

Semi-Annual Report #3

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

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## Introduction

This is the third 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 September 1, 1997 to February 28, 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 third 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 Sensors and Data Transmission System**

As stated in the previous semi-annual reports, a number of miniaturized piezoceramic sensors are being integrated into the "intelligent" grinding wheel core to measure force and acoustic emission (AE) for in-process monitoring of the wheel condition. Criteria taken into consideration for selecting the number and location of the sensors included the wheel geometry and its rotational speed, required measurement resolution, signal sampling and transmission rate, bandwidth required, complexity of the electronics, and space limitation for wheel integration. In addition, configuration of the bonded abrasive material on the wheel periphery also needed to be considered. The original wheel core design for force measurement included a total of sixteen sensors at the wheel periphery. However, the abrasive manufacturer (Norton Company) recommended that the abrasive on the grinding wheel be built up from twenty-two segments glued to the periphery. In order to maintain a symmetrical sensor arrangement, the number of abrasive segments should be a whole multiple of the number of force sensors. Therefore it was decided to use eleven piezoceramic sensors on the periphery of the wheel core for force measurement. For acoustic emission measurement, a minimum of three AE sensors are needed in order to pinpoint the circumferential location of the acoustic emission source at the wheel periphery by signal triangulation. In order to provide some system redundancy and

increased measurement accuracy, it was decided to use four AE sensors mounted on the face of the grinding wheel near its bore. Therefore, a total of fifteen sensors are used for both force and AE measurement.

The electronic circuit has been designed to handle inputs from all of the fifteen sensors in a time-multiplexed fashion. As shown in Fig. 1.1, the circuit consists of three functional blocks:

- An analog signal conditioner for sensor interface;
- An analog-to-digital signal converter (ADC) and a digital signal processor (DSP);
- An RF transmitter for telemetric data transmission.

This circuit was designed and initially implemented on breadboards. Based on the verification of its functionality, a circuit layout featuring both standard DIP (dual-in-line package) and SMD (surface mount device) components was developed for printed circuit board (PCB) implementation. The layout design was accomplished using a combination of manual and auto-routing techniques. The PCB was then fabricated by an external vendor, with the final size being approximately 4" x 5". Components were placed on the PCB by manual soldering under a special magnifier designed for SMD components handling.

This circuit board was then interfaced to a DSP evaluation kit, which contains a TMS320C542 Digital Signal Processor from Texas Instruments. The DSP kit was then connected to a PC by an emulator, which provides access to internal memory and registers of the DSP. This entire circuit was operated with a single J size 6-Volt battery 48 x 36 x 9

mm in size. The flat shape of the battery is particularly suitable for integration into the grinding wheel. The DSP was programmed to acquire the data from test signals fed to various sensor channels. Various data acquisition software was used to sample data from the ADC (Analog-to-Digital Converter). Multiplexing among the sensors was found to be successful. The analog signal conditioner and the DSP kit has exactly the same functionality required for data acquisition, except for a DSP-emulator connection which is needed for programming the DSP and data retrieval.

For the planned RF telemetric data transmission, tests were conducted independently by using signals with voltage levels compatible to those of the DSP serial port data output. Data was transmitted on the 900 MHz, FCC license-free ISM (Instrumentation, Science, and Medical) band. Various digital signal test patterns (ASCII strings) were transmitted and received without any error over a distance of about 8 meters at a rate of 9,600 bits per second.

Upon successful testing of each of the electronic functional blocks, the entire circuit will be mounted, together with a battery, on an "L" shaped bracket and attached to the face of a grinding wheel. A photograph of the assembled electronic circuit is shown in Fig. 1.2. The wheel-integrated electronics will be tested with the grinding wheel rotating first at relatively low speeds. The DSP will transfer the acquired data through its serial port to the RF transmitter, which then transmits the data wirelessly to the external receiver.

Each sensor being integrated into the wheel was calibrated by applying loads on an Instron

testing machine and measuring the output using a Kistler charge amplifier. The calibration information, along with the wheel rotating speeds, will provide realistic data on the required functionality for the final circuitry. Based on this information, the functional blocks of the circuit will be modified and miniaturized to fit on a PCB 2.5" x 3.5" in size. The RF transmitter will be fabricated separately on a PCB of 1.5" x 1". The RF transmitter will be physically isolated from the sensitive analog electronics to ensure that the signals from the sensors are not corrupted by EMI (Electromagnetic Interference). The circuit boards will also be individually shielded by aluminum foil to protect them from external EMI.

During grinding as the wheel-workpiece contact sweeps past an embedded force sensor, an impulse output signal is generated which is proportional to the force acting on the grinding wheel. For a sensor of width  $w$  and peripheral wheel velocity  $v_s$ , the time duration of the impulse is approximately  $T = w/v_s$ . For example, a wheel velocity of 60 m/s and sensor width of 3 mm would give  $T = 50$  ms. This corresponds to a signal frequency centered at 20 kHz. The force sensors also respond to AE signals having a larger bandwidth. To derive the force component from the recorded signals, it is necessary to implement a bandpass filter centered at the frequency of the force component, e.g., 20 kHz. The filtering operation will be conducted by the DSP. The block diagram of the signal processing to derive the force signal is shown in Fig. 1.3. Implementation of the bandpass filter requires accurate information of the wheel speed in order to calculate the pulse width  $T$  of the force signal. Once the pulse width is known, the bandpass filter parameters can be fixed to derive the force value.

## Task 2. Design of Grinding Wheel and Adapter Plate

Structural modification of the wheel core was necessary in order to accommodate the fifteen force and acoustic emission sensors. Space also was needed for the data processing and transmission electronics. For this purpose a special adapter plate was designed. This section describes the design of the grinding wheel and the adapter plate.

The wheel core design and sensor locations are shown in Figure 2.1. In order to utilize standard abrasive segments provided by Norton Company, the design of the wheel core was changed to include twenty-two abrasive segments on the periphery of the aluminum wheel core. This resulted in an effective wheel diameter of 14 inches. Based on results from the static tests (see previous report) and in order to maintain a symmetrical arrangement with the abrasive segments, it was decided to use eleven force sensors equally spaced 32.76 degrees apart around the wheel periphery. The sensors were placed sufficiently far away from the joints between the abrasive segments, and cemented into eleven slots machined on the periphery of the wheel core. In addition to these force sensors, four acoustic emission sensors were symmetrically placed around the wheel closer to the bore, as described under Task 1.

In order to minimize structural modifications to the wheel core and facilitate access and maintenance of the electronic circuitry, it was decided to mount the electronic circuitry, the leads, the RF transmitter, and the power supply on an adapter plate attached to the face of the wheel as shown in Figure 2.2. A similar "dummy" plate will also be fastened to

the opposite wheel face in order to maintain symmetry and balance. This modular (re-configurable) design also provides flexibility enabling use of the same adapter plate with other sensor-embedded wheels differing somewhat in size and abrasive content. It furthers allows easy maintenance of the electronic circuitry/components and programming of the DSP without dismounting the wheel from the machine spindle. The wheel may be used for regular production while electronic maintenance is being undertaken.

An annular recess in the adapter plate will be used to house the electronics required for signal conditioning, processing, and transmission. The electronics will be anchored to the adapter plate by means of screws. A cover (gasket) will be sandwiched between the adapter plate and the wheel to protect the electronics from environmental disturbances such as grinding fluids. Two dowel pins embedded in the wheel core will be used to precisely locate the adapter plate with respect to the wheel core. The adapter plate will be fastened to the wheel by screws. Furthermore, the outer face of the adapter plate will be shielded from outside electrical noise by means of aluminum guards (shields). Connector terminals are provided on the adapter plate for every sensor. These connectors will be secured to the leads by bolts to provide good electric contact. The leads from the connectors will be laid out in the shallow grooves at the bottom face of the annular recess running directly under the electronic circuitry. Finally the electronic circuitry will be sealed to insulate it from grinding debris that may seep in during grinding.

Both the wheel core and the adapter plate have been manufactured. Abrasive segments will be bonded on to the wheel core during the first week of April. The final electronic

circuitry is expected to be ready by May. Afterwards preliminary tests will be conducted with the wheel rotating at slow speeds. The wheel, together with the associated electronics, will be mounted on the spindle of the grinding machine. The performance of the ADC, signal processing and telemetry equipment will be evaluated by rotating the wheel against a friction plate (or roll). The results of this test will help to establish a basis for miniaturization of the various electronic circuits.

### **Publications**

- Sumukh Pathare, Robert Gao, Biju Varghese, Changsheng Guo, and Stephen Malkin, "A DSP-Based Telemetric Data Acquisition System for In-Process Monitoring of Grinding Operation," accepted for publication in *Proc. 1998 IEEE Instrumentation and Measurement Technology Conference (IMTC/98)*, St. Paul, Minnesota, May 18-21, 1998.

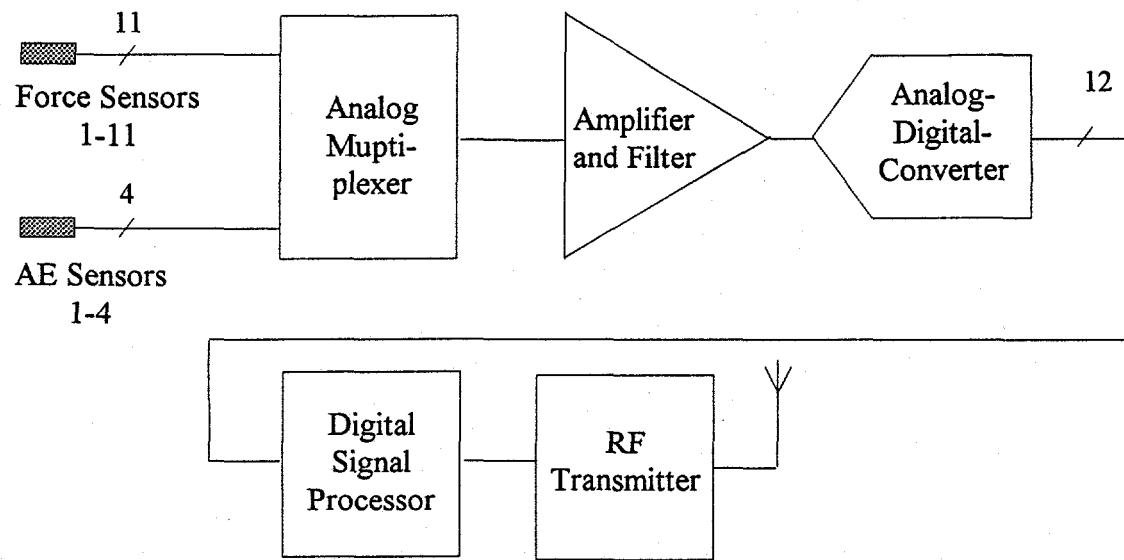
### **Trips and Meetings**

None to report during this period.

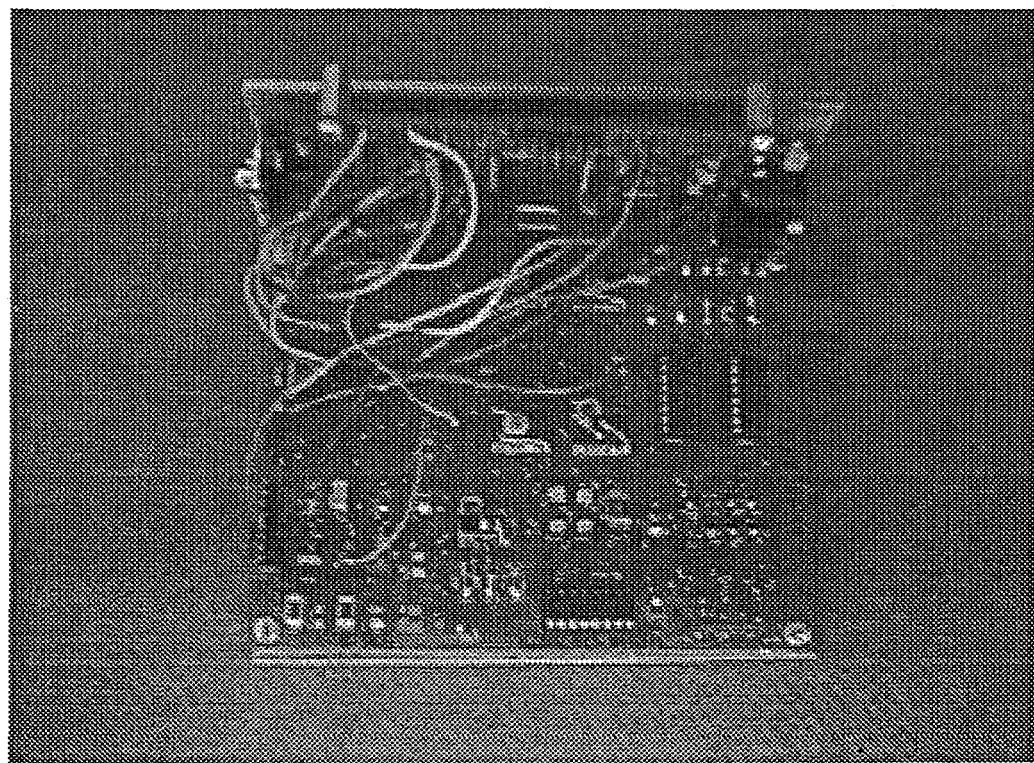
### **Personnel**

- 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.

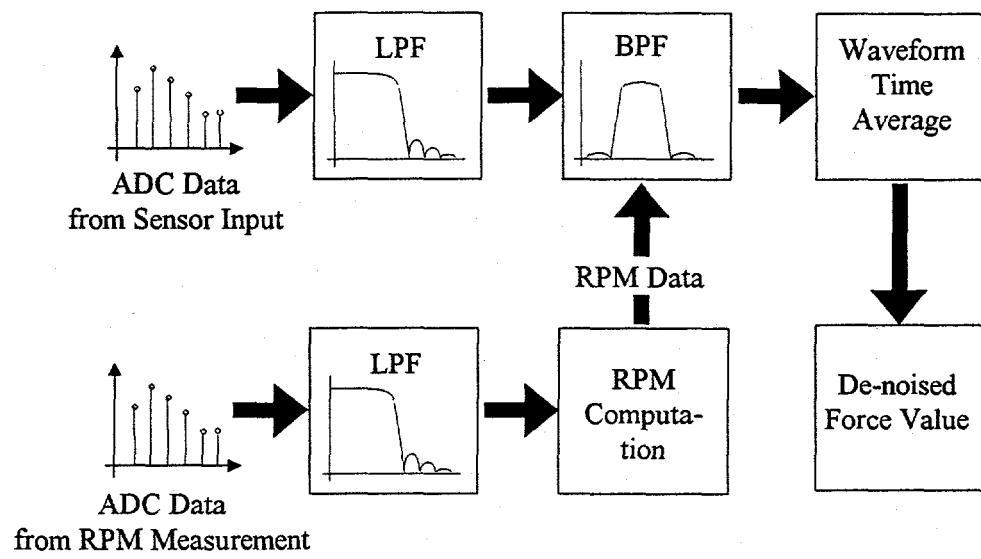
- Changsheng Guo, Ph.D., Senior Research Fellow, Co-Principal Investigator  
Mechanical design, setup, testing and prototyping of grinding wheel.
- Biju Varghese, Graduate Research Assistant, Ph.D. Student  
Mechanical design, calibration, training and testing of the grinding wheel prototype
- Sumukh Pathare, Graduate Research Assistant, M.S. Student  
Sensor development, electronic circuits design, implementation, and testing



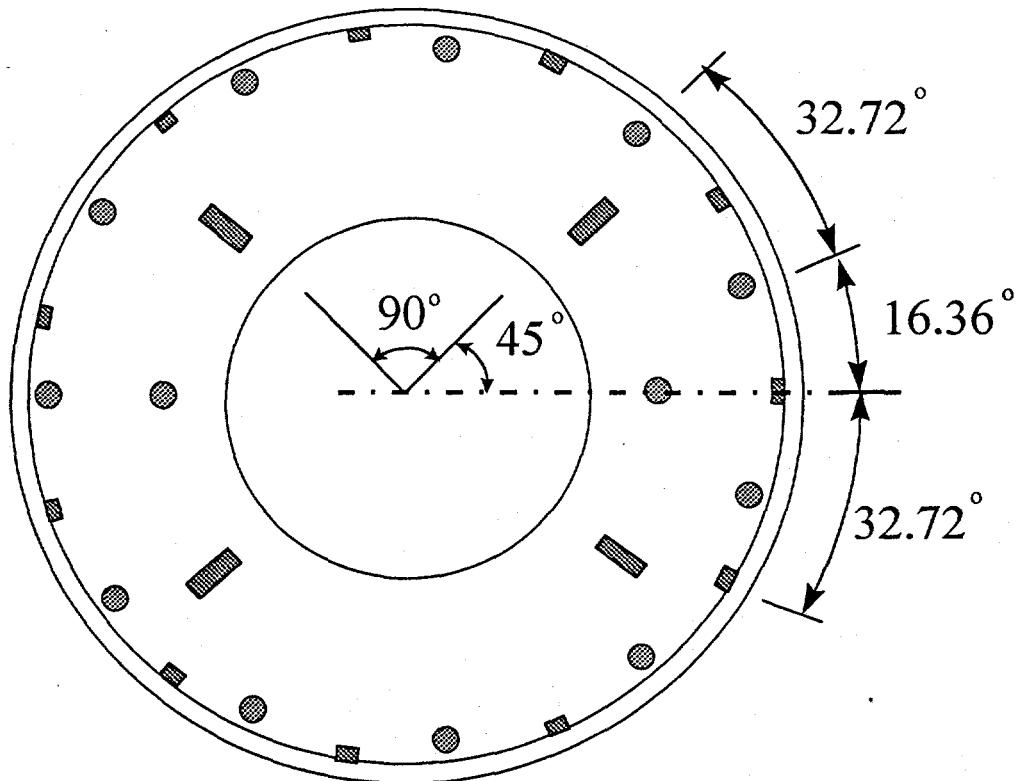
**Figure 1.1. Block diagram of the wheel-integrated sensors and electronics**



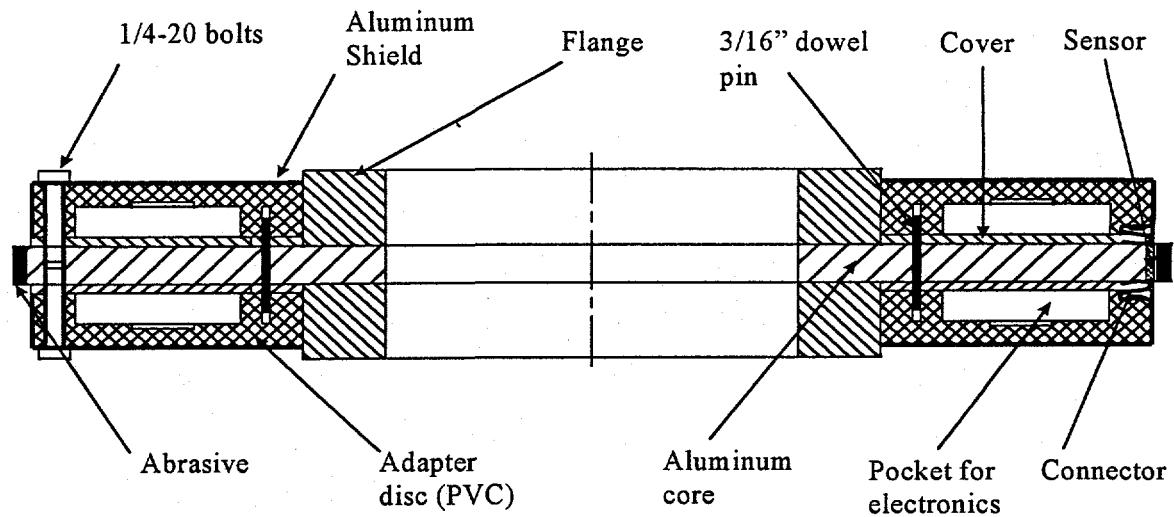
**Figure. 1.2. Photograph of the wheel electronics**



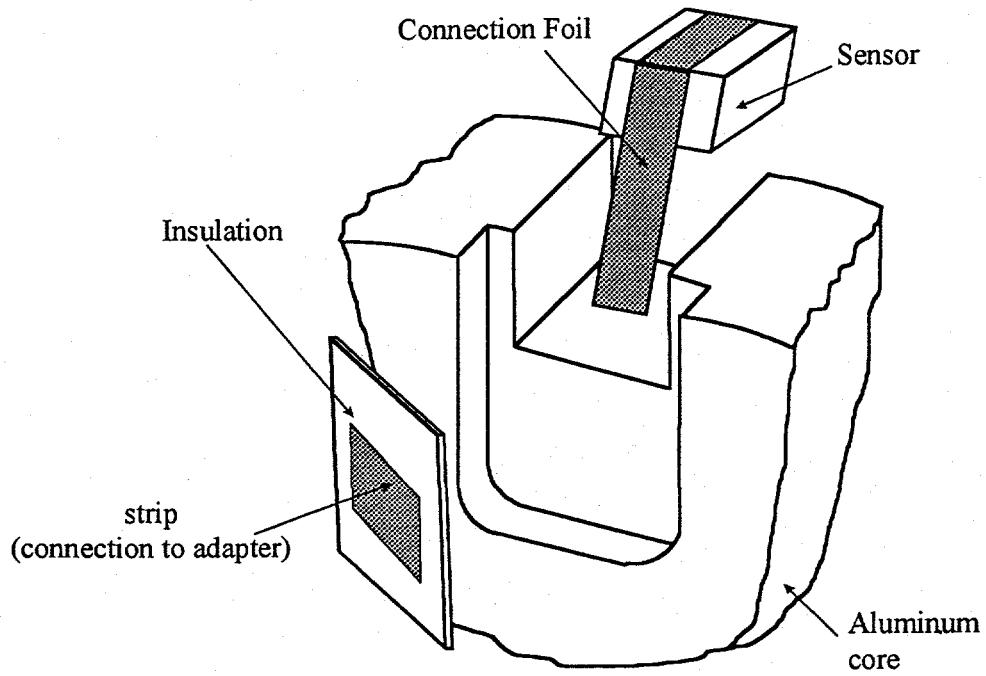
**Figure. 1.3. Filtering of force signals**



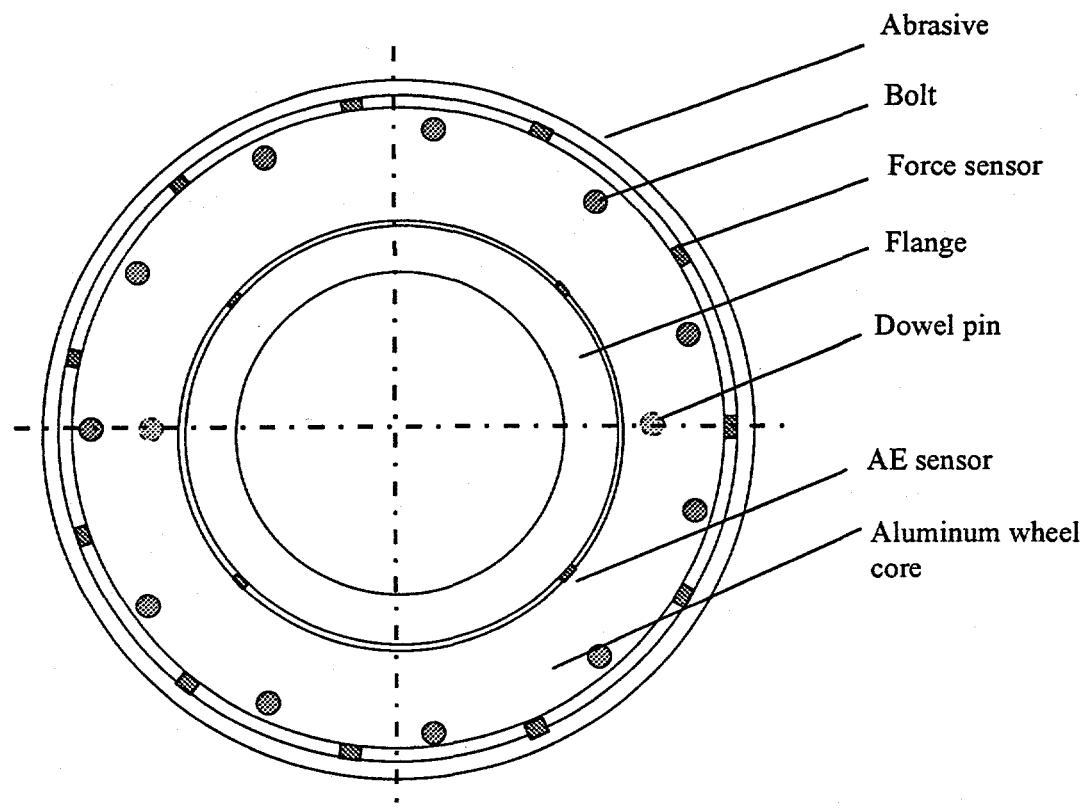
**Figure. 2.1. Sensor arrangement in wheel core**



**Figure. 2.2. Cross sectional view of the wheel core assembly**



**Figure. 2.3. Connection of the sensors to the wheel core**



**Figure. 2.4. Cross sectional view of the wheel assembly**