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Semi-Annual Report #4

Development of an "Intelligent Grinding Wheel" for In-Process Monitoring of Ceramic Grinding

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Introduction

This is the fourth semi-annual report for the project "Development of an Intelligent Grinding Wheel for In-Process Monitoring of Ceramic Grinding." This report covers the period from March 1, 1998 to August 31, 1998.

The overall objective of this project is to develop sensor-integrated "intelligent" diamond wheels for grinding of ceramics. Such wheels will be "smart" enough to monitor and supervise both the wheel preparation and grinding processes without the need to instrument the machine tool. Intelligent wheels will utilize re-useable cores integrated with sensors: to measure the acoustic emission (AE) and grinding force. Signals from the sensors will be transmitted from a rotating wheel to a receiver by telemetry. Wheels will be "trained" to recognize distinct characteristics associated with truing, dressing and grinding.

Technical Progress

This overall project is divided into six tasks as follows:

1. Development of miniaturized sensors and data transmission system,
2. Wheel design and sensor configuration,
3. Calibration of the sensor integrated wheel,
4. Training of the intelligent wheel,
5. Grinding tests,
6. Prototype demonstration.

The technical progress is summarized in this report according to the tasks. All activity during this period has been concerned with the first two interrelated tasks, which need to be completed before undertaking the remaining tasks.

Task 1. Development of Miniaturized Data Transmission Electronics

As mentioned in the third Semi-Annual report, the grinding wheel has a total of fifteen embedded sensors. Eleven of them are configured as force sensors and located around the periphery of the grinding wheel. The remaining four are acoustic emission sensors and placed on the face and towards the center of the grinding wheel. Design considerations for sensor selection and their placement strategy were described in the previous report.

The development of data acquisition and transmission electronics has been conducted in three consecutive stages:

1) Bread-board level design and implementation of various functional modules of the entire circuitry,
2) Integration of various functional modules on a PCB for interfacing and combined circuit operation verification, and
3) Design, simulation, and fabrication of a miniaturized circuit board using surface-mount devices (SMD).

For the previous reporting period, research was focused on stage three where the surface mount technique was explored for circuit miniaturization. Results from the first and second stage development provided valuable inputs to fine tune the final design. In addition to meeting the circuit functionality requirement, the design also has taken into account the space limitation determined by the targeted grinding wheel.

Figure 1.1 shows a block diagram of the final miniaturized circuit. The circuit was implemented as a six-layered PCB board (Printed Circuit Board) which has been fabricated by a commercial vendor. A photograph of the fabricated PCB is shown in Figure 1.2, with components soldered on both sides. Of the six layers, four have been used as signal routing layers and two for the power supply rails (V_{cc} and Ground). The use of four routing layers significantly reduces the length of connection tracks between individual components. The two dedicated layers for power supply rails are essential for providing a ripple-free voltage supply to the circuitry. Furthermore, they provide good shielding for the entire circuitry against ambient electrical noise. This is especially important considering the high frequency range in which the circuits will operate.

1.1 Description of the Circuitry:

As shown in Figure 1.1, there are three main functional modules within the circuitry:

1) An analog front-end which provides interface to the fifteen sensors and contains an Analog-to-Digital Converter,
2) A digital signal processing module centered around a 16-bit DSP, and
3) An RF transmitter for wireless data transmission.

In order to prevent interference and cross talk, inductors have been used to separate AC links between the analog and digital circuitry. This is necessary to prevent high frequency noise generated by a fast switching digital circuit from corrupting the analog signals.

There are three components in the circuit which need a clock signal: the Analog-to-Digital Converter (ADC), Digital Signal Processor (DSP), and the RF interface circuit. In order to minimize the size of the entire circuitry, a single clock chip operating at 1.84 MHz was used. Therefore, the ADC is operated at a frequency slightly lower than its nominal value of 3 MHz. An internal Phase Locked Loop (PLL) within the DSP is used to step up the clock frequency by fifteen times to 27.6 MHz, such that the DSP can be operated at its full speed. The RF interface circuit divides the input clock of 1.84 MHz and transmits data at 4800 bits per second.

The anti-aliasing filter used in the miniaturized version of the circuit is a simple RC filter. Earlier versions of the circuit utilized a four-pole active filter. Preliminary tests revealed that this type of filter introduced distortion to input signals of more than 0.8 V p-p amplitude, which considerably limited the dynamic operating range of the charge amplifier.

1.2 Verification of the Circuit Board:

The fabricated circuit boards were visually and functionally tested for bad or wrong electrical connections. In the next step, SMD components were hand-soldered on to the board under a specially designed magnifier. A digital signal processor emulator was used for programming the DSP. The program further verified various functional blocks of the circuit including the attenuator selector, sensor selector, ADC, RF transmitter interface, and RF transmission.

Several software driver modules have been developed using the “C” language to access the DSP peripherals. Further development of signal processing algorithms is currently under way.

Task 2. Wheel Design & Manufacture

The design of the sensor integrated grinding wheel was described in detail in the Third Semi-Annual Report. This section describes the design of the adapter disk which houses the on-board electronics and the manufacture of the sensor-integrated grinding wheel.

2.1 Design of the Adapter Disk

As described in the previous report, an adapter disk is used to house the electronic circuitry. The adapter disk is fastened to the wheel core during grinding for the purpose of monitoring the process in real-time. This design minimizes the need for structural alterations to the wheel core and facilitates easy access to the electronics.

The layout of the adapter disk together with the on-board electronics is shown in Figure 2.1. A set of fifteen connectors is mounted on the periphery of the adapter disk. Each sensor is electrically connected to the "on-board" electronics by means of these connectors. The electronics is physically separated into three segments: data acquisition system, radio frequency (RF) transmitter, and power supply. The data acquisition system consists of a signal multiplexer, charge amplifier, anti-aliasing filter, analog to digital converter, and digital signal processor (DSP). Wires laid out in the annular recess of the adapter disk provide connections to the RF transmitter and the power. The electronic circuitry, together with the power supply, are anchored to the adapter plates by means of screws. An aluminum cover on the outer face of the adapter disk provides EMI shielding.

2.2 Manufacture of the Sensor Integrated Grinding Wheel

The wheel core is designed with 11 equally spaced slots around its periphery which hold the piezoceramic sensors. Prior to being mounted in the wheel, responses of the individual sensors were measured by subjecting each of them to a fluctuating load of 5 ± 2 lbs applied by a universal testing machine (Instron) at a frequency of 5 Hz. The results are summarized in Figure 2.2. Clearly there are some variations in the individual responses of these sensors, which is taken into account during electronic calibration of the wheel.

After testing, brass strips were attached to the positive face of each sensor (the negative face has a distinguishing "black dot"). The negative face of each sensor was then attached to the periphery of the wheel core in its slot as shown in Figure 2.3. Each sensor was fixed in place by means of a two-component epoxy adhesive (EPOTECH) and cured for two hours at 60° C. The brass strip was soldered to the connection pads. The connection pads together with the wheel core form the positive and negative terminals of the sensor. The entire machined slot was filled with epoxy adhesive to ensure adequate abrasive-sensor contact and to provide sensor protection (physical & thermal) during wheel manufacture and operation.

The wheel core with the sensors mounted was machined on the outer periphery to form a clean surface for bonding the abrasive. Diamond abrasives segments were attached to the sensor integrated core at the Norton Company. Two sensor integrated grinding wheels were manufactured in this manner. One of these wheels is shown in Figure 2.4.

Task 3 Testing & Calibration

This section describes the procedure and results obtained while testing the individual components of the grinding wheel monitoring system.

3.1 Wheel Balance & Spin Test

The two sensor-integrated grinding wheels were statically balanced and spin tested at Norton Company in Worcester, Massachusetts. For this purpose, each sensor-integrated grinding wheel together with the mounting flanges was placed on a static balancing device. Both wheels were statically balanced by removing excess material from the wheel core. The balanced wheels were then spin tested at peripheral speeds up to 90 m/s to ensure safe operation during grinding. The wheels were qualified by Norton Company to operate at a maximum surface speed of 60 m/s (3275 rpm , 14 inch diameter wheel).

After the manufacture of all sub-systems is completed, the wheel along with the adapter disk and the miniaturized electronics will be dynamically balanced at Norton Company.

3.2 Response of the Sensor Integrated Wheel

A set of experiments was conducted to determine the response of the sensor-integrated wheel. Using an Instron universal testing machine, a precise cyclic radial load of 5 ± 2 lbs was applied to the wheel periphery at five locations 2 degrees apart in the vicinity of each sensor. The sensors were connected to a data acquisition system to acquire data in real-time.

Figure 3.1 shows the response of each sensor to the dynamic load. It is clear that there is some variation among the individual sensor responses. These variations can be attributed to such factors as the inherent sensor variability, voids in the epoxy adhesive, and variation in angular location of the loading member. Furthermore, it can be seen the sensor response is only about 10% of that observed for the individual sensors, which was expected. This is due to the added stiffness of the abrasive and epoxy layer placed above the sensor. The variation in sensor response will be taken in account during electronic calibration of the wheel prior to actual grinding.

3.3 Testing a Model System

In order to facilitate the development and implementation of data conditioning/processing routines and telemetry, a test system was fabricated. The test system consisted of a sensor embedded wheel, bread board level data acquisition and digital signal processor circuitry, and an RF transmitter/receiver. Data processing software with a graphical user interface was developed for data reception, processing, grinding feature extraction, and presentation. The digital signal processor (DSP) was programmed to acquire data when the wheel was excited by an impulse and to transmit the acquired data to an external receiver. This task was successfully accomplished and demonstrated.

The system was also used to test the reliability of data transfer by telemetry in the vicinity of the machine and in the presence of grinding sparks. The test system was placed approximately 6 feet from the grinding machine, while the receiver was positioned very close (within 3 inches) of the grinding zone. The DSP was programmed to transmit a pre-defined signal during grinding. The transmitted data was acquired by means of the RF receiver and displayed on an external computer. Figure 3.2 shows the results of this test. Although there is some noise in the data, the presence of grinding sparks does not appear to significantly affect the data transfer. It should be noted that the data was transmitted without any error checking/correcting code. Errors in data transmission can be minimized by implementing a simple error checking code, reducing the transmission distance, and re-transmission of data.

Publications

- S. Pathare, R. Gao, B. Varghese, C. Guo, and S. Malkin, "A DSP-based telemetric data acquisition system for in-process monitoring of grinding operation", *Proc. IEEE Instrumentation and Measurement Technology Conference (IMTC/98)*, pp. 191-196, St. Paul, MN, May 18-21, 1998.

Trips and Meetings

Robert Gao attended the 1998 IEEE Instrumentation and Measurement Technology Conference (IMTC/98) at St. Paul, Minnesota in May 1998 and presented a paper on DSP-based telemetric data acquisition system development for the current project (see Publications). In June 1998, he also attended a workshop on the frontiers of microfabrication sponsored by the Beckman Institute at the University of Illinois at Urbana-Champaign. This material covered in this workshop is directly applicable to the intelligent grinding wheel project.

Changsheng Guo, Biju Varghese and Sumukh Pathare visited Norton Company in April 1998 to discuss ways to bond the abrasive segments on to the wheel core. Biju Varghese visited Norton Company again in May in order to conduct static balance and spin testing on the sensor integrated grinding wheel.

Biju Varghese was selected to attend a workshop on "Team Building Skills" at the University of Michigan, Ann Arbor on June 15 and 16. The purpose of this workshop was to develop skills necessary for effective participation in interdisciplinary teams, such as the grinding wheel project. The registration fee and travel expenses for his participation in this workshop were covered by the University of Michigan.

Personnel

- Stephen Malkin, Sc.D., Distinguished Professor, Principal Investigator

  Overall project management, grinding test and analysis.

- Robert Gao, Ph.D., Assistant Professor, Co-Principal Investigator

  Design of miniaturized sensors, telemetry, and microelectronics; testing, and prototype demonstration.

- Changsheng Guo, Ph.D., Senior Research Fellow, Co-Principal Investigator

  Mechanical design, setup, testing and prototyping of grinding wheel.

- Biju Varghese, Graduate Research Assistant, Ph.D. Student

  Mechanical design, calibration, training and testing of the grinding wheel prototype

- Sumukh Pathare, Graduate Research Assistant, M.S. Student

  Sensor development, electronic circuits design, implementation, and testing

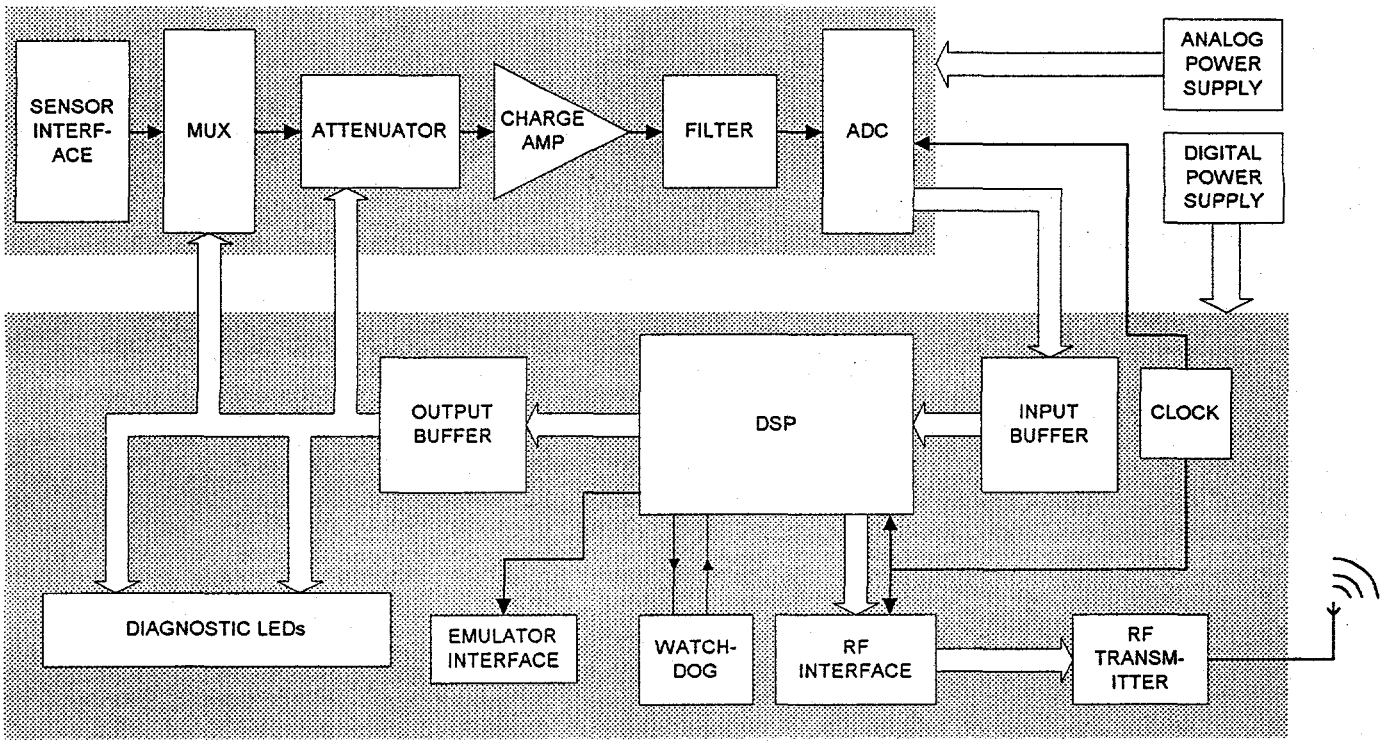

Figure 1.1 Block diagram of the miniaturized circuit

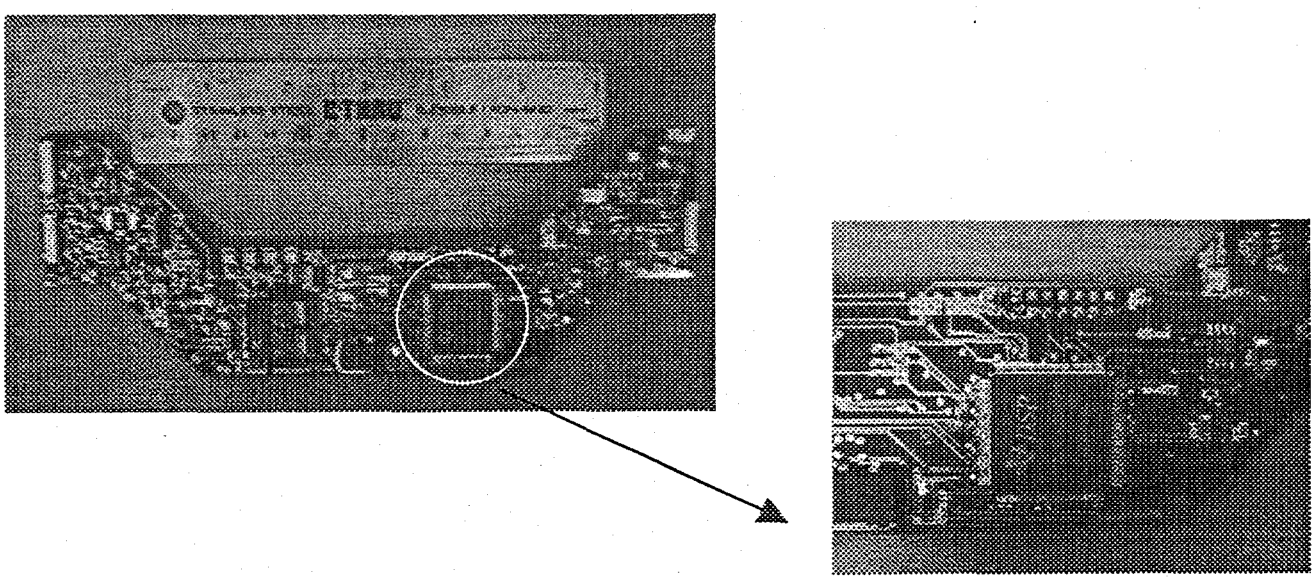

Figure 1.2 Photograph of the fabricated circuit

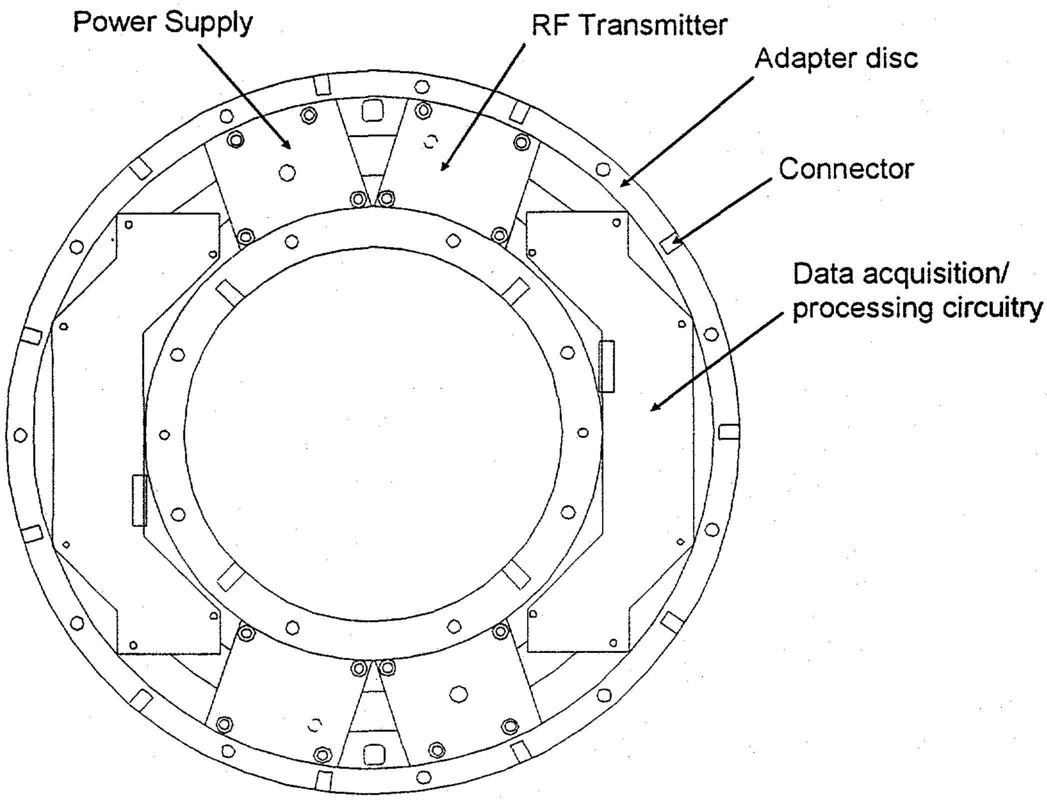

Figure 2.1 Adapter disk assembly

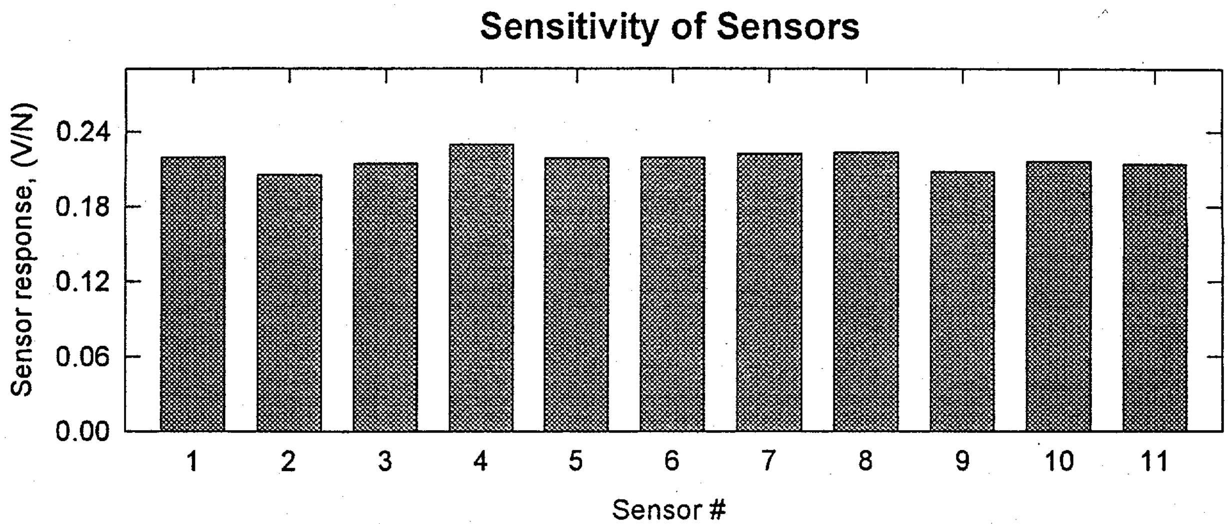

Figure 2.2 Response of individual sensors prior to their integration into the wheel core

(load : 5 ± 2 lbs at 5 Hz)

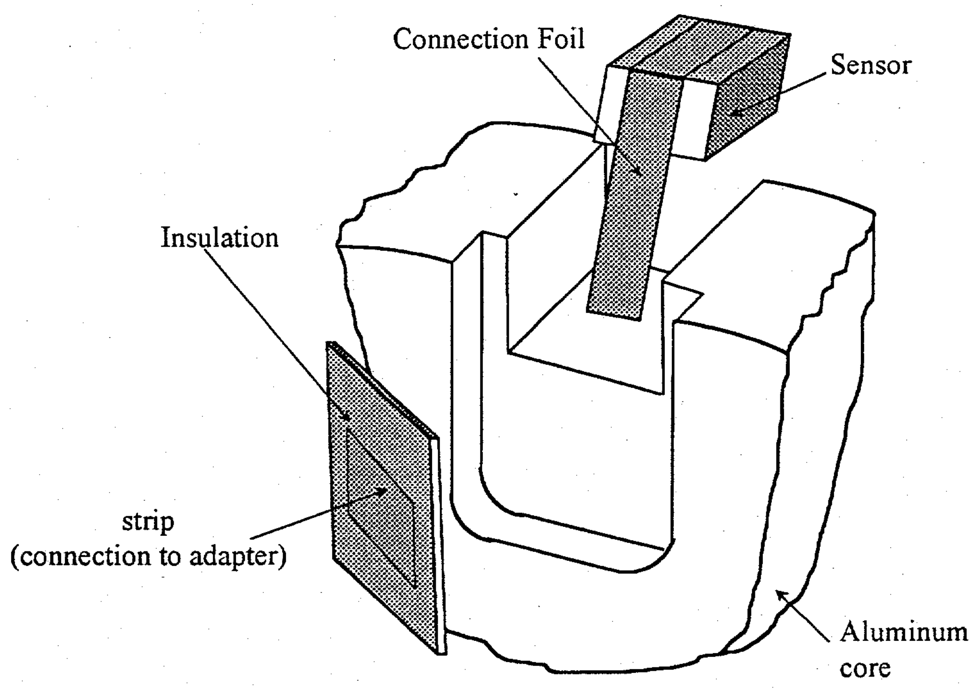

Figure 2.3 Arrangement for mounting sensors in slots around wheel core periphery.

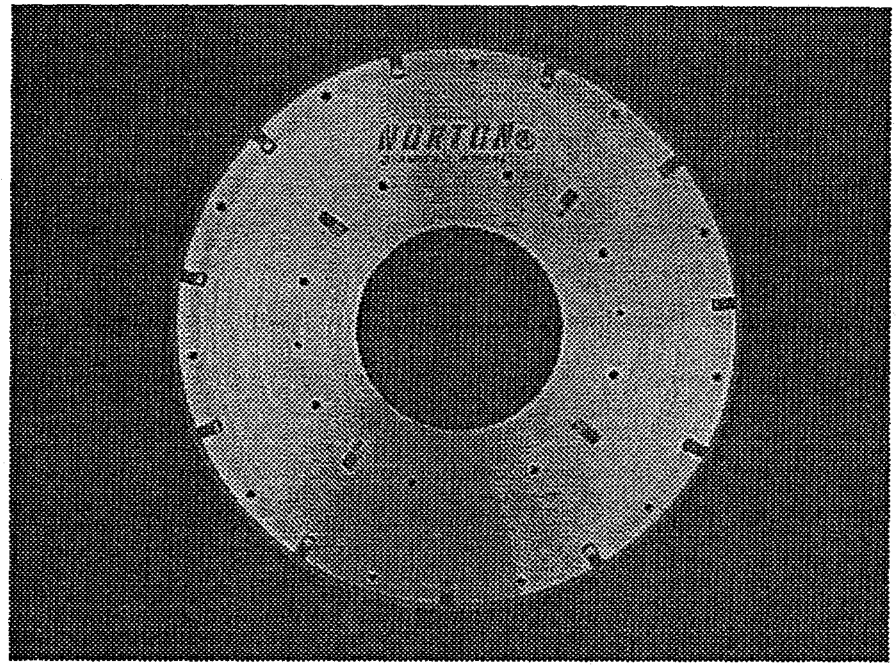

Figure 2.4 Photograph of grinding wheel

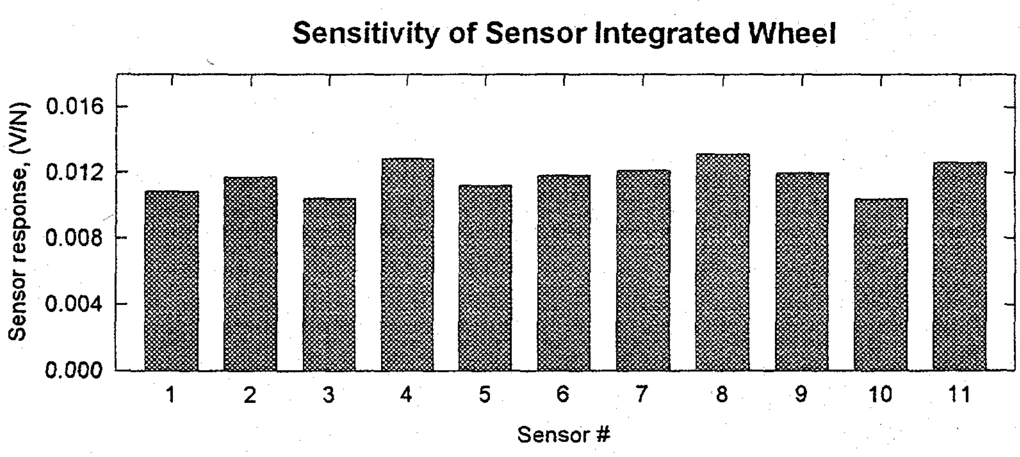

Figure 3.1 Response of sensor-integrated wheel
(load : 5 ± 2 lbs at 5 Hz)

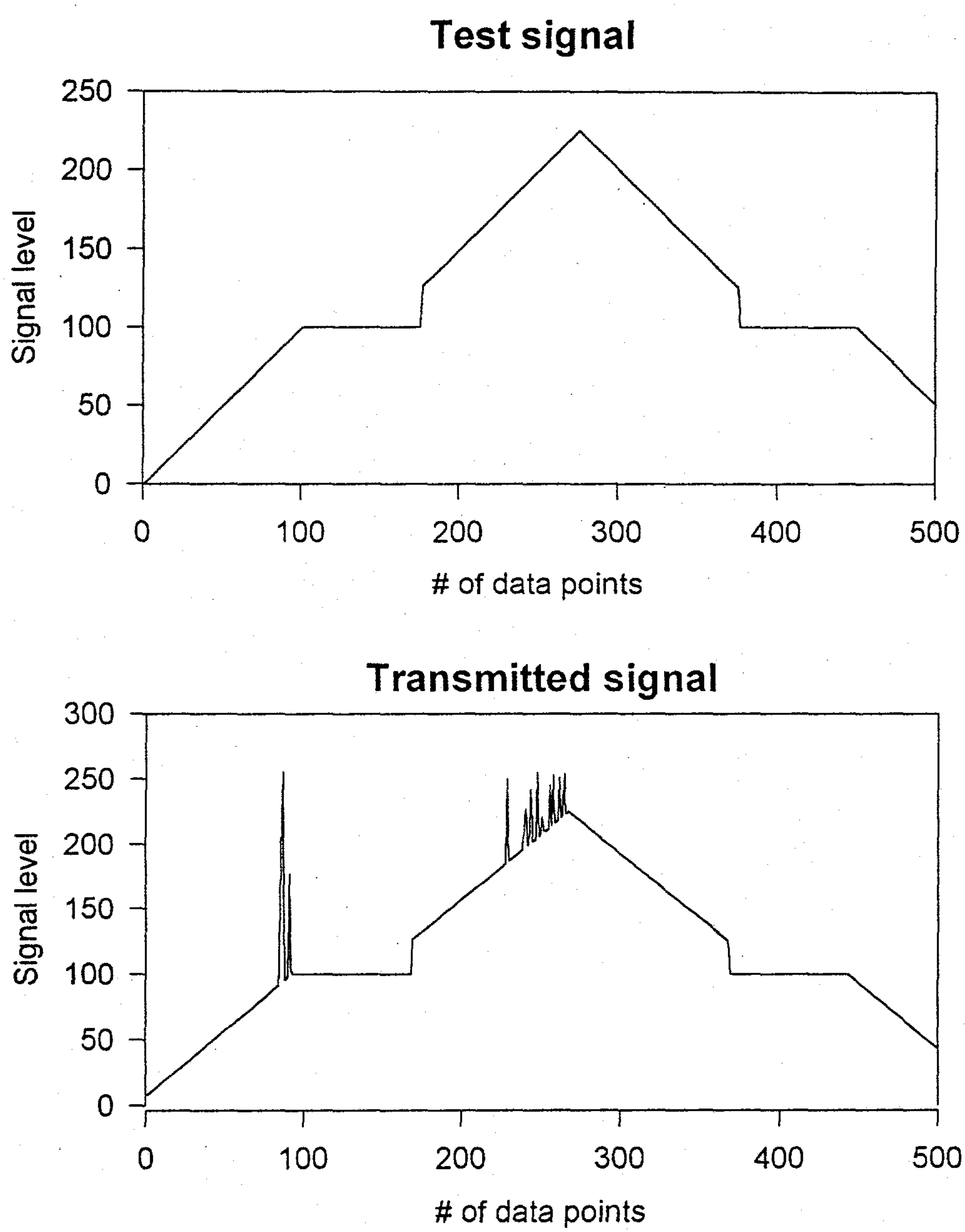

Figure 3.2 Results of telemetric data transfer test in the vicinity of the grinding process