-5 1994

# Sensing the Abrasive Water Jet Nozzle Wear

R. Kovacevic
Center for Robotics and Manufacturing Systems
210E CRMS Bldg.
University of Kentucky
Lexington, KY 40506-0108, USA
Fax No. (606) 257-3342

Received August 10, 1992

Accepted December 15, 1992

One of the most critical parts that influences the technical and economical performance of an abrasive water jet cutting system is the abrasive water jet nozzle. Sensing nozzle wear is a key aspect in producing high quality parts on a fully automated abrasive water jet cutting system.The purpose of the paper is to review a number of sensing methodologies that can be used to track abrasive water jet nozzle wear. Several new abrasive water jet nozzle wear sensing systems are proposed.

## Introduction

The arrival of the abrasive water jet has broadened the potential use of the fluid jet technology in various machining applications. Abrasive water jet cutting (AWJ) is a viable alternative to traditional cutting techniques in several industrial and manufacturing applications. It consists of a thin, high velocity water jet that accelerates abrasive particles through a nozzle and directs it to the target material. It can be used for machining hard materials, such as, titanium, super alloys, glass, composites, metal matrix composites, and advanced ceramics. Applications include turning, drilling small holes, and milling.

One of the most critical parts that influences the technical and economical performance of an abrasive water jet cutting system is the AWJ nozzle. It consists of a mixing chamber and a focusing tube and is usually made of tungsten carbide. Its average life time varies from four hours when used with garnet to just five minutes when used with aluminum oxide as abrasive. The main function of the AWJ nozzle is to accelerate the abrasive particles and to focus the spreading jet. In this process, it is subjected to abrasive and erosive modes of wear. At the entrance, the abrasive particles impact the walls of the nozzle at random angles. However, in the tube the abrasive particles tend to travel parallel to the wall, causing either abrasive or shallow-impact erosion (**1**). Nozzle wear is influenced by various cutting parameters, namely, water pressure and flow rate, type of abrasive material, its size and flow rate and, geometry and material of fabrication. Since quality of the parts produced on a fully automated AWJ system is highly dependent on the AWJ nozzle, sensing its wear is quite important.

The methods used to detect the AWJ nozzle wear can be categorized as either direct or indirect. Qualitative methods consist of direct visual inspection of the tip of the nozzle and indirect observation of any deterioration in the quality of the cut surface or the undesirable changes in dimensions of the workpiece. Direct quantitative methods consist of assessing the nozzle wear by either measuring the inside diameter of the nozzle at its tip, or measuring the material loss of the nozzle by radiometric techniques. Both methods suffer from serious drawbacks. The former technique requires the interruption of the cutting process by turning the jet off and thus is unsuitable for on-line wear measurement. Radiometric technique on the other hand requires special preparation of the nozzle and also poses potential hazards due to radioactivity. Indirect methods are based on the measurements of some parameters, such as the change in the stream diameter at the nozzle exit or the normal force on the workpiece, noise, vibration, etc., that can be correlated to the nozzle wear.

During the last few years, several attempts have been made at developing a satisfactory nozzle wear tracking system. This paper considers some new methods.

## Abrasive Water Jet Cutting System and Nozzle Wear

In order to understand the problems related to AWJ nozzle wear, an explanation of the abrasive water jet system will be helpful. A standard abrasive water jet system consists of a high-pressure water pump, a cutting head, an abrasive delivering system, and a CNC positioning system. The cutting head consists of a sapphire orifice, a mixing chamber and an AWJ nozzle. As shown in Figure 1, it is manipulated by a x-y positioning table with the CNC controller. High-pressure water, supplied through an ON/OFF pneumatic valve by the intensifier pump, carries the abrasive material. The ON/OFF valve provides rapid control of the water jet at the sapphire nozzle. The abrasive material stored in the hopper is introduced into the water jet stream at the mixing chamber. The flow rate of abrasives is controlled by the metering valve located below the hopper. The slurry formed in the mixing chamber exits through the tungsten carbide AWJ nozzle towards the material being cut. The function of the AWJ nozzle is to accelerate the abrasive particles and to focus the abrasive-entrained water jet.

As indicated in Figure 2, the abrasive water jet cutting technique involves many factors. The outcome of the process, such as, rate of material removal, surface quality and dimensional accuracy (depth and width of cut), depends on the interrelationships between these factors. Any one of these factors can be used as a control variable. However, the limitations of currently available abrasive water jet cutting systems reduce the number of control variables to the following four: jet traverse speed, direction of motion, angle of impingement and the nozzle standoff distance. Variables such as pressure, abrasive flow rate, abrasive grain size, abrasive material, AWJ nozzle and the sapphire nozzle diameter can be used as control variables between individual operations. For example, a change in the inside diameter of the abrasive water jet nozzle can influence the depth of cut or surface quality. When the inside diameter becomes larger, the mixing of abrasives with water decreases due to lower transverse particle velocity which results in incomplete mixing of the abrasive particles with the water jet and consequently a reduction in its cutting ability. Thus, the rate of change of the inside diameter at the nozzle outlet can be used to quantify nozzle wear. The new generation of abrasive water jet cutting systems, as shown in Figure 3, will be equipped with control systems to regulate various parameters to allow on-line monitoring of nozzle wear, depth of cut, etc. The nozzle wear sensing systems discussed in this paper can be divided into three groups with respect to the measured object:

- sensing systems that have an AWJ nozzle as the measured object;
- sensing systems that have an abrasive water jet as the measured object;
- sensing systems that have a workpiece as the measured object.

## Wear Sensing Systems that Have an AWJ Nozzle as a Measured Object

Direct tracking of nozzle wear can be achieved with a sensing unit embedded at the tip of the nozzle. Two such sensing units are possible **(2, 3)**. The first sensing unit is based on a conductive loop designed to detect a predetermined threshold representing the nozzle life. The criterion for nozzle life can be specified in terms of the maximum allowable increase in the nozzle inside diameter, determined through experiments. The criterion for nozzle wear can be physical or technological. The physical criterion specifies the nozzle to be worn out when accelerated wear begins. Although direct determination of this point is not possible, it may be determined by some phenomena accompanying it, such as, for example, a change in the stream diameter at the nozzle exit, cutting force, noise or vibration. The technological criterion, on the other hand, is specified in terms of loss of accuracy (exceeding tolerance limits) or deterioration of quality of cut surface (increase in surface roughness).

The electrical circuitry of the sensing unit consists of a conductive loop, a power supply, a control relay and the solenoid of a pneumatic valve. When the nozzle inside diameter reaches a predetermined threshold value, the circuitry will be interrupted, causing closure of the pneumatic valve which shuts off the entire system. Through an appropriate alarm device, the operator can be alerted to take appropriate corrective action. However, this type of sensing system is not capable of on-line monitoring of the nozzle wear or provide the operator with the necessary information to take remedial actions. In order to eliminate these drawbacks, an AWJ nozzle wear sensing system based on wearable probes can be used **(3)**. As shown in Figure 4, this system consists of a wear sensing probe and a digital logic unit connected to a PC. The wear probe consists of a ceramic substrate with a central hole of the same diameter as the new AWJ nozzle and is divided into four quadrants, each with several conductive loops spaced 0.05 mm apart. The sensor, attached to the tip of the AWJ nozzle, will be subjected to the same modes of erosion as the nozzle itself. Therefore, a break in any one of the conductive loops is an indication of the nozzle wear to the diameter of that loop. The diameter of the last conductive loop can be set to the allowable increase in the AWJ nozzle diameter. Figure 5 illustrates the manner in which an automated AWJ can compensate for wear during cutting. The main function of the logic unit, shown in Figure 6, is to monitor the continuity of the loop in the sensor.

## Wear Sensing Systems that Have an Abrasive Water Jet as the Measured Object

The abrasive water jet diameter near the AWJ nozzle outlet can be used as a variable for monitoring the nozzle wear. The jet diameter can be measured directly by a solid-state CCD matrix or line-array camera. A typical PC based monitoring system **(4)**, shown in Figure 7, consists essentially of a CCD matrix array camera, a frame grabber and a video interface board. However, because of the complexity of the AWJ cutting process, the procedure requires periodic interruption of the cutting process. It should be remembered that the accuracy of the estimate of the actual nozzle outlet diameter will be influenced by jet spreading which is also a function of pressure. Despite these drawbacks, micro-computer based, non-intrusive vision systems are well suited to flexible automation.

Another promising approach, an acoustic sensing method, can be used to detect wear in the AWJ nozzle **(5)**. This is based on the fact that a change in the inside diameter of the nozzle affects the sound generated by the jet. Depending on the geometry of the nozzle, the sound generated may be tonal (generated by periodic vortex shedding) or random noise (generated by turbulence). It should be noted that the tonal frequency depends on the jet velocity. In order to investigate the feasibility of using the acoustic sensing technique, a preliminary experiment was conducted using the setup shown in Figure 8. It consisted of an AWJ cutting system, a microphone, a modular precision sound-level meter, a dual-channel analyzer, a tape recorder and a plotter. Sound spectrum results obtained with a new and a worn AWJ nozzle are shown in Figure 9. Assuming that noises from other sources (for example, noise from jet impingement on the workpiece, etc.) were similar during both tests, it is clear from this figure that as the AWJ nozzle wear increases, the level of noise also increases, particularly at frequencies over 20 kHz, indicating that the technique can be adopted for monitoring the nozzle wear.

### Wear Sensing Systems that Have a Workpiece as the Measured Object

A number of experiments have shown (see Figure 10) that the normal force generated by an abrasive water jet on a workpiece will increase with an increase in the nozzle diameter, assuming that other variables remain constant during the cutting process **(7, 8, 9)**. This indicates that the variation in the normal force can be used as an indicator of the nozzle wear. Furthermore, as reported earlier **(8, 9)**, it is possible to detect and analyze the dynamic portion, that is, the A.C. component of the workpiece normal force signal and relate it to the nozzle wear. A time-series analysis technique can be used to characterize the workpiece normal force signal with an autoregressive model. A strong correlation has been found to exist between the nozzle wear and the autoregressive model parameters **(8, 9)**. The current value of the measured workpiece normal force can be expressed using a N-th order autoregressive model which is simply a linear combination of N previous values as indicated below:

$$F(t) = a(t)F(t-i) + n(t) \tag{1}$$

where:

$F(t)$ = predicted value of the workpiece normal force

$F(t-i)$ = magnitude of the workpiece normal force at the sampling instant $(t-i)$ where $i$ is the number of sampling periods

$a(t)$ = a model parameter and $n(t)$ is white noise.

In order to establish the relative importance of the model parameters, a discrimination index parameter, which is capable of separating different cutting conditions, can be used. This index is simply an indication of how two nozzle wear conditions can be separated through the monitoring of the i-th model parameter. The most important parameter is the one that maximizes the discrimination index. Figures 11a and 11b show 2-D parameter planes that provide a relationship between the two most significant parameters under selected nozzle wear conditions for two different AWJ operations and for two experimental runs. It is evident that there exists a distinct difference between the nozzle wear conditions in both operations and, that there is a very small difference in the magnitude of the model parameters for both experimental runs in the scope of one operation.

In practice it is common, for a given workpiece material and thickness, to select the optimal combination of the cutting variables (water jet pressure, abrasive flow rate, etc.) in advance. Under such conditions, nozzle wear can be monitored by the magnitudes of the autoregressive model parameters. Furthermore, most often, the jet traverse speed is used as an easy-to-control variable, while keeping other cutting variables constant. In such a case, monitoring nozzle wear requires a slightly different approach. In order to separate the effect of nozzle wear on the workpiece normal force caused by variations in the traverse speed, the total force (F) is separated into two components as follows **(10)**:

$$F = Fo + dF \tag{2}$$

where Fo is the workpiece normal force when the nozzle is new and dF is a measure of the nozzle wear. Both Fo and dF are functions of the cutting variables.

### Conclusions

The shape of the abrasive water jet and its cutting performance are determined by the outlet of the nozzle which is subjected to erosion wear. Several indirect methods for tracking nozzle wear were discussed. These include:

- sensing systems that have an AWJ nozzle as the measured object;
- sensing systems that have an abrasive water jet as

the measured object;
- sensing systems that have a workpiece as the measured object.

It is shown that an increase in the nozzle diameter due to wear results in an increase in the workpiece normal force. The change in the magnitude of the normal force can be monitored to detect the nozzle wear. A wear sensor system based on a conductive loop for direct and almost on-line tracking of the wear of an abrasive water jet nozzle has been proposed. The proposed sensing methodologies are based on sensing by contact, either with a workpiece or the nozzle. However, practicality of the methodologies will depend on the complexity of the AWJ cutting process. Micro-computer based machine vision systems are well suited for flexible automation.

## References

1. Hashish, M. 1987: Wear in abrasive water jet cutting systems. Proc. International Conference on Wear of Materials (April, Houston, USA). ASME. USA: 769-776.

2. Kovacevic, R. 1988: Sensor for detecting the nozzle wear in abrasive water jet cutting systems. Invention Disclosure (March). Syracuse University, Syracuse, NY, USA.

3. Kovacevic, R. 1991: A new sensing system to monitor abrasive water jet nozzle wear. Journal of Materials Processing Technology. V.28: 117-125.

4. Kovacevic, R. 1991: Development of opto-electronic sensor for monitoring the abrasive water jet nozzle wear. Proc. ASME Winter Annual Meeting: Symposium on Sensors, Controls, and Quality Issues in Manufacturing (December, Atlanta, USA).

5. Braeuel, M., F. Nadeau, and M.M. Bayoumi 1987: Defects in nozzle of plasma cutting torches. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control. V.UFFC-34, N.2: 259-262.

6. Kovacevic, R., and M. Evizi 1990: Nozzle wear detection in abrasive water jet cutting systems. Materials Evaluation. V.48: 348-353.

7. Kovacevic, R. 1989: Nozzle wear sensing in turning operation with abrasive water jets. Proc. SME Non-traditional Machining Conference "Nontrad for the 90's" (October, Orlando, USA).

8. Kovacevic, R., and G. Chen 1989: A workpiece reactive force as a parameter for monitoring the nozzle wear in turning operations by abrasive water jet. Proc. ASME 1989 Winter Annual Meeting - The High Energy Beam Manufacturing Technology Session. (December, San Francisco, USA).

9. Kovacevic, R. 1991: Detection of abrasive water jet nozzle wear by using time series modelling technique. NAMRI Transactions. May: 96-100.

10. Kovacevic, R. 1990: Estimation of nozzle wear under varying cutting condition. Proc. ASME 1990 Winter Annual Meeting, Symposium on Monitoring and Control for Manufacturing Processes: Sensors and Signal Processing (November, Dallas, USA): 9-16.

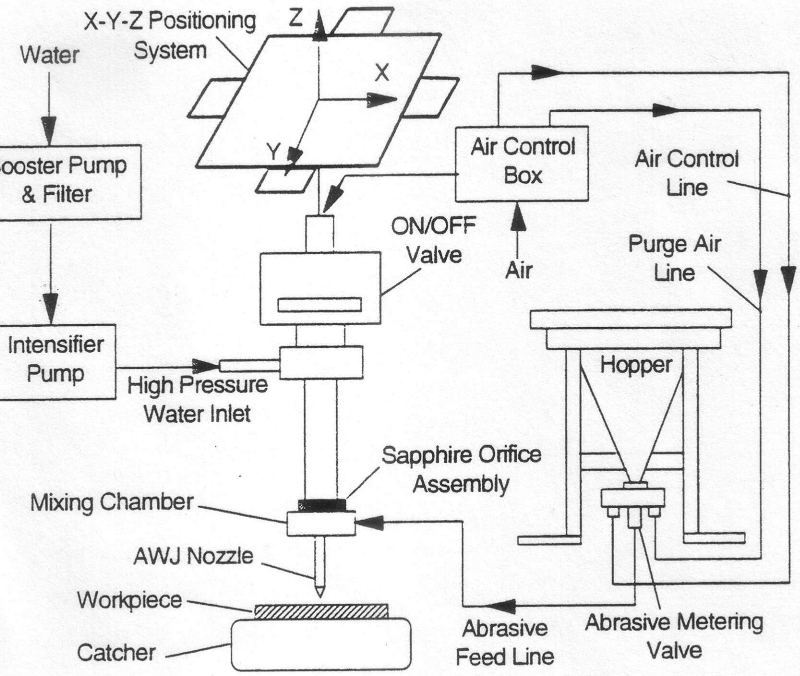



Figure I. A general concept of an abrasive water jet cutting system.

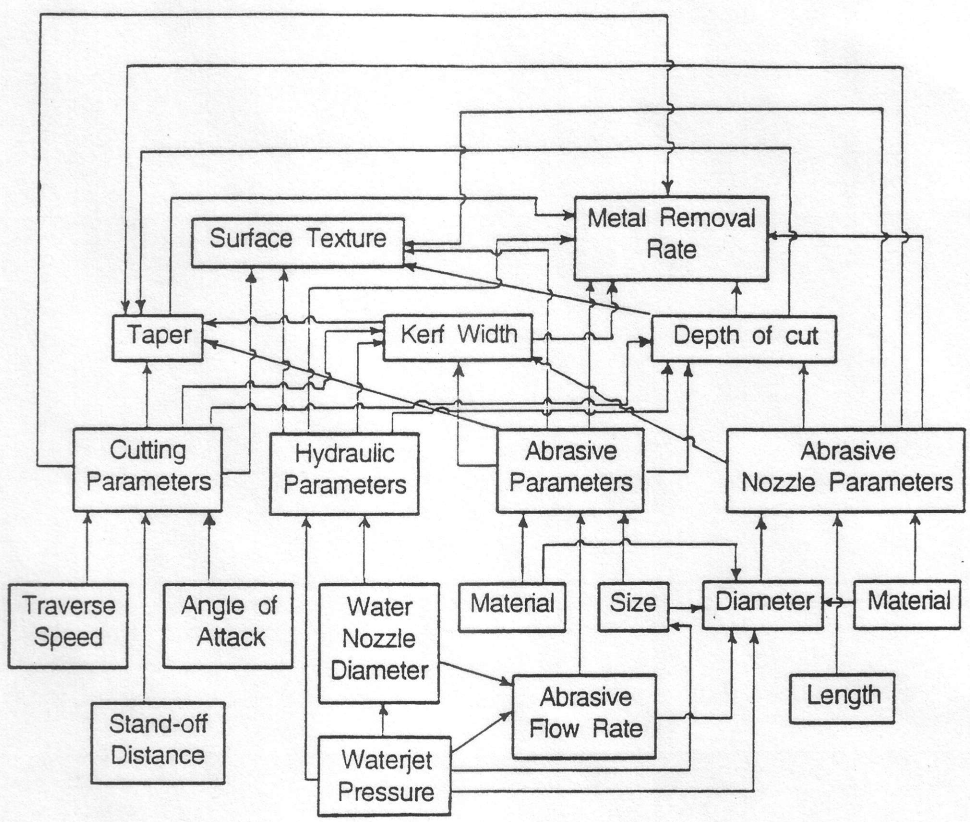



Figure 2. The relationship between the various parameters in an abrasive water jet system.

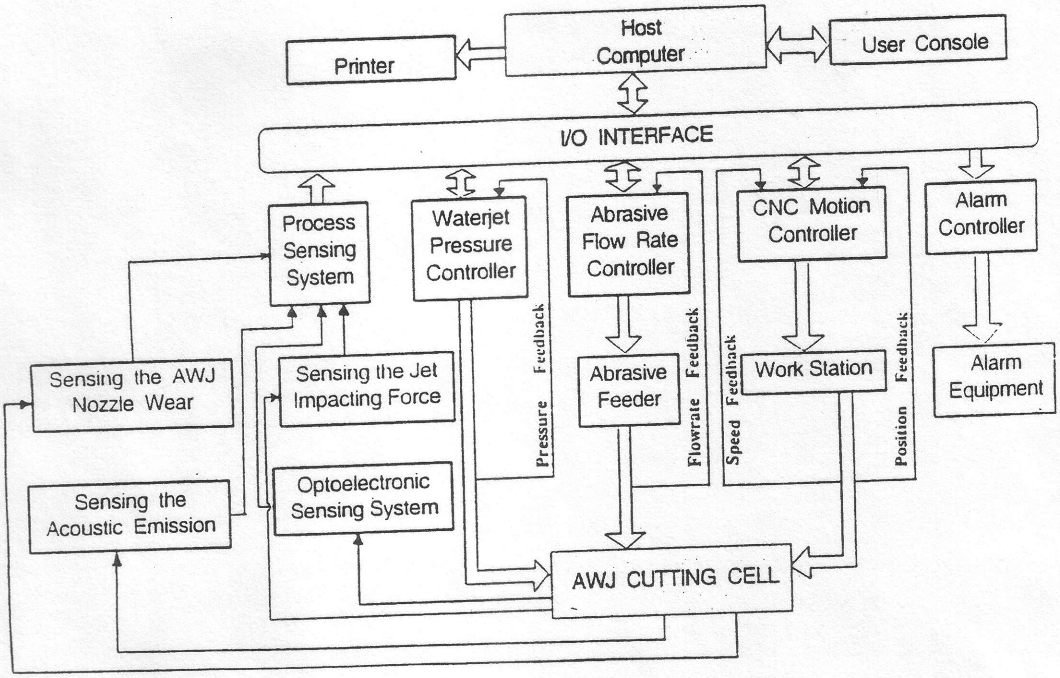



Figure 3. Block diagram for a new generation of abrasive water jet cutting systems.

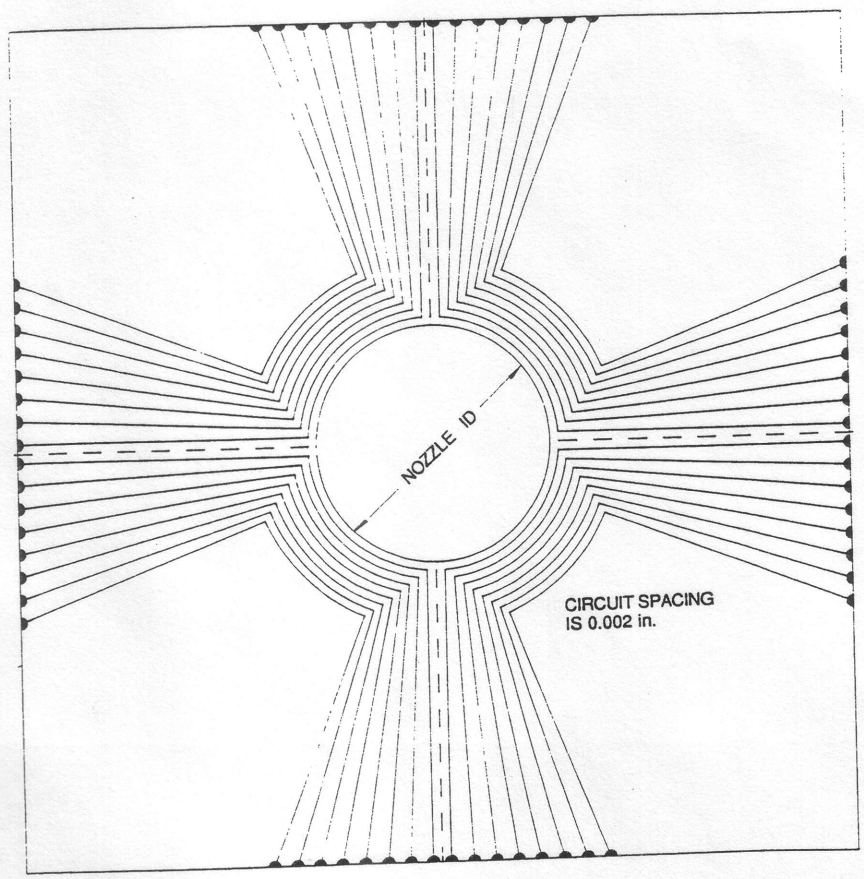



Figure 4. Abrasive water jet nozzle wear probe.

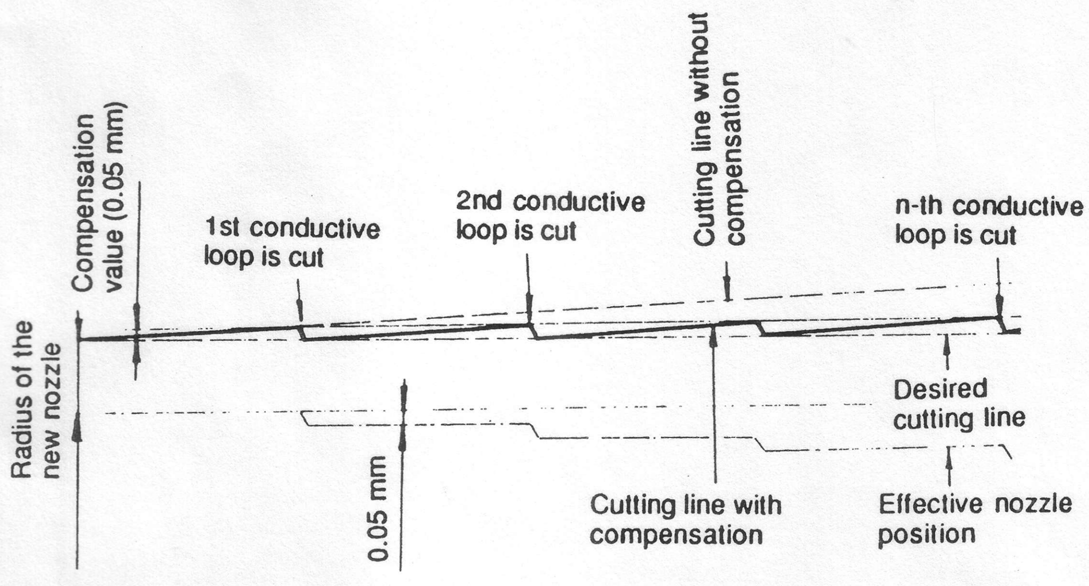



Figure 5. Cutting a straight line with the AWJ by compensating for increases in the nozzle's inside diameter.

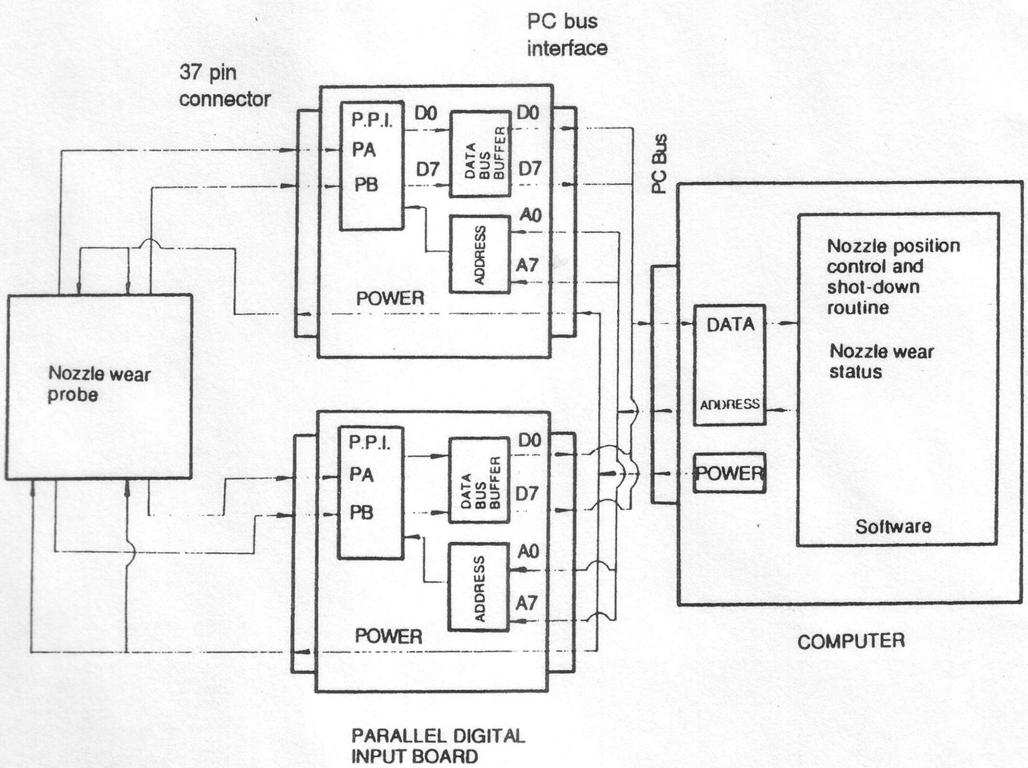



Figure 6. Block diagram of a digital logic device.

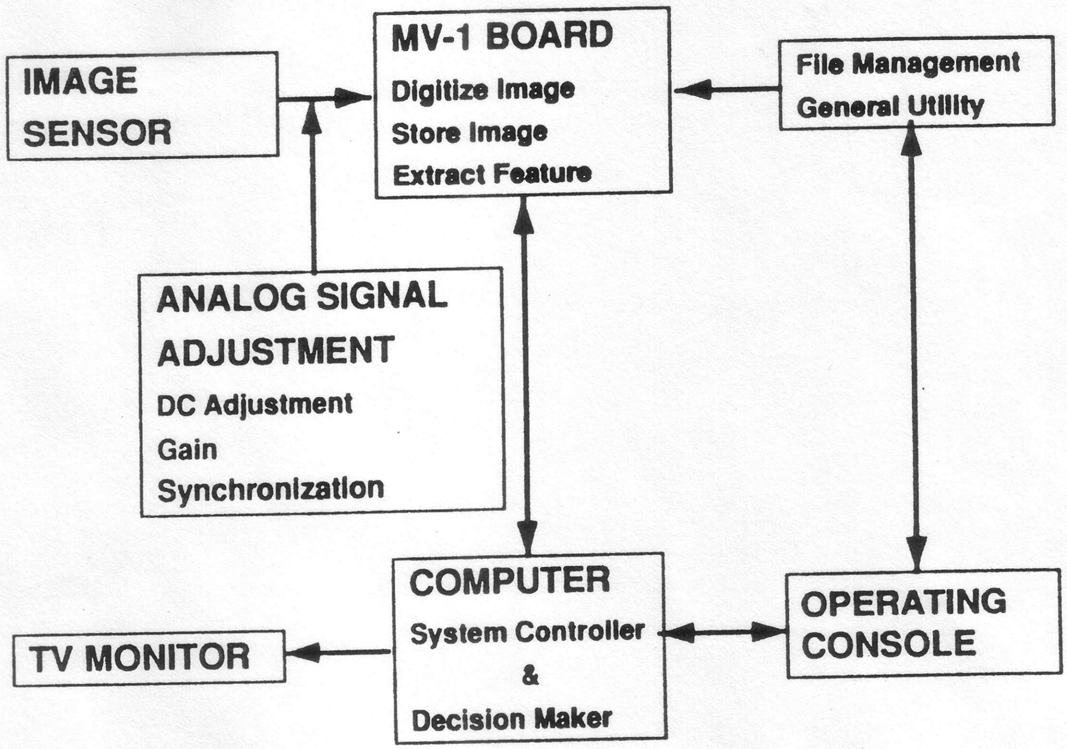



Figure 7. Block diagram of a video system to monitor the AWJ nozzle diameter.

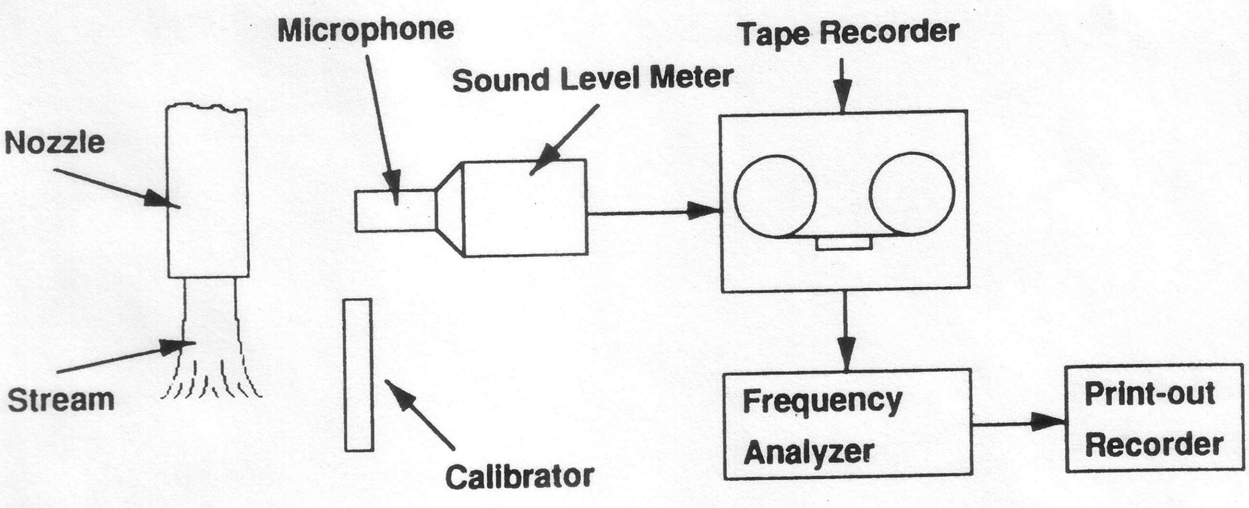



Figure 8. A typical setup for noise monitoring in an AWJ cutting system.

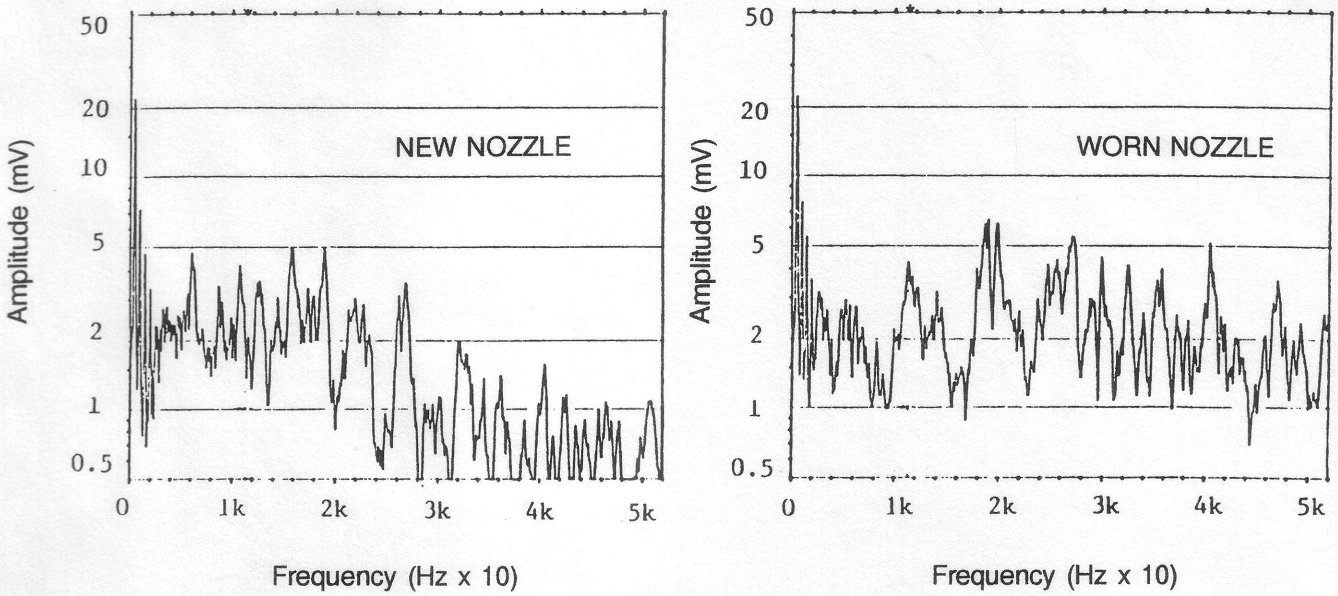



Figure 9. Sound wave spectra of an abrasive water jet flowing through a new and a worn long nozzle.

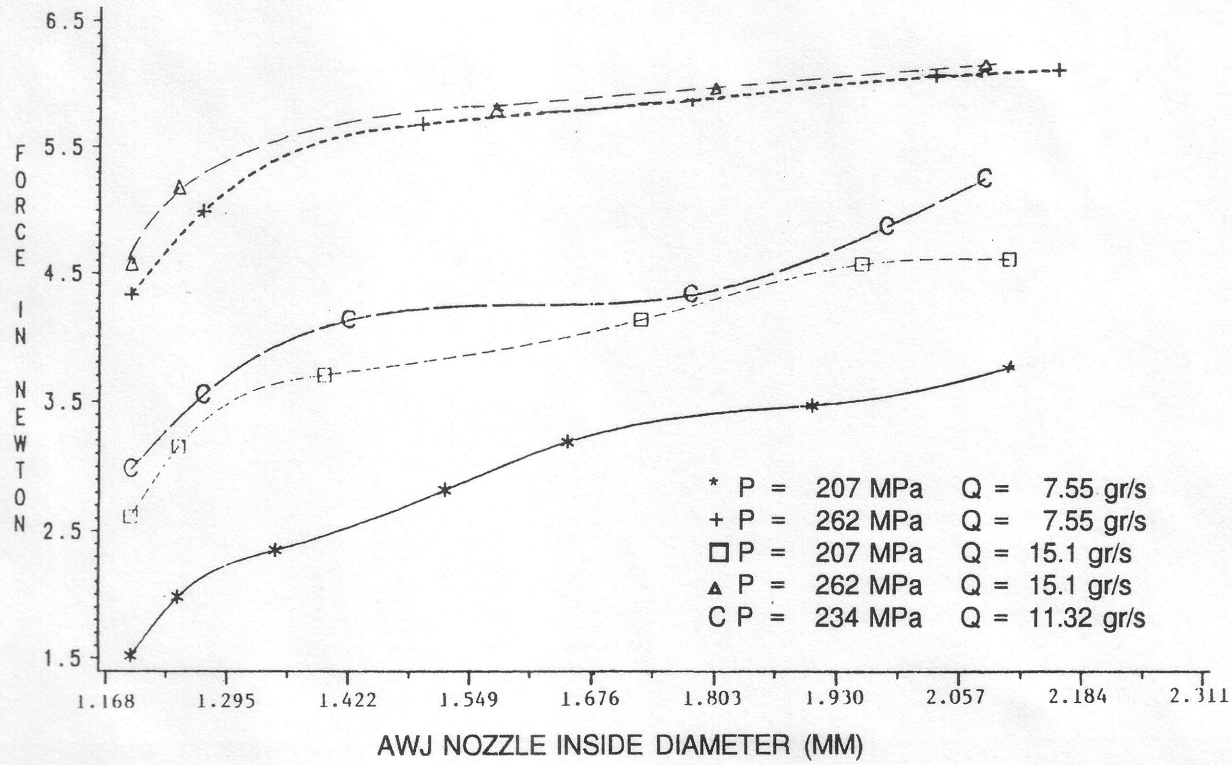
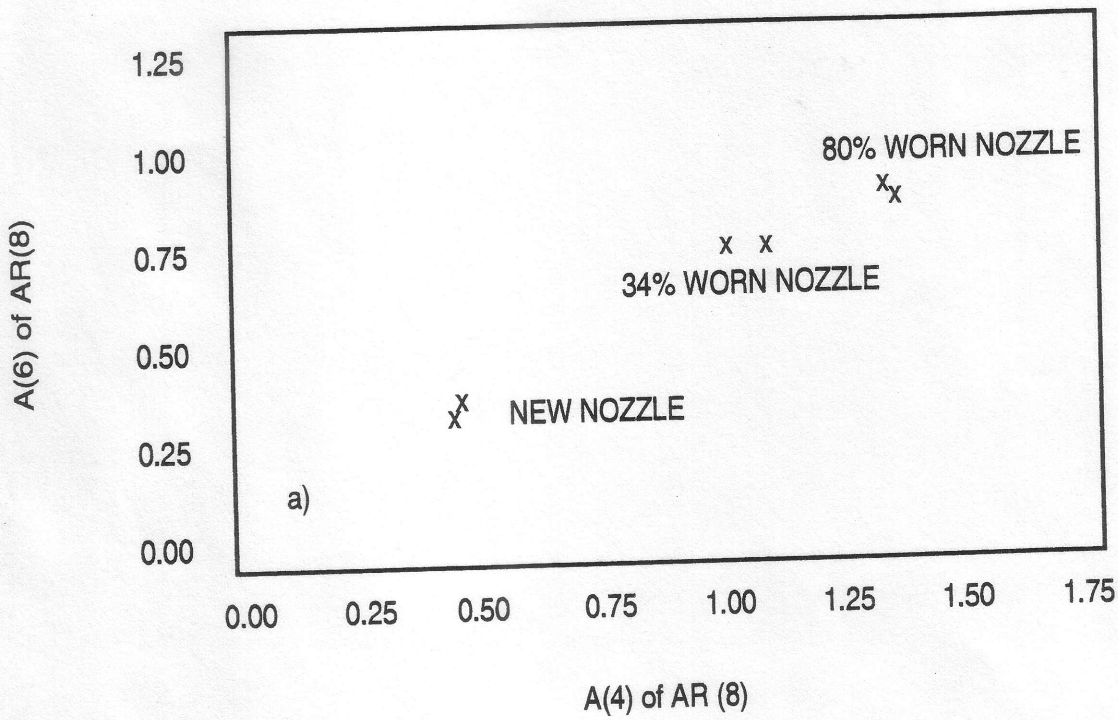



Figure 10. The average workpiece normal force for various nozzle inside diameters at different combinations of water jet pressure and abrasive flow rates.



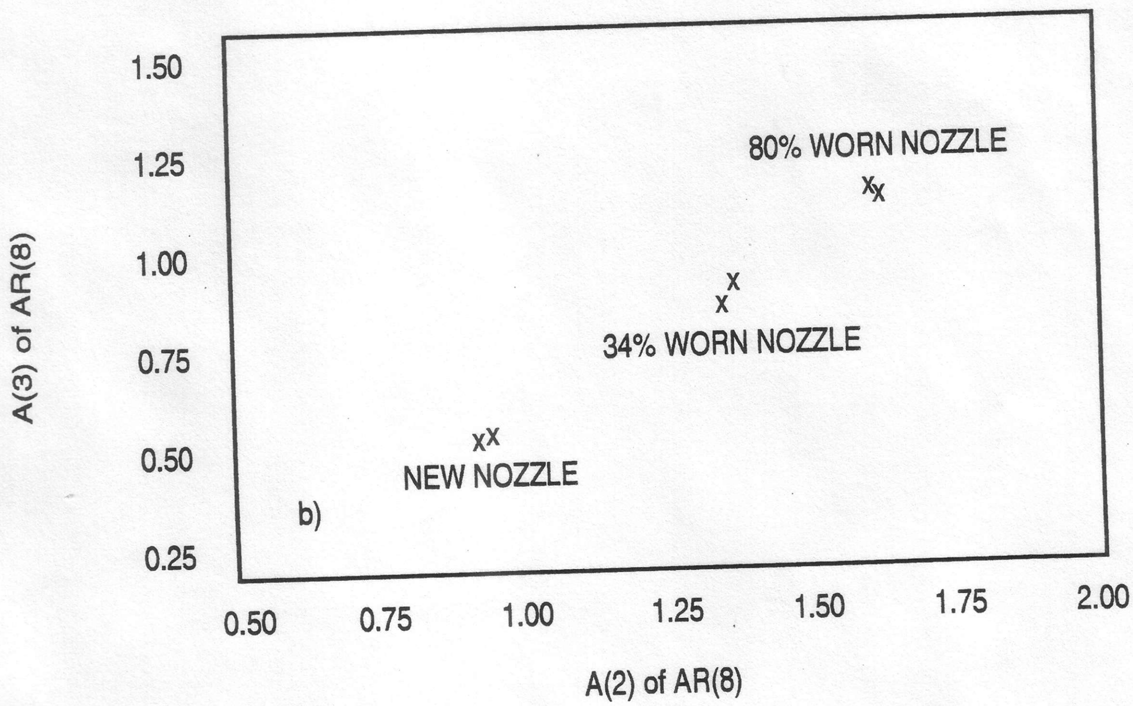




Figure 11. 2-D parameter planes of three different nozzle wear conditions and two test runs in a) milling, b) cutting through.