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Semi-Annual Report #2

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

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Introduction

This is the second 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, 1997 to August 31, 1997.

The overall objective of this project is to develop sensor-integrated "intelligent" diamond wheels for grinding 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 two types of sensors : acoustic emission (AE) and dynamic force transducers. Signals from the sensors will be transmitted from a rotating wheel to a receiver by telemetry. Intelligent 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 :

- Development of miniaturized sensors and data transmission system
- Wheel design and sensor configuration
- Calibration of the sensor integrated wheel
- Training of the intelligent wheel
- Grinding tests
- Prototype demonstration.

The technical progress is summarized in this report according to the tasks. All the activity during this second 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 first semi-annual report, the "intelligent" grinding wheel will utilize a multiple number of miniaturized piezoceramic sensors that are placed in slots on the wheel core periphery to monitor the wheel condition during its operation. Based on preliminary analysis on the wheel operating parameters, as well as the signal sampling and transmission rate and bandwidth required, a total of sixteen piezoceramic sensors will be integrated into the wheel. The output from these sensors will be connected to an analog multiplexer and then fed to a data acquisition system consisting of a charge amplifier, an anti-aliasing filter, an analog-to-digital converter (ADC), a digital signal processor (DSP), and a RF signal transmission module. A block diagram illustrating the data acquisition system is shown in Figure 1.1. The electronic components of the system will be housed in one or several enclosures which are then integrated into an adapter disc, as described under Task 2.

The communication between the data acquisition system integrated on the wheel and a remote data processing system implemented in a PC is by radio frequency. The data sampled from various sensors is compressed and transmitted in digital form. Digital signal transmission is preferred over analog transmission because of several reasons. First of all, digital systems make more efficient use of the bandwidth, since the RF bandwidth for signal transmission has little relation with that of the base band. This is not true with analog system where the RF bandwidth is dictated by the base band frequencies of the signal. Secondly, due to the better error correction mechanism, digital signal transmission allows for optimum utilization of transmission power, making low power transmission possible. Thirdly, digital data transmission allows for easy time multiplexing to accommodate input signals from multiple sensors. Last but not least, digital signal transmission makes it possible to use multiple transmitters and receivers within the same frequency band by means of TDMA (Time Division Multiple Access) without introducing much complexity in the transmitter/receiver hardware.

The frequency band used is the 902 - 928 MHz ISM band for which an FCC license is not required. The data acquisition system will gather data from the sixteen wheel integrated sensors and transmit them on the same frequency band. The bandwidth allocated to each sensor output is 1MHz to accommodate a wide range of dynamic signals due to wheel-workpiece interaction. Accordingly, it would require a total bandwidth of at least 16 MHz with as many carrier frequencies to transmit these signals by analog transmission, which is impractical due to the high circuit complexity.

To separate useful, high-frequency (HF) signals generated during grinding operations from the relatively low-frequency (LF) background noise and to relate them to the specific condition of the abrasive material as well as the grinding processes, the spectral characteristics of the signals need to be analyzed carefully, in addition to their time domain behavior. This can be achieved by taking the wavelet transforms of the signals. Wavelets transforms preserve both the frequency and time domain information of a signal, and allow for simultaneous extraction of HF and LF signals with different frequency resolutions which is not possible with a conventional FFT (Fast Fourier Transformation).

Considering the computation-intensive nature of algorithms involving wavelet transforms or FFT, it was decided to use a Digital Signal Processor (DSP) instead of a microcontroller for the signal analysis. The RISC-based architecture (Reduced Instruction Set Computer) of DSPs enables very time effective computation of large amount of numbers, which is ideal for high speed, multi-sensor applications as required in this project. Typically, DSPs have multiple internal data buses and DARAM (dual access RAM) which enable simultaneous addition and multiplication operations. These features are not present in a microcontroller which is generally designed for conventional applications requiring low to medium speed data acquisition, instead of intensive numerical calculation. As an example, DSPs can accomplish operations of up to 50 MIPS (Million instructions per second), while achieving a performance of 10 MIPS from a microcontroller is difficult.

To speed up the circuit development process, an DSP evaluation board with a sixteen-bit, fixed-point digital signal processor (TMS320C542 from Texas Instruments) was selected. The input to the DSP board is being provided by an Analog-to-Digital Conversion circuitry (ADC) which was designed and implemented using commercially available ICs. This particular DSP was chosen due to its large on-chip RAM (32 kBytes), low supply voltage requirement (3 V), multiple on-chip serial ports (3 ports), high speed calculation capability (100 MIPs), and a small package size, as compared to that of floating-point DSPs. Figure 1.2 shows the schematic diagram of the ADC circuit board and its connection to the rest of the measurement electronics. A detailed circuit diagram of the electronics is shown in Figure 1.3.

The ADC board contains two precision analog multiplexers, each of which can handle eight analog inputs from eight piezoceramic sensors simultaneously. All the electronic components selected for the signal conditioning system feature low power dissipation and can be battery operated.

To prevent the signal conditioning electronics from being damaged by high voltages from the piezoceramic sensors, a diode protective circuitry was added to each of the inputs of the multiplexer. These diodes from Motorola feature high speed and low reverse leakage current which is required for protective applications. In addition, their low parasitic capacitance helps preserve the signal quality.

The ADC has a resolution of 12 bits and can sample signals at 3 Mega samples per seconds. The sampling rate was chosen to meet the Nyquist criterion for sampling signals with a bandwidth of 1 MHz. The output of the ADC is connected to the DSP board by means of a flat ribbon connector (FRC).

The DSP was programmed in C language to access the ADC output and display the read data on a PC screen. Its connection to the PC was established via an emulator. The DSP is being programmed to compress incoming data from the sensors and to transmit them further to the PC by an RF transmitter circuitry. The protocol for RF data transmission is being developed using two RF transmitter kits from the RF Monolithics Inc. The data communication rate between the DSP and the PC is 4800 bps (bit per second).

Task 2 Wheel Design and Sensor Configuration

As described in the previous report, a set of experiments was planned to evaluate the feasibility of using piezoceramic sensors for the wheel integration. This section describes the experimental set-up and the results obtained from the experiments.

2.1 Experimental Set-up

As shown in Figure 2.1, five identical piezoceramic chips were placed in slots on the wheel core periphery within one quadrant of an aluminum disk. The periphery of the disc was covered then with a two-component epoxy (Araldite AV1258 with hardener HV1258) to simulate the structural characteristics of the bonded abrasive rim and to protect the sensors. Electronic circuitry for amplification and filtering of the sensor output was enclosed in a box which is then mounted onto the side of the aluminum disc. An Instron testing machine was used to precisely apply a cyclic load (normal) to the sensors. An Analog-to-Digital Converter Board (ADC) type DT2821 was connected to the sensor conditioning electronics to convert the analog sensor outputs to digital data bits which were then processed in a PC.

2.2 Experimental Results

The first set of the experiments was intended to determine the response of the sensors to applied loads at various angular positions. A static load of 442.9 N was first applied to the sensors to simulate a preload that will be applied to the sensors. Then, a dynamic (sinusoidal) load with a peak-to-peak variation of $\pm$100.7 N was applied and the response of the sensors was recorded. A typical example of the output obtained from the sensors is shown in Figure 2.2. It is evident that the sensor output closely follows the variation in the applied load. For data analysis and comparison, the response of the sensors at the peak load is used. As illustrated in Figure 2.3, the response was at its maximum when a load was applied directly where the sensor is located (mean sensor location with load application angle $\theta = 0$ degree). The magnitude of the sensor response decreased steeply as the applied load was moved away from the sensor. Virtually no appreciable response was obtained when the load was moved more than 5 degrees away from the mean sensor location.

Since the sensors are placed 22.5 degrees apart from each other, the above results imply that a signal obtained from a certain sensor will be the result of load application in the vicinity of that sensor only. To verify this conclusion, the same tests were repeated for all the five sensors at a lower load (static load 220.5 N, peak to peak variation = $\pm$ 26.5 N). The results are summarized in Figure 2.4. It can be seen that the output from all the sensors followed a similar trend with a similar region of response. However, the amplitude level of the sensor output varied from sensor to sensor, even though the load applied was the same. In Figure 2.5, the maximum response of the five sensors to a load applied to their respective mean position is shown. The difference observed in the sensor response can be possibly traced back to the presence of voids and variation in the thickness of the epoxy that covers the sensors, to the variations in the exact location of the loads applied, to differences in the sensor sensitivity, and to the variation in gains of individual preamplifiers used for each sensor.

To ensure correct measurement and data analysis, output from different sensors to the same load must remain the same. In order to compensate for the imperfections in the measurement system as discussed above, calibration of the system is needed before each system run. This can be done by applying a known load to each sensor and adjust the individual output electronically until the same output is obtained. To minimize the influence of amplifier gain variations on the signal, a single preamplifier will be used which is connected to each individual sensors by means of multiplexing. The calibrated output will then serve as a reference for further signal processing. Furthermore, it is planned to use segmented abrasives that will be bonded to the wheel core for sensor coverage. Compared to the epoxy used for the preliminary experiments, this will greatly reduce the presence of voids. It is also planned to evaluate/record the sensitivity of each piezoelectric chip before mounting it onto the wheel core.

A second set of experiments was conducted using the same setup to obtain the relationship between the response of the sensors and the applied load. For this purpose, a static load of 442.9 N was first applied to a sensor (e.g., sensor # 3) at its mean location, and the response of this sensor to the peak value of a 5 Hz sinusoidal load that varied between 1 and 22 lb was recorded. Figure 2.6 shows that the sensor output increases linearly with the applied load, which represents an ideal behavior. With this performance characteristic, the actual value of the load applied to the wheel during grinding operations can be readily calculated from the output voltage of the sensors.

The next step will involve testing the wheel and sensor configuration during actual rotation. The wheel and the associated electronics will be mounted on the spindle of a grinding machine. The performance of the ADC, signal processing, and telemetry electronics will be evaluated by rotating this disk against a friction plate (or roll). The results of this test will help establish a basis for miniaturization of the electronic circuits. This test will be followed by preliminary tests to evaluate an algorithm to detect the wheel out-of-roundness, which is described in the next section.

2.3 A Strategy for Detecting Wheel Out-of-Roundness

Results from the experiments described so far indicate that it is not feasible to detect a load applied to any arbitrary angular position on the grinding wheel with only a small number of discrete sensors. A load applied between two adjacent sensors may not be accurately identified, due to the localizing effect of the sensors. While this represents a limitation in the system "resolution", it is advantageous to help pinpoint the loading condition of a specific location on the wheel. To increase the "resolution" of the wheel-integrated measurement system, the number of sensors can be increased, e.g. from 16 to 64, to reduce the size of the non-reacting region on the wheel periphery. However, such an approach not only increases the system's cost, but also introduce complexity in signal conditioning, processing and transmission.

Therefore, it is proposed to use the present sensor configuration (16 sensors mounted on the wheel periphery) and develop a software algorithm to help enhance the resolution. As a step towards this goal, a strategy has been developed to detect out-of-roundness of the wheel. The details of this proposed method are illustrated in the flowchart shown in Figure 2.7. With this method the output from a randomly selected sensor will be tracked until it passes through the grinding zone. Data will then be collected from all the remaining 15 sensors within a few rotations of the wheel. Thereafter data will be continuously collected and analyzed. At the start of the truing process only a portion of the wheel periphery (abrasive) will contact the truing device if the wheel is not round. Therefore, variations of sensor outputs can be observed, which depend on the extent of the wheel's out-of-roundness and the eccentricity in the wheel installation. The output from the 16 sensors will constitute a pattern of signal variation. As the wheel truing process proceeds, the wheel progressively becomes round, and the signal levels will tend to equalize, leading to a stable signal pattern.

The wheel can be considered to be round and ready for use in grinding when the variation in the signal pattern is within a specified limit. The signal pattern from the first few rotations during grinding will be stored. The signal output at this point represents the force pattern from a sharp wheel, which form the basis for comparison with the force and AE signals obtained during subsequent grinding operations. An increase in the force levels during grinding will indicate a progressive dulling of the wheel.

It is also proposed to house the electronic circuitry, leads, the RF transmitter and the power supply on an adapter disc, which will be fastened to the side of the wheel as shown in Figure 2.8. A dummy disc with identical mass distribution will then be fastened to the other side of the wheel to maintain wheel symmetry and balance. The use of an adapter disc will result in minimal structural modification of the wheel core, and facilitate easy access as well as maintenance of the integrated electronic circuitry. This modular or reconfigurable design also provides the flexibility of using the same measurement electronics for a variety of wheels of different abrasive thickness and width, thus greatly expanding the scope of applications. It further makes it possible to modify/update the electronics for measuring other wheel-related parameters, without dismounting the entire wheel from the machine spindle. The wheel may be used for conventional grinding operation, while the electronics are being modified.

The leads from the sensors will be laid out in the shallow grooves on the inner face of the adapter disc, as shown in Figure 2.8. They will be connected to the sensors, which are mounted in the wheel, by means of quick change connectors. The details of realizing the quick change connectors are being explored. The entire measurement electronics, including the DSP and the RF transmitter will be embedded into the adapter disc. The antenna for telemetric signal transmission will be laid out on the outer face of the adapter disc. The adapter disc will be fastened onto the sensor-integrated wheel by means of connecting bolts and nuts.

Publications

None to date.

Trips and Meetings

Robert Gao attended a symposium in June in Austin, TX, organized by Motorola, on microsensors and sensing solutions to system integration. He also attended a workshop in July on packaging for microelectronic devices at the San Jose State University. The purpose of these trips was to be investigate solutions to various technical issues related to the grinding wheel sensor integration.

Changsheng Guo and Biju Varghese visited Norton Company in Worster, MA on August 25, 1997 for technical discussions regarding preparing abrasive rim for the intelligent wheel.

Four representatives from Norton Company visited University of Massachusetts at Amherst for further discussion regarding bonded abrasive rim for the intelligent wheel.

Personnel

- Stephen Malkin, Sc.D., 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.

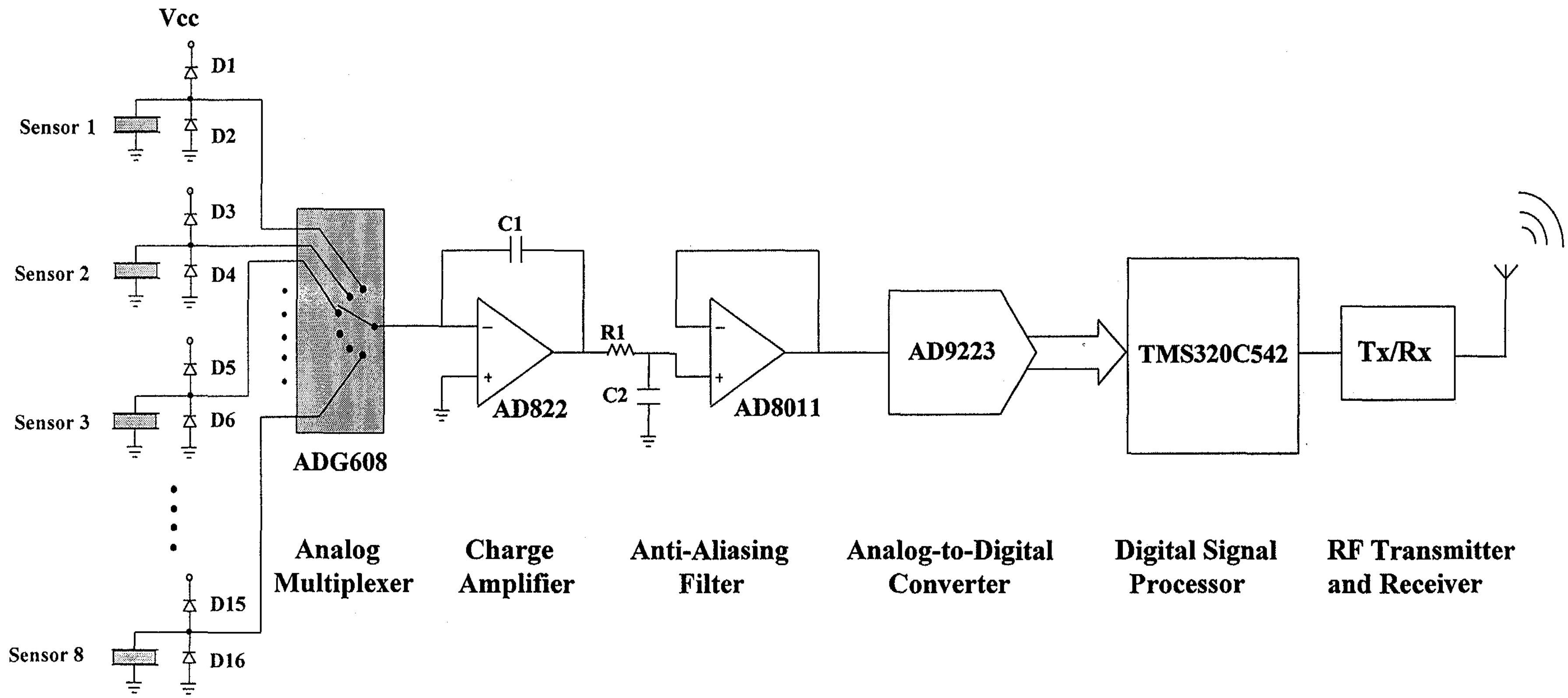


Fig. 1.1 Block diagram of the data acquisition system

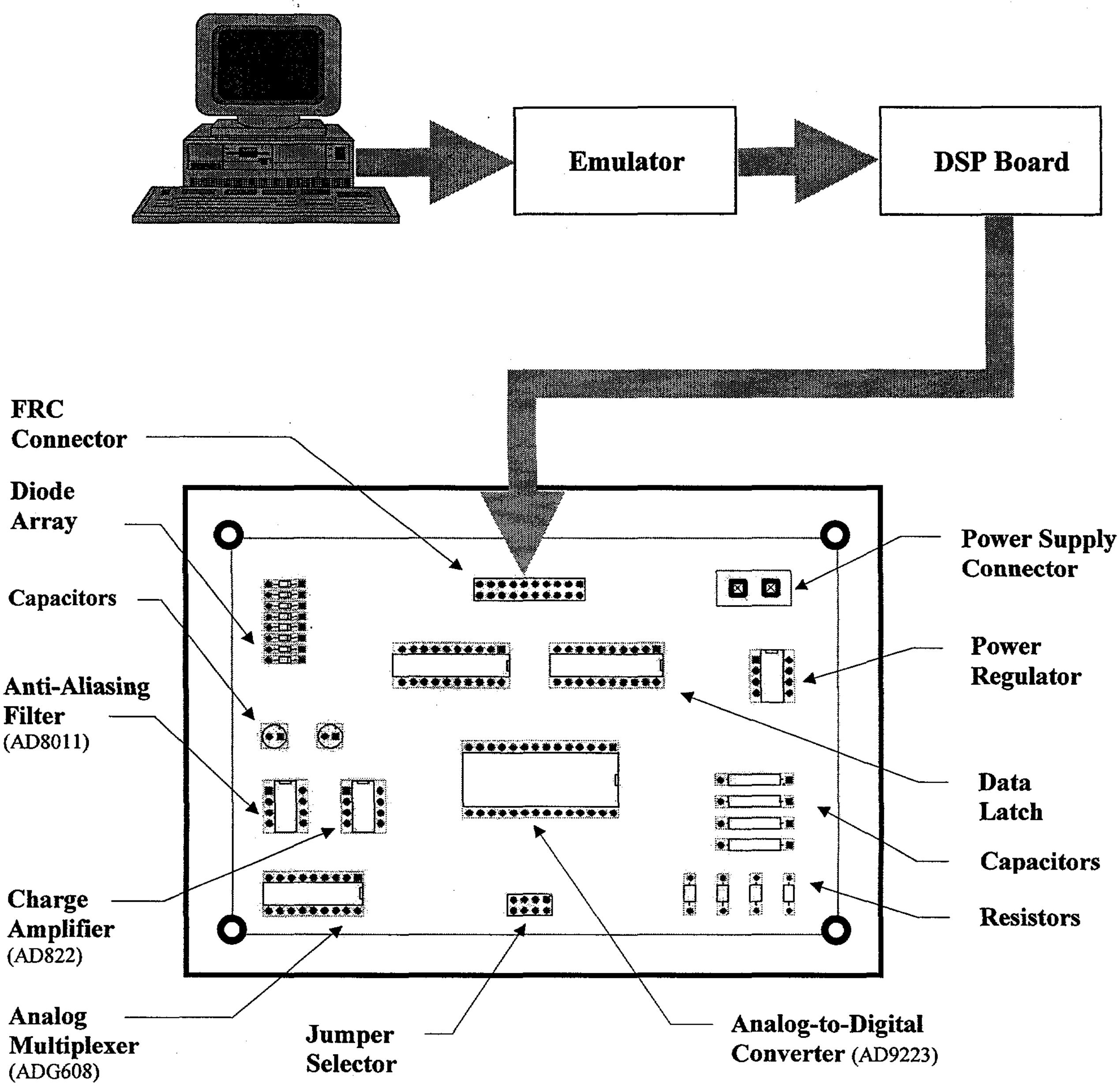


Fig. 1.2 Schematic diagram of the ADC circuit board

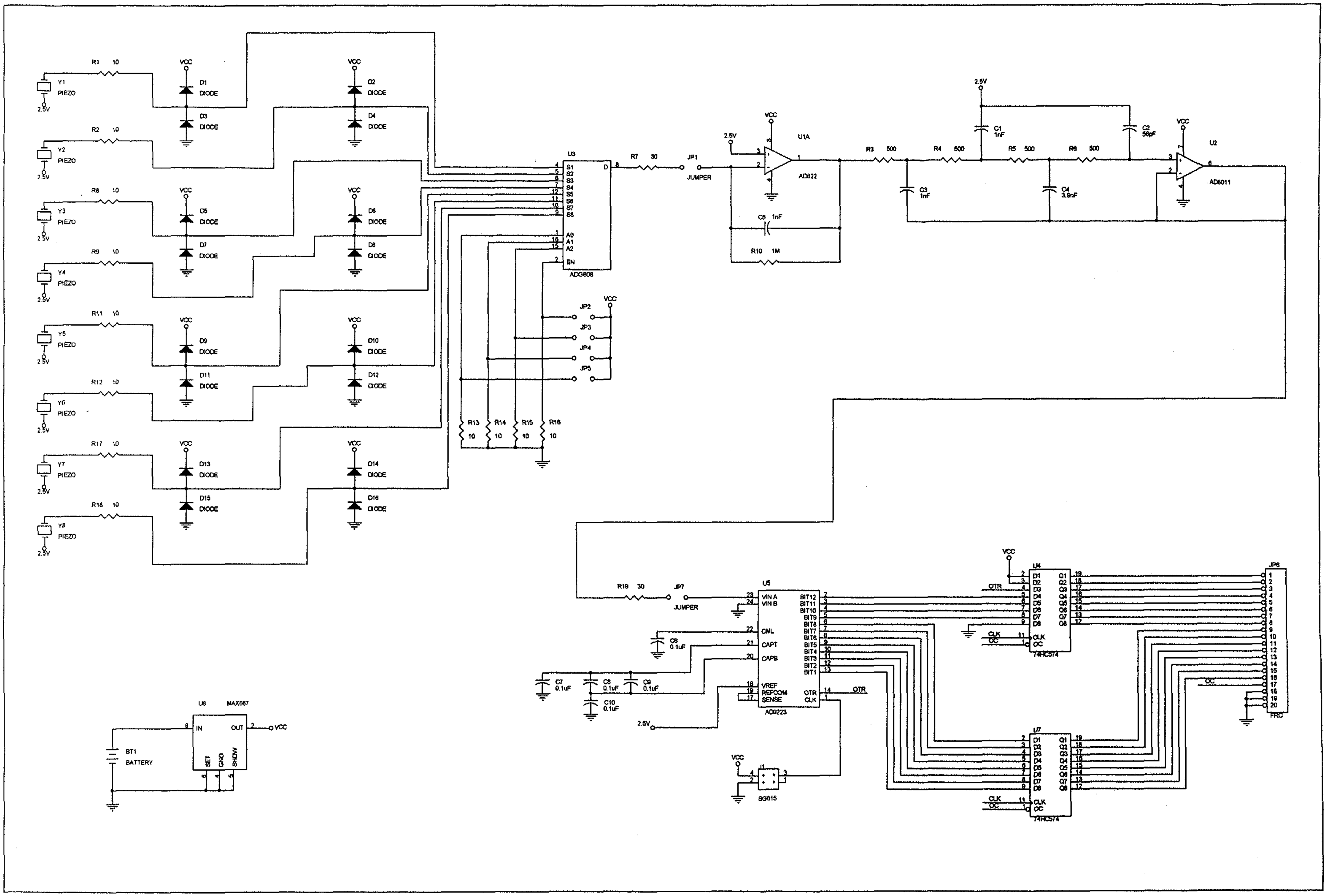


Figure 1.3 Circuit diagram of the signal conditioning electronics

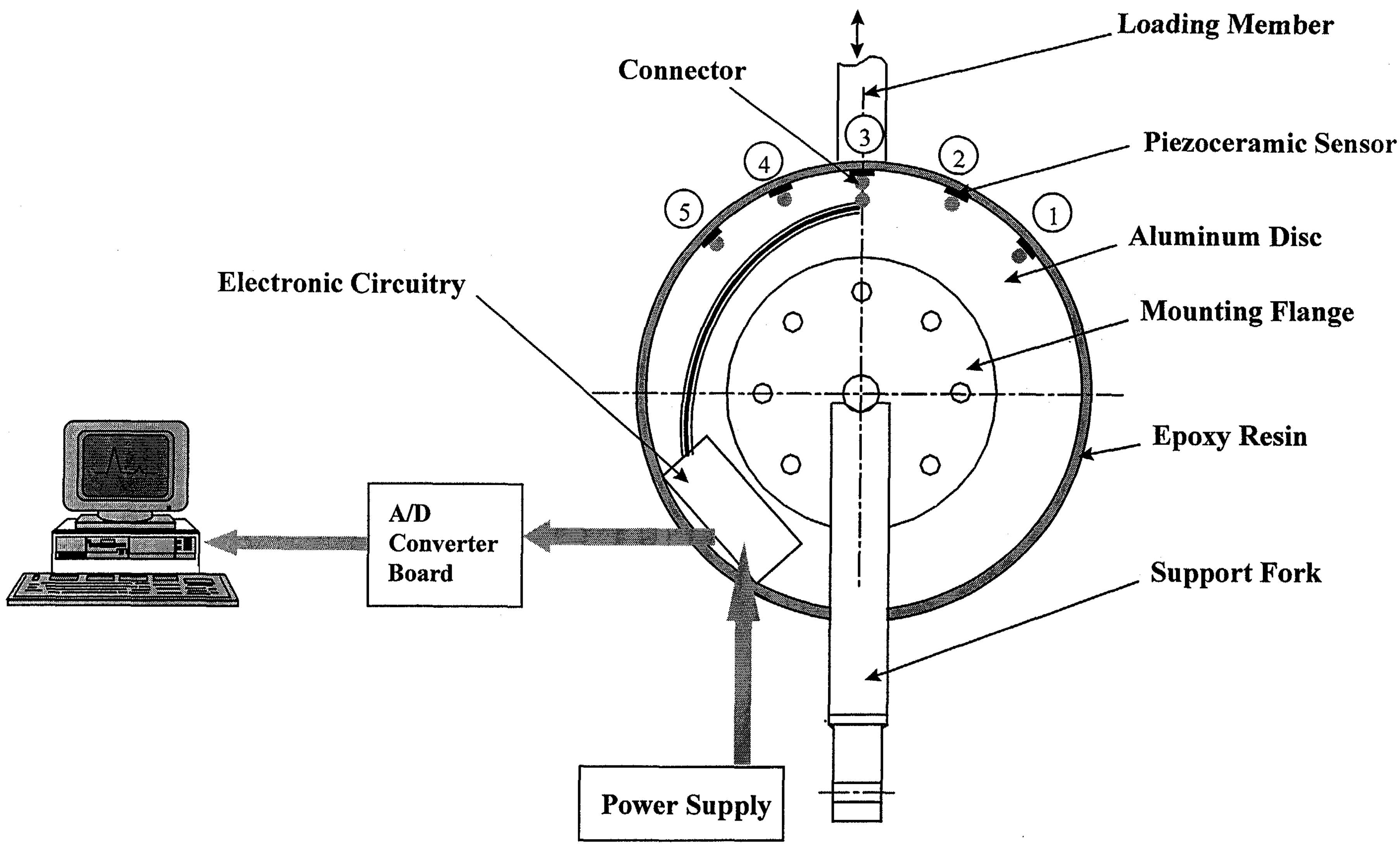


Fig. 2.1 Schematic view of the experimental setup for wheel testing

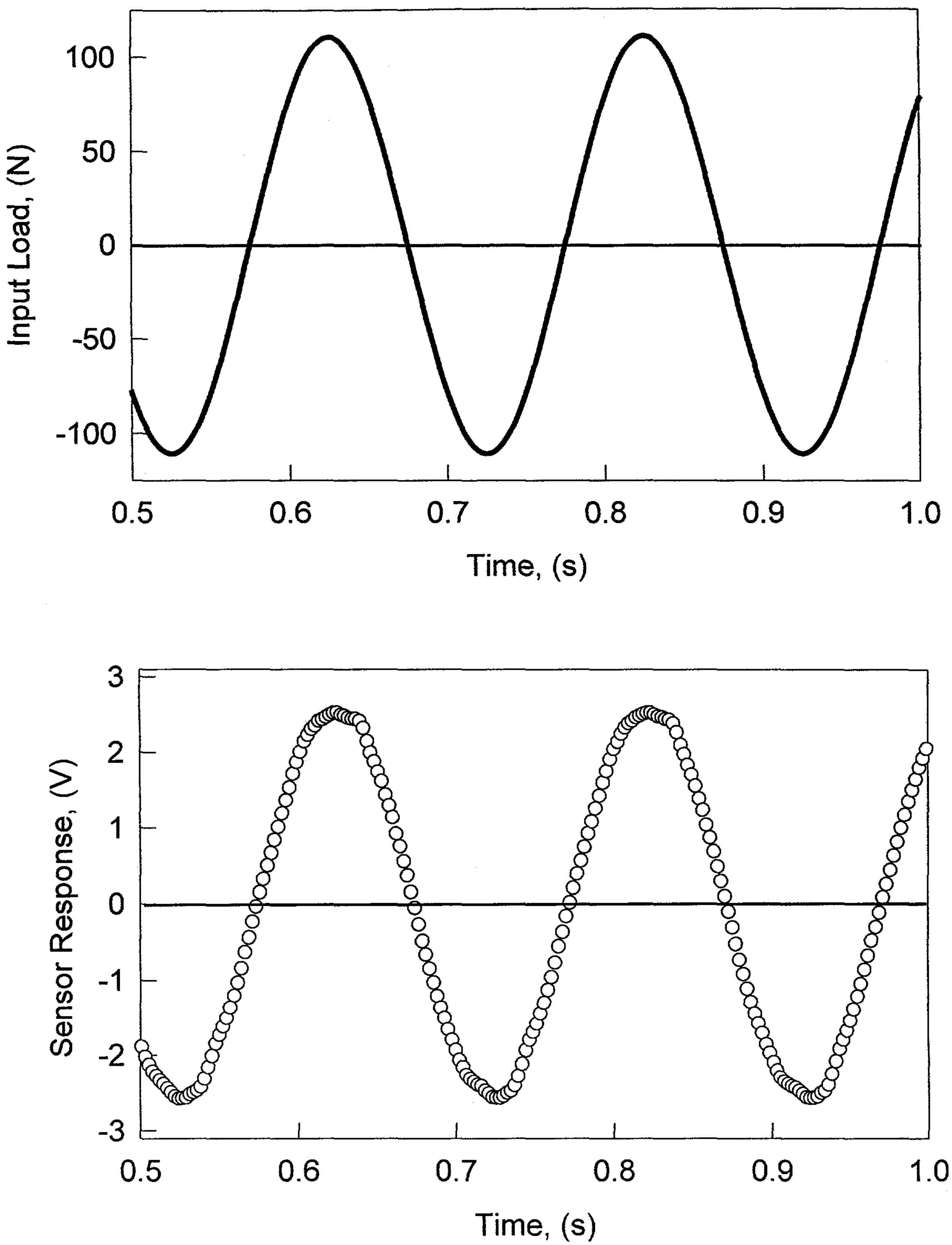


Fig. 2.2 A typical sensor output during the wheel test

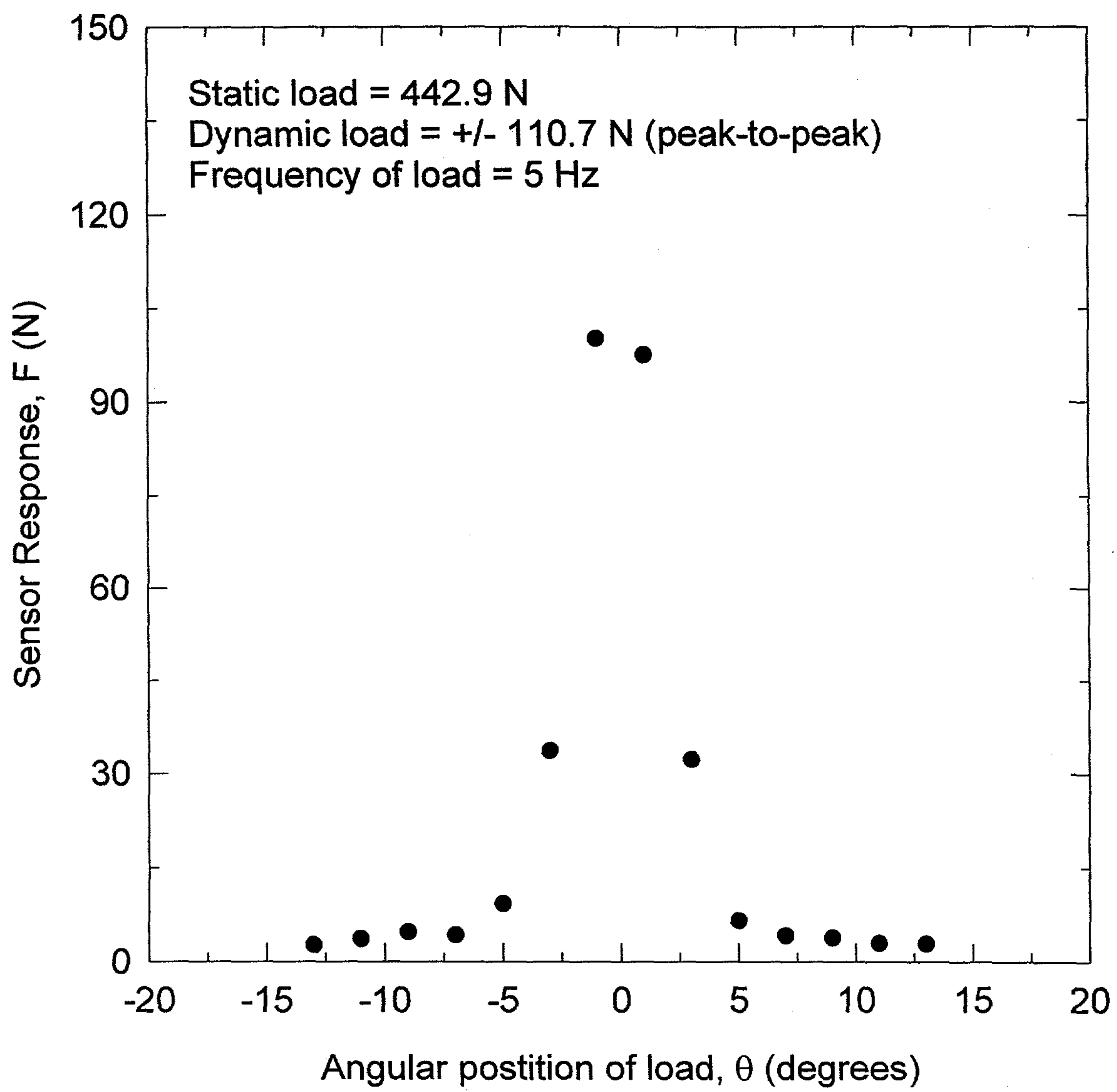


Fig. 2.3 Sensor response versus angular position of applied load (for sensor # 3)

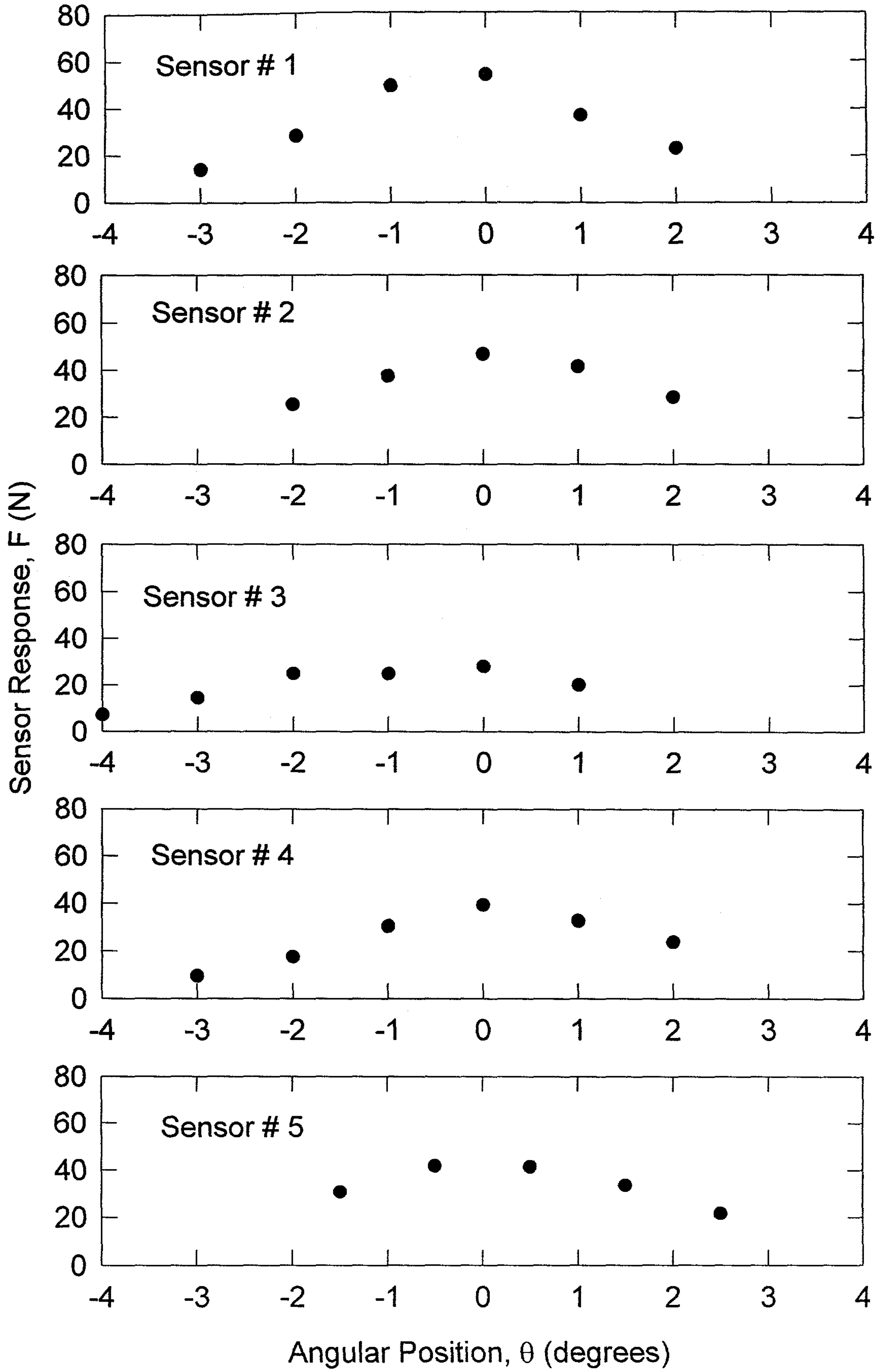


Fig. 2.4 Sensor response versus angular position of applied load

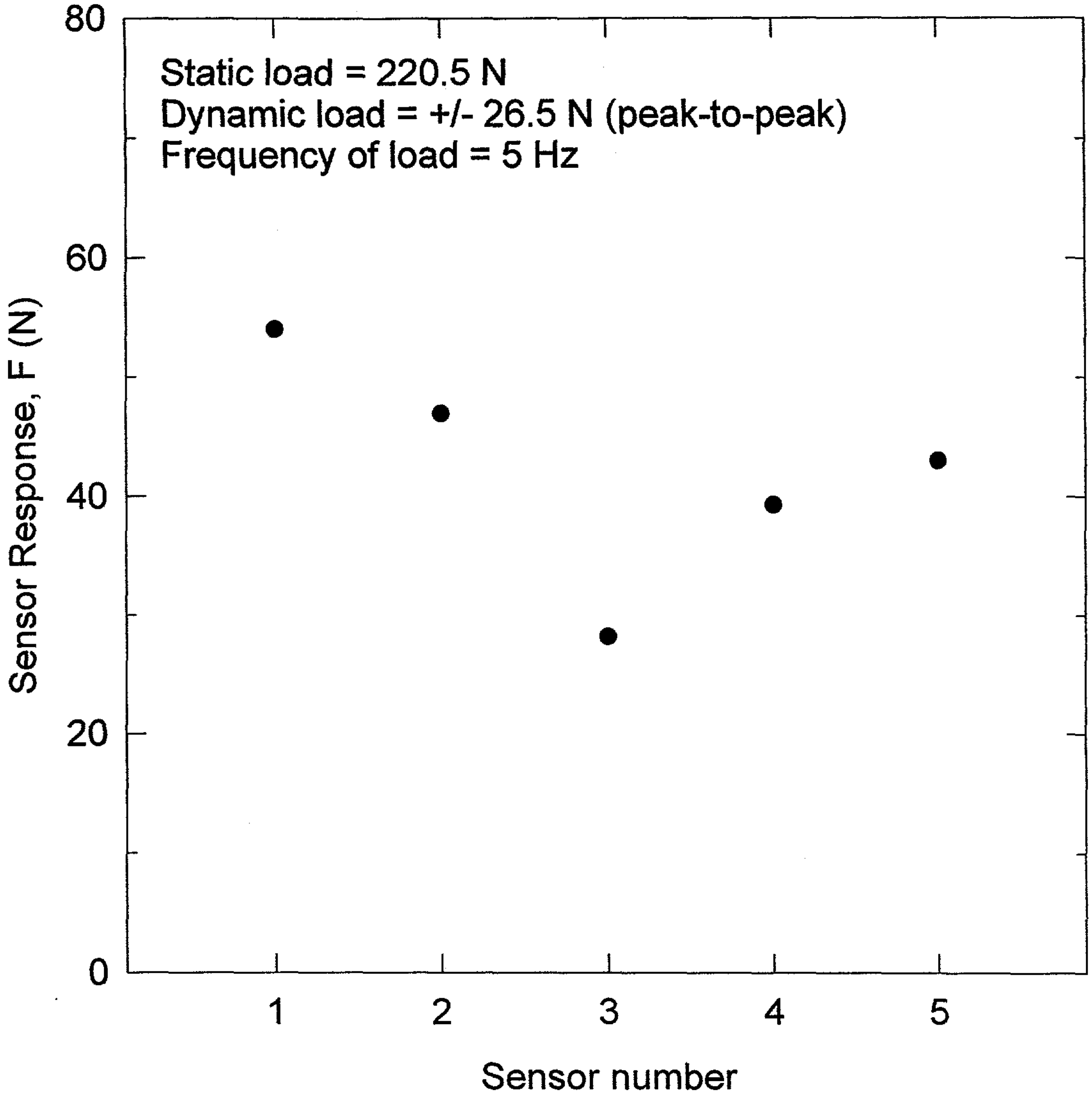


Fig. 2.5 Peak response of sensors

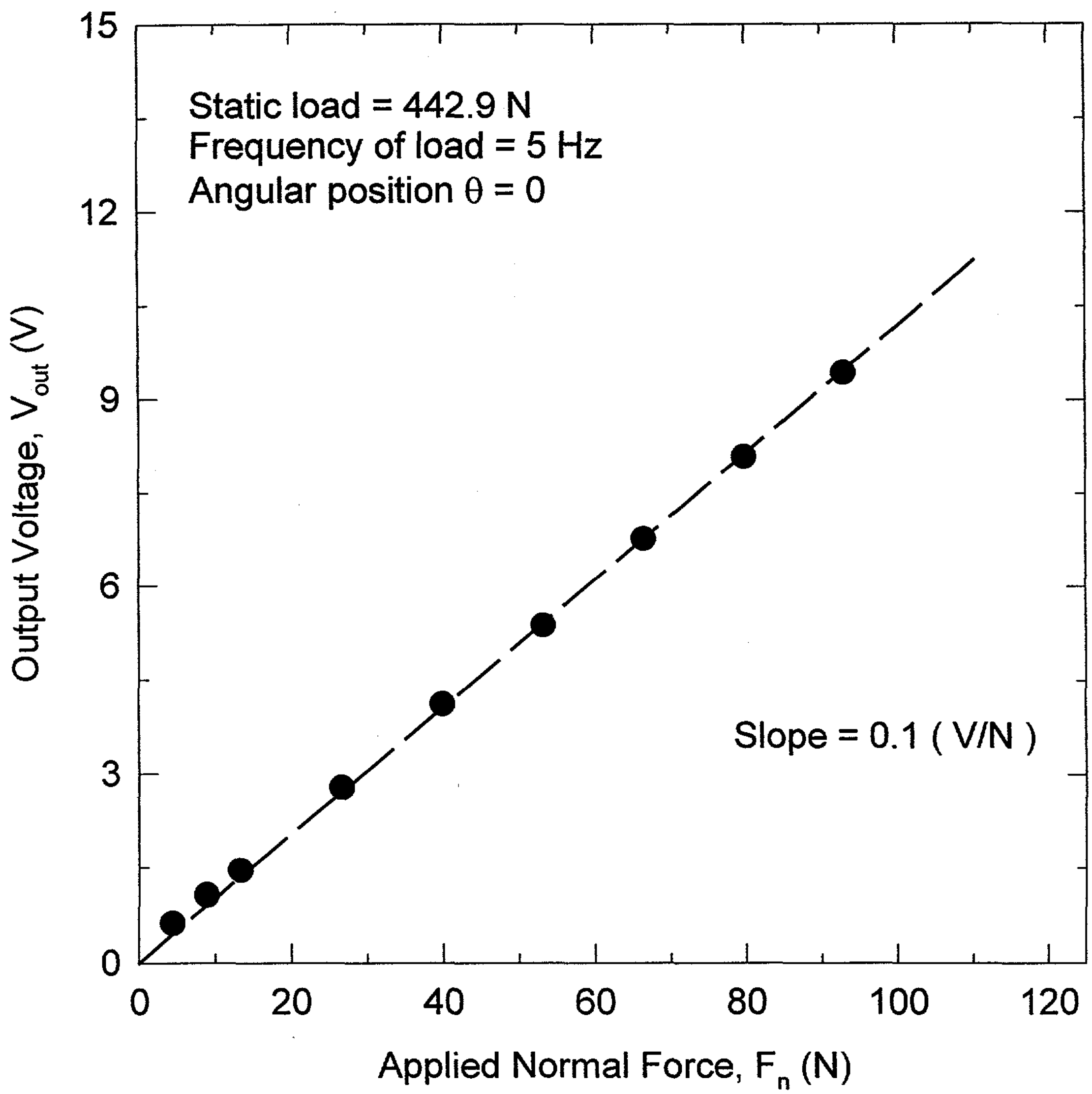
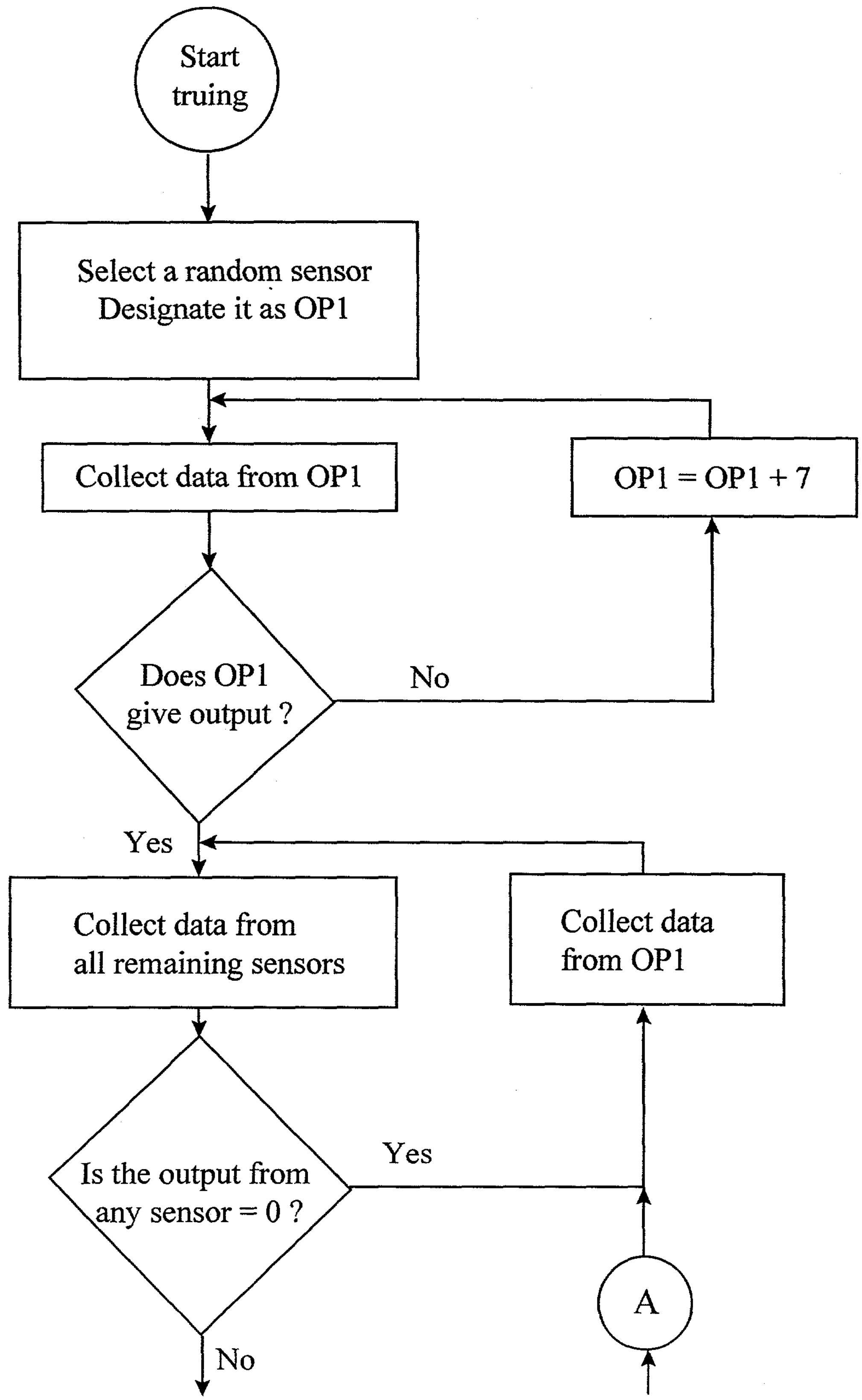


Fig. 2.6 Output voltage versus applied normal force


Start truing
Select a random sensor
Designate it as OP1
Collect data from OP1
OP1 = OP1 + 7
Does OP1 give output ?
No
Yes
Collect data from all remaining sensors
Collect data from OP1
Is the output from any sensor = 0 ?
Yes
No
A

continued...

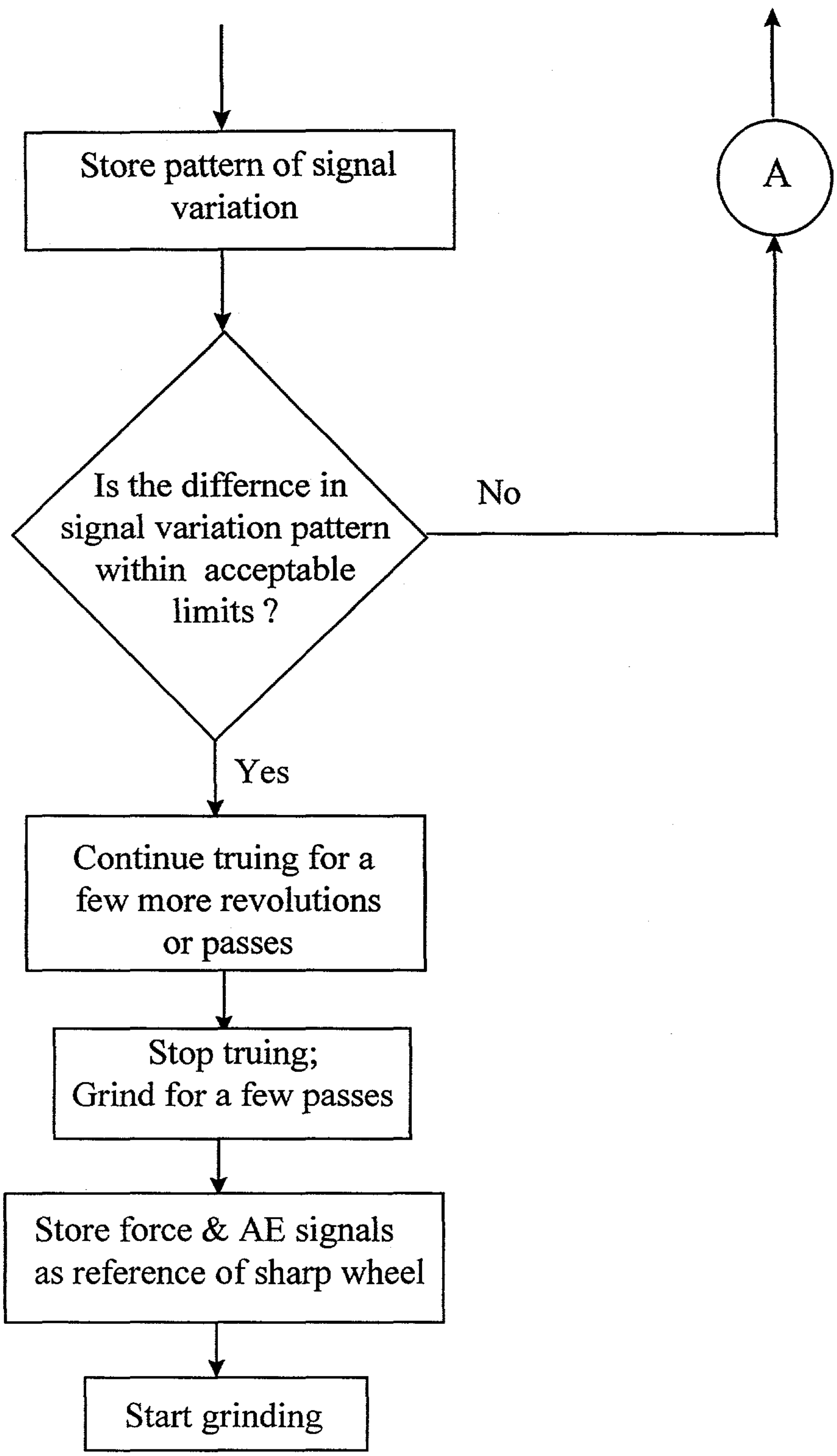


Fig. 2.7 Flowchart for detecting wheel out-of-roundness

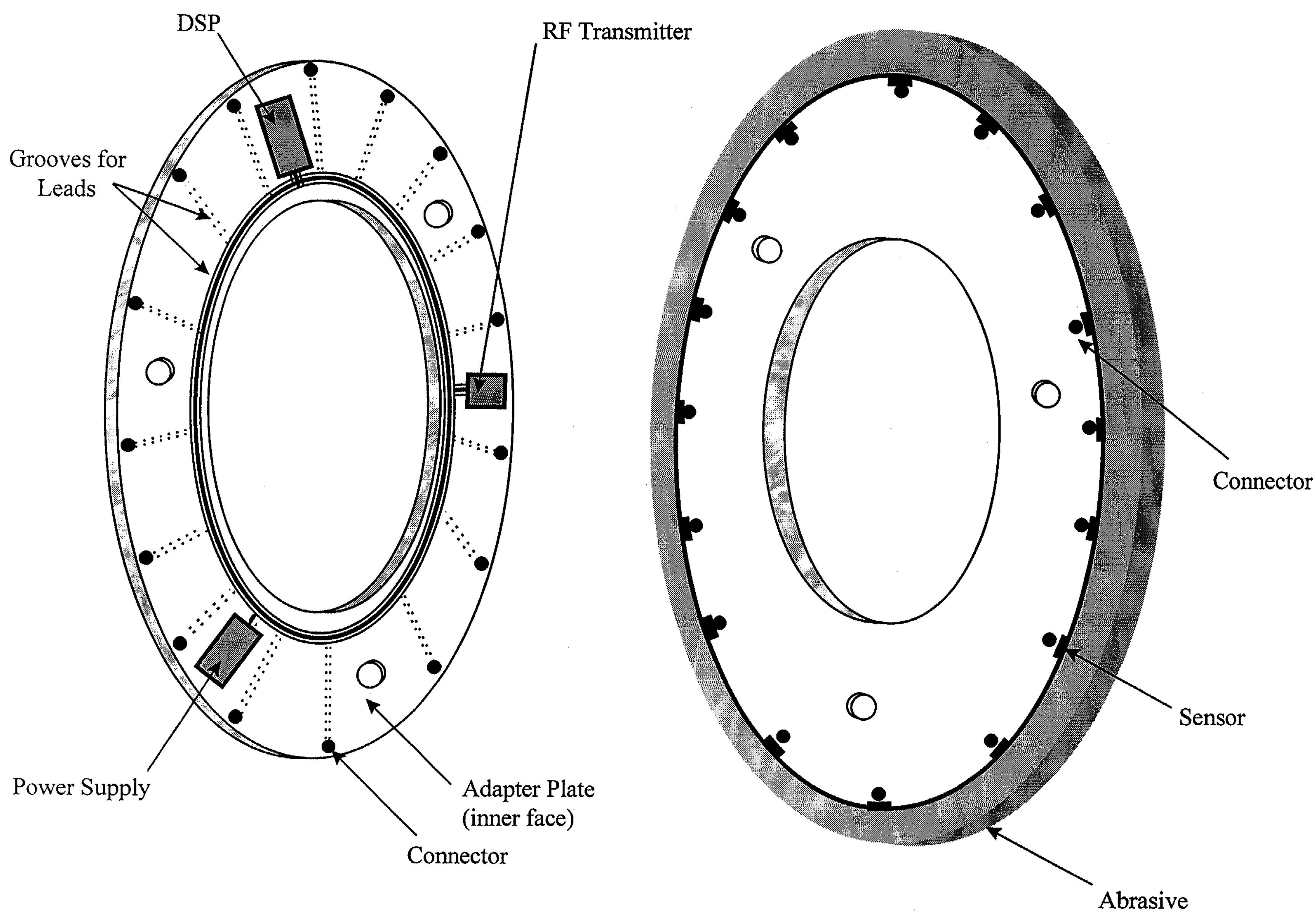


Fig. 2.8 Adapter disc for a sensor integrated wheel