



# Development of Real-time Grinding Process Monitoring and Analysis System

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## Abstract

The success of the manufacturing process which involves grinding as one of the stages depends solely on the accuracy of the grinding process. Being the last stage of the manufacturing path, it is mostly done to provide the desired surface finish to the product. This makes the stage very crucial. To prevent the ruining of all the previous stages and efforts, the real-time monitoring of the grinding stage becomes necessary which will make a room for better production planning and avoidance of failure occurrence. Conventionally the quality is dependent on the machine behavior as well as the operator's skill. To make the process in par with the latest industry 4.0, real-time process monitoring of the grinding process with the use of a vibration sensor is considered. The developed system in the paper focusses on the monitoring of the process behavior and log the occurred changes. The hardware architecture and software modules are introduced in detail and the application of the developed system is demonstrated with the grinding of an automotive part. The developed system is convenient to use and very helpful in improving the overall productivity of the brake disc production facility by reducing the quality failures and hence saving the resources.

**Keywords** Process monitoring · Monitoring tool · Grinding process · Failure detection · Process optimization

## 1 Introduction

The grinding process is one of the most widely used machining processes to manufacture the parts with very high precision. In recent years with the increase in demand for high-quality products, the use of grinding has also increased. Today it accounts for more than 70% of the total precision machining [1–4]. Its wide presence can be seen in every industry, whether it is automotive aerospace, marine, medical, or the semiconductor industry [1–5]. Being the last stage of the manufacturing process, it is of utmost importance. The occurrence of any defect or anomaly in it will not only affect the quality and performance of the end product, but also it will ruin all the previous stages and efforts in the manufacturing of the product. Knowing its importance, there

has always been a focus of researchers in the knowhow of the grinding process. There has been a continuous focus on performance improvement of the grinding with the use of abrasives like CBN (Cubic Boron Nitride) or diamond in the grinding wheels. Comparatively the grinding consumes more specific energy than the melting of the materials [6]. So energy consumption consideration is also very important.

Grinding is important as well as a very complicated process because the grinding wheel is composed of irregular abrasive grains that go through wear [7]. There is always a continuous interaction between the grinding wheel and the workpiece. These characteristics of the grinding result into the occurrence of several surface-related failures like burn marks, chatter, white layer, and residual stress.

The detection of malfunction during the machining is a dire need among researchers and industries. Conventionally, it is solely dependent on the operator who fixes the process parameters and adjusts it based on the observation of the product quality. For the identification of process failures, direct monitoring is done, such as visual inspection and surface roughness measurement. The disadvantage is that operation must be halted or finished to analyze the parts. It eventually wastes time and raises the cost [8]. Only the continuous

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monitoring of the process without any disturbance can provide us the insight of the grinding. In this regard, several sensors assisted monitoring systems have been developed in the past. Monitoring of the machining process parameters with a variety of sensors represent a prime step for the reduction of poor quality and hence reduces the costs [9]. Among the sensor-based grinding monitoring, force measurement, pressure measurement, and acoustic measurement are well reported in many pieces of literature [10]. A lot of efforts have been made for the development of sensor-based grinding monitoring. A detailed review of the measurement approaches, and sensors for the grinding wheel monitoring is given by [11, 12]. Grinding force monitoring is also considered by some of the researchers with the use of dynamometer [13], although they are expensive as well as limited in implementation due to the complexity of the machine setup.

The monitoring of grinding with power sensors has also been explored by many researchers. Grinding power is recognized as an important indicator for monitoring. Literature like [14–18] has successfully used a power sensor to characterize the grinding process and tool performance. Presently several grinding machine manufacturing companies like Micromatic Inc, India, and others have developed their own power monitoring devices. However, the use of a power sensor for monitoring has limitations of only able to compare the different power characteristics at different stages of the grinding. Authors in [19] have used a combination of Hall effect sensor, dynamometer, and Camera for the grinding wheel redress life estimation. The catch is that they have used it for a very simple part grinding, and the test setup allowed the assembly of such a system. To implement them successfully, the grinding process must have to be disturbed. It is one of the limitations of such a system. Andreas et. al used an optical sensor and miniaturized eddy current sensor for the non-destructive detection of the grinding burns [20]. Some of them have also used machine vision techniques for the grinding wheel wear assessment [21]. In the monitoring of the grinding process, the automatic detection of surface defects is very important, however, the introduced methods are unable to recognize such failures. [22, 23] demonstrated that the vibration characteristics of the grinding process have a very good relationship with the process behavior and product quality. Several investigations have been carried out to relate the vibration characteristics to the exact process behavior and occurrence of failure. Other sensor-based monitoring has its limitations, but the vibration is produced by cyclic variations in the dynamic components of grinding machine. Work has also been done to find the relationship between the change of grinding force and vibration characteristics [24].

Authors in [25, 26] have used vibration sensors and AE sensors. Due to the high dependency of industry on the grinding process, the damage control due to the process

failure is of great interest. Three major goals of any monitoring system are process monitoring, failure detection, and information sharing for the optimization of the process [27]. Simultaneously it must contribute to the development of a database that can determine the control parameters. The existing system utilizing vibration characteristics is not fully explored and it has a lot of scope of further development regarding the reliability and its implementation. The available systems have their limitations. The grinding process still faces a lot of failure instances resulting in huge losses to the company. The introduced research findings are either theoretical in nature or they have been tried for a very simple part having freedom of sensor installation. Most of the monitoring system which is in use collects the data from the installed sensors and later the data is analyzed in the offline mode. The occurrence of the failure is predicted and verified with the finished product quality feedback. Some of the methods also focus on the wheel life, redress schedule, or the predictive maintenance of the machine components. These methods help in planning the whole process in a better way but the real-time monitoring of the grinding process is still unexplored. To overcome the difficulties of current methodologies the presented paper advocates a portable vibration monitoring system for the grinding, that can give a real insight into the ongoing grinding to the user. The goal of the study is to develop a vibration monitoring set up so that the failure detection in the grinding process can be made autonomous. Another goal is to make the whole setup convenient, easy to implement, test, and validate in a real industrial environment.

The rest of the paper is presented as follows: Methodologies giving the insights of the steps followed for it, Hardware and software module development, followed by its installation and demonstration at the real grinding machine. The paper is concluded with the achieved goal and targets set for the work.

## 2 Research Methodology

The presented work is focused on the development of a real-time process monitoring system for the grinding that can also be used for the monitoring of other manufacturing processes having vibration characteristics. For this purpose, a comprehensive research methodology is followed as described in Fig. 1. The research object chosen for the study is an automotive product, i.e. brake disc. It goes through grinding in the end to get the desired surface finish. As discussed earlier, the occurrence of any failure at this stage will ruin all the previous stages. So, the development of the monitoring system is a must.

Firstly a thorough analysis of the existing manufacturing execution system (MES) in the company is done to get the

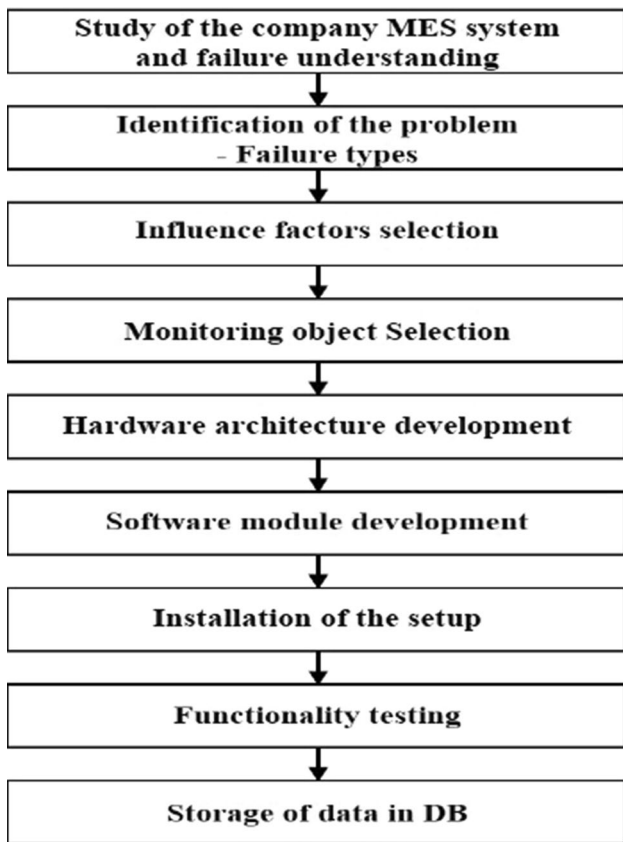


Fig. 1 Research strategy followed

record of the type of failures which occur during the machining. Additionally, the quality issues faced by the client during the operation of the delivered product is also considered. This analysis resulted in the realization that the major failures which occur are surface roughness, burn marks, DTV, Runout, and thermal damages to the surface. The grinding of the brake disc is done by a double-sided grinding machine as illustrated in Fig. 2. During the machining of the brake

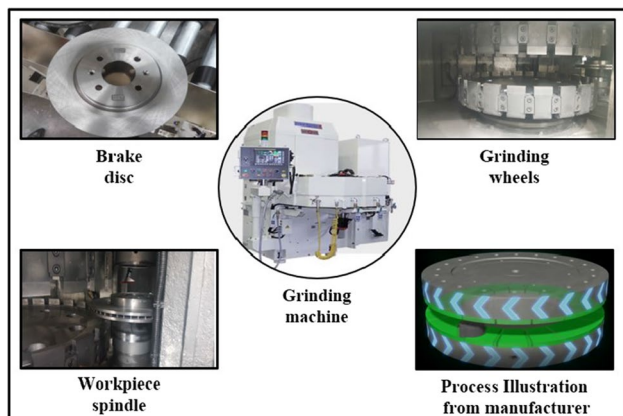


Fig. 2 Grinding process introduction

disc, the workpiece surface comes in contact with the upper grinding wheel as well as the lower grinding wheel. This dynamic movement sometimes becomes a reason for the change of process parameters and the occurrence of the failure.

Based on the failure types, influencing factors are selected. Among the materials, machine, operator, and processing its processing condition and process parameters which affects the quality the most. Most influencing process parameters are also selected as shown in Fig. 3. These parameters can be used to derive the reference processing conditions and optimization methods. The literature [28] explained that the vibration characteristics of the grinding process can reciprocate the process conditions in the most suitable way. And in the vibration characteristics, the root mean square (RMS) feature is the appropriate representation of surface-related failures. [28]The RMS for the vibration signal is calculated as:

$$f_{RMS} = \sqrt{\frac{1}{\Delta T} \int_0^{\Delta T} f_{raw}^2(t) dt}$$

where  $\Delta T$  is the integration time constant and the  $f_{raw}$  is the raw signal.

Later a vibration sensor-based monitoring system is developed. For this purpose, the hardware components like sensors, data acquisition (DAQ), mounting base, and connecting cables are chosen based on the requirement.

After that the core of the system, a software module is developed that can be integrated with the available hardware to visualize the process behavior. The software development comes with an analysis functionality that can distinguish good processing conditions from the bad one. After the lab-based testing of the developed system, the real installation of the sensors and all the setup is done and the functionality of the system is tested with the real case scenarios from the industry. The data collected from the developed monitoring system can be automatically stored to the company central

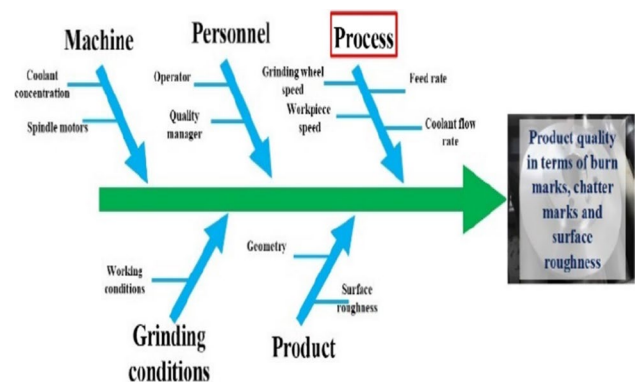


Fig. 3 Influential factors in terms of the product quality

DB system or the cloud services. It will help the planning managers to plan the manufacturing processes in a more efficient way.

### 3 Monitoring System Development

The monitoring system consists of a hardware module and a software module. In the hardware module, the pathway for signal acquisition from the machine is established so that the software system can read it in real-time and analysis can be done.

#### 3.1 Hardware Architecture and Setup Selection

The target of the proposed system is to extract the useful vibration signals from the grinding process and utilize it to build a reference model for failure detection. From the reference model, an interrelationship between the grinding process parameters and the quality as well as the vibration characteristics can be derived. The hardware setup facilitates the propagation of the requisite signal to the software module

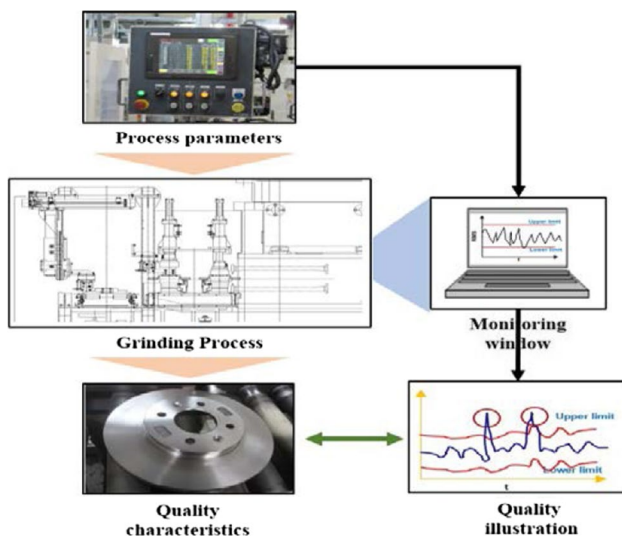


Fig. 4 Monitoring system

i.e. the core of the monitoring system. A brief description of the monitoring system is illustrated in Fig. 4. It can be seen that vibration signal and process parameters are the input to the monitoring system.

To record the vibration signal from the ongoing grinding process, several sensors available in the market are considered. Based on the requirement and processing conditions single-axis integrated electronics piezo-electric (IEPE) type accelerometers from the Kistler Group Switzerland is chosen. It is a general purpose vibration measurement sensor that can work in dynamic temperature environments. To provide ground isolation to the sensor, magnetic mounting base is used to attach it to the surface of the grinding enclosing. The magnetic mounting base and a data acquisition system (DAQ) is also from the Kistler group. A brief description of the sensor, mounting DAQ, and connecting cables are illustrated in Table 1. The vibration output of the grinding from the sensor is acquired with Kistler LabAmp 5165A DAQ device. It is connected to the monitoring PC through an ethernet connection. The DAQ has four input and four output channels. For our task, we have used two vibration sensors for the monitoring of process behavior from one grinding machine. The sampling rate varies throughout a wide range. To accommodate these hardware components with the machine without any disturbance, several modules, as well as the interfaces, are needed. The hardware connection setup is illustrated in Fig. 5.

#### 3.2 Software Module Development

An intuitive software application development is the biggest need. and soul of this monitoring system. To design the monitoring software module that can include hardware configuration, an open source visual programming language LabView from National instruments (NI), USA is used. Since the required software application has lot of complex function as well as separate functions, the standard state-machine design pattern in the LabView is used as shown in Fig. 6. The software has the functions of connection to the LabAmp for data transfer, signal acquisition, feature extraction, and filtering. The analysis of the data is also done to derive the quality pattern of the ongoing grinding cycle. In

Table 1 Hardware configuration

Mounting	Sensor	DAQ	Connecting cable
Material Stainless Steel Maximum temp 260 °C Weight 9 g Holding force 55 N Dimension 11.2×17.8×15.9 mm Type 8452A	Range 50 Sensitivity 100 Resonance 40 kHz Housing base Titanium Temp range – 196~165 °C Type 8703A50M1 No 2	Frequency response 0.1 ~ 1,000,000 Hz Channels 4 Output voltage 10 V Output current 2 mA Mass 1.2 kg Type 5165A	Type 1761B/CA Ethernet cable

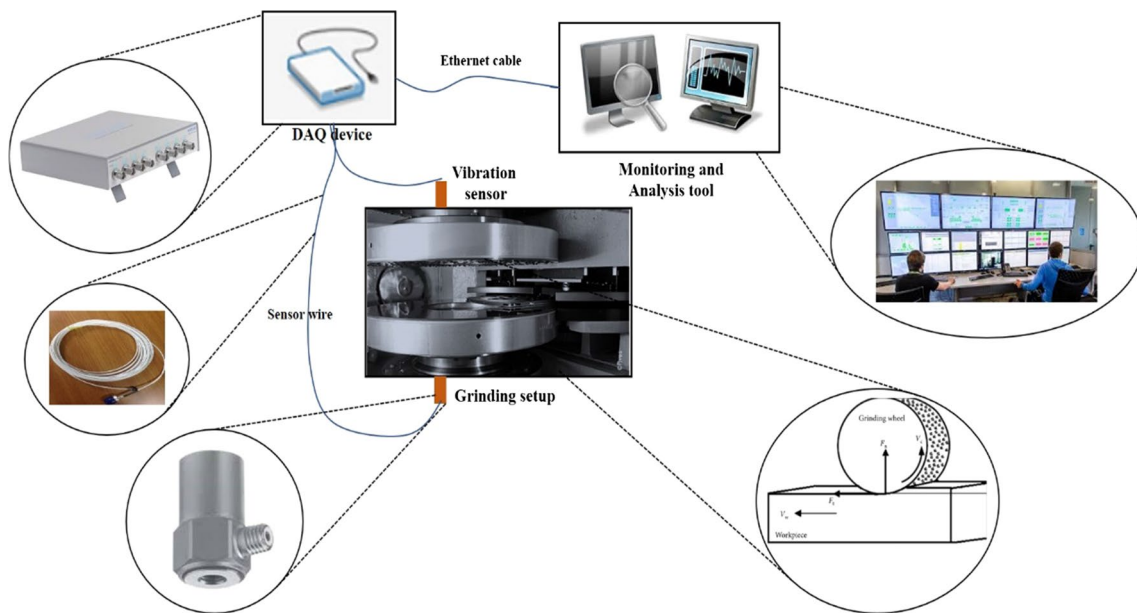


Fig. 5 Hardware connection for the monitoring system

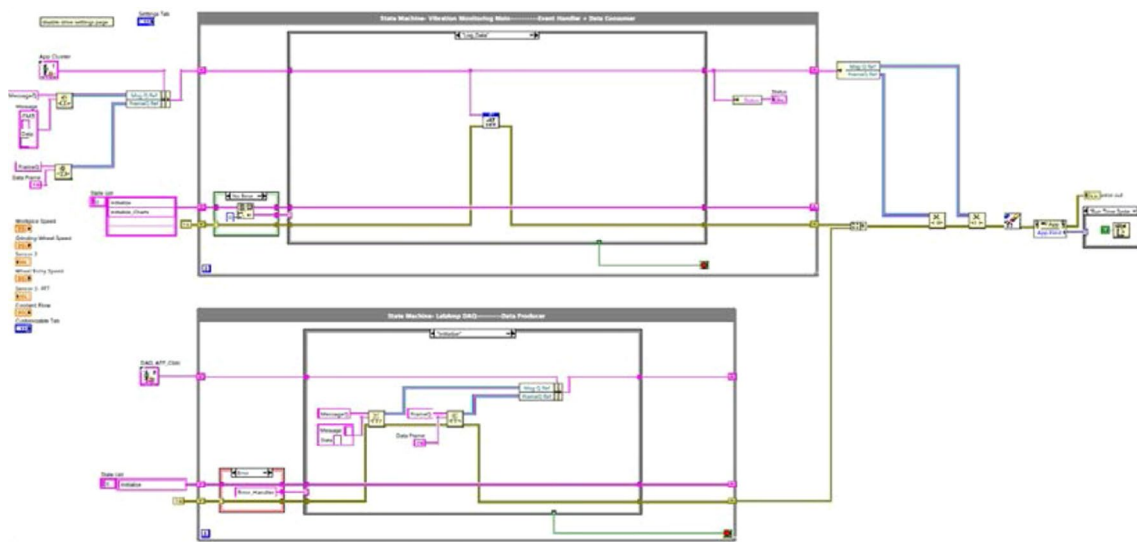


Fig. 6 LabView block diagram for developed software module

the signal acquisition module, the vibration data from the grinding wheel and the workpiece interaction is collected and sent to the DAQ. The module has the function of selecting different sampling rates based on the grinding conditions and the requirement. Dedicated buttons are assigned for the configuration of the data transmitted to the software with respect to the time. Real time vibration behavior from the process can be monitored using a dedicated display window.

As earlier discussed, the RMS feature of the vibration is directly related to the surface quality of the machined product. To reduce the noise factors from the raw signal,

several filtering modules have also been designed in the software. The user can select the filtering method from the dropdown menu before starting the monitoring system. Doing that can filter out the low or high frequency signals coming from the other part of the machine. It has a separate data collection module, that saves all the vibration data coming from the machine to a designated folder. These data can be used to build a reference model that can be used during the real implementation of the monitoring system. The communication between DAQ and the software inside the PC takes place through TCP/IP protocol.

User configures the sensor and DAQ by entering the correct details about the devices, as shown in Fig. 7. It has dedicated buttons ‘connect’, ‘start’ and ‘stop’ for the connections, monitoring initiation and termination the monitoring respectively. Additionally, the machine programmable logic controller (PLC) is connected to the system with open platform communications (OPC) server. There is also the functionality of plotting fast fourier transform (FFT) for the vibration signal. In second window of the system, as shown in Fig. 8, real time process parameters

and vibration signal can be plotted in real time. Several data extraction techniques, and the digital signal processing methods can be applied to analyze the data and derive control algorithms.

After the successful testing of the software module, it is converted in to an installer application file. Afterwards, it can work independently without any other commercial software including LabView. It can work with any computer having Microsoft windows.

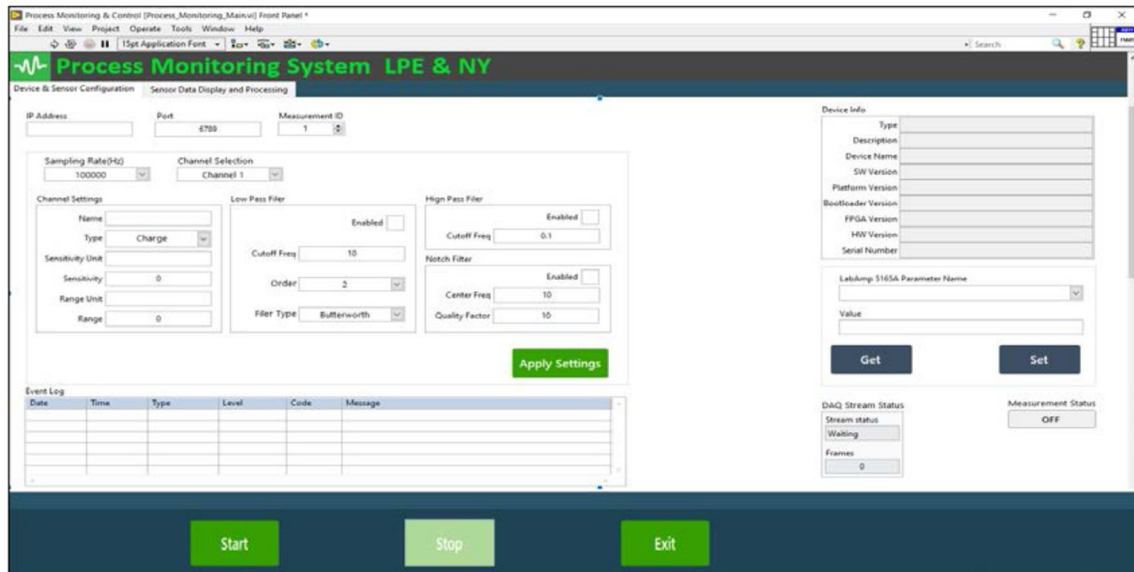


Fig. 7 Front panel for device configuration of the monitoring system

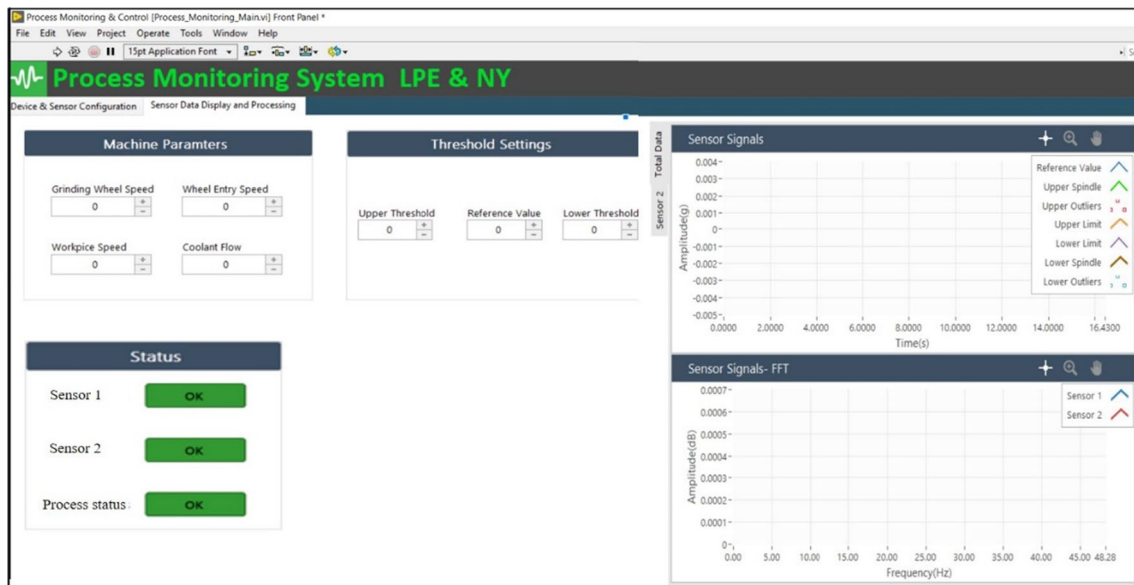


Fig. 8 Front panel for sensor data display and processing for monitoring

## 4 Application for Grinding Process Monitoring

The developed process monitoring system for the grinding can be easily applied on a grinding machine for multiple purposes. It is an externally applied portable system, which can be used for any grinding machine without affecting its grinding controllers or the assembly.

### 4.1 Building the Reference Model from the Database

With use of the monitoring tool, real vibration data depicting the process conditions can be acquired and stored in a database (DB). The monitoring system has the functionality of storing the data in CSV (comma separated values) format to any connected DB system. Based on these various types of data, a reference model can be built and routinely updated with the occurrence of the failures. In that way, the occurrence of any deviation from the standard can be recognized. For a grinding cycle to be in good shape, the processing conditions in the monitoring system must be under the threshold limits. If any deviation occurs, the alarm and notification to the operator will be flagged and simultaneously logged into the database for the attention of the plant manager. A data flow diagram for the developed monitoring system is shown in Fig. 9. Through OPC server communication, the PLC can broadcast the real time process parameters. The created DB has information like process parameters, vibration, and alarm occurrence instances. A typical vibration signal plot for different stages of the grinding is plotted in Fig. 10.

### 4.2 Process Parameter Optimization

Further digital signal processing method and analysis of the sensor signals can give an important insight about the interrelationship between the processing conditions and

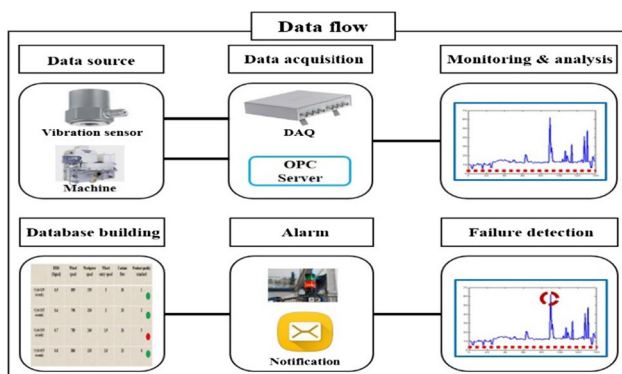


Fig. 9 Data flow diagram

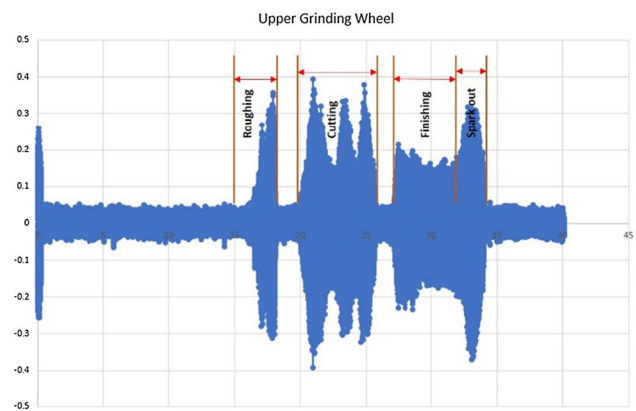


Fig. 10 Grinding process vibration signal plot

the product quality. Such additional modules can be added to the developed monitoring system. The effects of the important process parameters like grinding wheel speed, workpiece speed, and feed rate can be directly linked with the RMS feature of the vibration signal. The surface related quality characteristics are directly related to these. With such optimization techniques cycle time as well as the cost of the grinding process can be optimized and several control algorithms can be derived. Major surface quality failures can be easily detected from the vibration signal coming from the processing spot. It can be also avoided with use of the latest AI based control algorithms. If not a in real time cycle, then at least in the next cycle. In this way we can reduce the number of scrap parts produced.

### 4.3 Grinding Wheel and Machine Component Life Analysis

Grinding wheel is composed of abrasive grates, that goes through continuous wear. The changes in the grains properties affects the product quality. Its continuous monitoring can also be done by setting the threshold limits for its vibration features and based on that dressing schedule can be fixed for the grinding wheel. Other components going through continuous wear and fatigue, and may fail includes the bearings in the workpiece or the grinding wheel spindle. The detailed study of the collected data can be used for the condition monitoring of the machine components like bearings.

The developed monitoring system can be used for multiple kinds of task with slight modifications. Despite of its multipurpose use, our advocated piece of work is focused on the monitoring of real time behavior of the grinding process and notification to the user when any process failure occurs and storage of the data with the information of such instances.

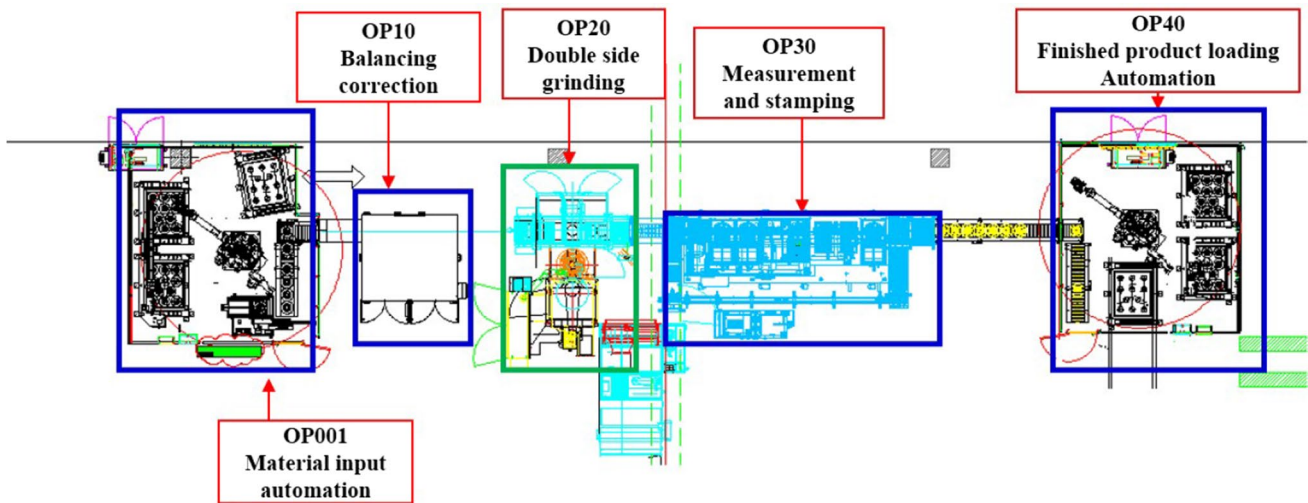


Fig. 11 Stage selection for the installation of the monitoring system

Table 2 Processing conditions

Grinding wheel rpm	850 ± 10
Workpiece rpm	250 ~ 130
Clamp pressure	0.5 ~ 1.5 Mpa
Spark out time	3.0 s

## 5 Functionality Testing of the Developed System

The working behavior of the developed software module is installed at the production line of the brake disc. Several steps of the brake disc grinding line is shown and the stage OP20 is also highlighted in Fig. 11. At this stage double sided grinding takes place. The machine chosen for the installation of the system is a vertical type GRV-585 series, from Daisho Seiki Corporation, Japan. The process parameters for the machining are written in Table 2.

### 5.1 Installation of the Setup at the Industry

The sensors, DAQ, mountings, sensor cables are all installed at the grinding machine in the factory. The design constraints of the machine is also considered before the installation. Two vibration sensors are installed at the upper and lower grinding spindle respectively. The sensor signals are propagated to the monitoring system through DAQ. The real time process parameters are also delivered to the monitoring system through OPC server. The detailed pictures from the site is shown in Fig. 12. From the figure

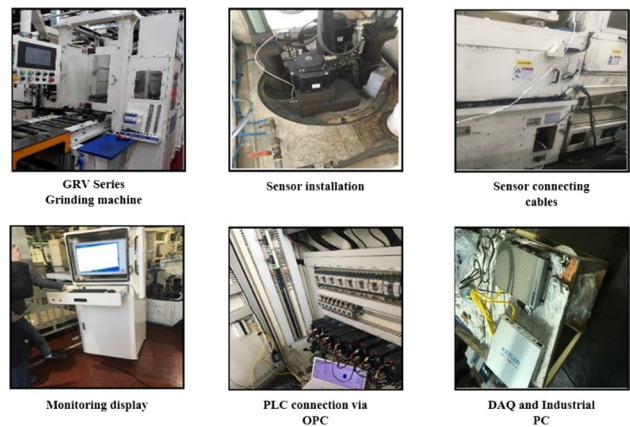


Fig. 12 Installation at the site

we can see that the laptop is used to get the process parameter from the ports of the PLC.

### 5.2 Testing of the Monitoring Functionality

After the successful installation of the hardware as well as the software modules, it is tested while grinding machine is running. The software can be launched just by a double click to its icon. The sensors are attached to the DAQ channels and the DAQ is connected to the monitoring PC by ethernet cable. Sensors and the DAQ are configured with their specifications. After this the threshold values for the occurrence of alarm and failure detection is selected from the reference model built in the earlier stages of this development. Once the connection is established, the monitoring system starts showing the vibration signals from the both the sensors. The display window is depicted in Fig. 13. Real





Fig. 13 Monitoring testing display

time FFT diagram for the vibration signal is also displayed. In the planning phase of the grinding, the FFT diagram will surely help in the problem identification.

### 5.3 Failure Occurrence Scenario and Related Process Parameters

Process status is dependent on the both of the sensor signals. The alarm is programmed in such a way that it will occur even if one sensor signal is out of its threshold limits. In the regular working conditions of the machine, it is very difficult to find failure instances. Only few failure scenarios are recorded with human induced variations and threshold limit variations. The monitoring window display at the time of process failure is shown in Fig. 14. Along with the display of the failure behavior, an alarm with beep sound is also generated for the attention of the operator. The failures for next cycles that will eventually make the whole lot scrap can



Fig. 14 Failure scenario while monitoring

be stopped by the operator. It can be done either by changing the processing conditions or the stopping the machine.

### 5.4 Integration to the Company Control Room Structure

The partner company Namyang Nexmo, Korea has a dedicated control room for the purpose of visualizing the working status of all the machines in the factory for the manufacturing of the brake disc. The developed system, is also connected to the companies conventional MES and monitoring system with the use of transfer control protocol/internet communication protocol (TCP/IP). The local industrial PC at the machine is connected to the control room of the company. The same process monitoring conditions can be visualized by the plant manager simultaneously and the necessary steps can be taken for its correction. The connection between the local PC and the control room is shown along with the control room window in Fig. 15.

### 6 Conclusion

The advocated work has presented a novel approach and methodology for the monitoring of the double-sided grinding process in the manufacturing of the brake disc. Based on the vibration characteristics of process behavior, a software module is developed which facilitates the real-time monitoring of the grinding process. The developed system comprises of vibration sensor, data acquisition device, monitoring window, as the hardware components. The developed system has modules like signal acquisition, feature extraction, threshold limiting, failure detection, alarm as well as data storage. It can be used further for training as well as better manufacturing planning and hence reducing the occurrence of quality failures. The developed process monitoring software is user friendly and convenient to use in the factory environment. After conceptualization and development, the system is successfully implemented to the grinding

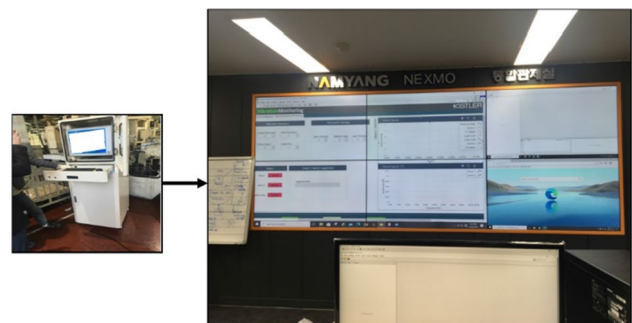


Fig. 15 Monitoring display in control room

machine at the factory and its functionality has also been demonstrated. Conventionally these monitoring system are not implemented at the production site. However, we have tried to solve the real quality issues faced by the grinding manufacturer. The inclusion of such a system is surely helping the manufacturer in reducing the surface defect failures like surface roughness and grinding burns. By reducing the overconsumption of resources like energy, manpower, and the raw material, it is effectively helpful in increasing the overall productivity of the manufacturer. The future path for this work leads to the addition of the predictive maintenance system for the grinding wheel into the same software. It can be done after collection of sufficient run to failure vibration data from grinding. In future, all the grinding machines in the factory can also be connected for information sharing, once the development of the system as platform is achieved.

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