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Comparison of Sensors Signal Quality when Drilling Inconel 718

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Abstract

Aero engines clearly differ from other propulsion systems used in general mechanical engineering particularly through the materials used and the extreme stresses that occur during operation. Boltholes in rotating turbine and compressor disks are among the most highly-stressed geometric features of jet-engines. For manufacturers of jet-engine components it is important to assess the quality of these at an early stage in the manufacturing of the product. The use of commercially available monitoring systems in hole-making has been successful in individual cases so far. Major reasons for this lack of effectiveness are the large material variations within one production batch, the overall difficult machinability of the materials applied, the small lot size which makes "teach-in" operations ineffective. Additional challenges occur during the implementation of monitoring systems in production. Here, the monitoring solution is judged predominantly by its robustness, its reliability against false alarms and its level of integration in the machine tool. A high level of integration can be achieved by using internal data, provided by the components of the machine tools themselves. The paper describes a new approach in real-time monitoring for drilling boltholes. In an experimental setup, process data origination from the NC of a Sinumeric 840D, collected by an OPC-Server had been processed. Comparing OPC data logging, DAU data logging and profibus data logging with respect to data quality, sample rate and real-time behaviour, profibus data logging appears to be the favourable choice. Compared to the price of many dedicated external sensors, all three methods to log internal data provide data access with small investments on a high level of integration. The experimental results indicate that OPC-data are suitable for tool wear monitoring and surface quality evaluation after drilling with solid carbide drills and face cutting reamers in Inconel718 workpieces.

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Keywords: Monitoring; drilling; tool wear;

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1. Introduction

Today, propulsion systems for planes have to meet increasingly more challenging requirements in terms of performance, cost-effectiveness, operational safety and environmental compatibility. To be able to compete in the international marketplace, engine manufacturers must develop innovative solutions for the design, manufacture and quality assurance of highly stressed jet-engine components to satisfy the requirements of air-lines [1]. Aero engines clearly differ from other propulsion systems used in general mechanical engineering and in vehicle construction above all by the materials used and the extreme stresses occurring in operation. Boltholes in rotating turbine and compressor disks belong to the most highly stressed geometric features of aero engines.

Nomenclature

DAU	Digital-Analog-Umsetzer (German expression)
OPC	OLE for process control
OLE	Object linking and embedding
PLC	Programmable logic controller

Consequently, it is important for engine manufacturers to assess the quality of these holes in an early stage of the manufacturing chain and not as late as in final inspection [2].

The use of commercially available monitoring systems in hole-making has been successful in individual cases so far. Major reasons for this lack of effectiveness are the large material variations within one production batch, the overall difficult machinability of the materials applied, the small lot

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size which makes “teach-in” operations ineffective, insufficient reliability of the monitoring system and the missing knowledge about the link between process signals and surface integrity that manifests itself in the microstructural condition, the formation of residual stress and the service life of the component [3].

The integrity and reliability of the machined engine component is the ultimate goal of all efforts within the system of design, material selection, manufacturing and inspection of rotating aero engine components [3, 4].

Thise paper is intended to make a contribution towards a safer production of boltholes in highly stressed turbine disks made from Inconel718 by providing solutions for the extraction and processing of internal controller data for the purpose of linking it to tool wear and the integrity of machined workpieces.

1.1. State of the Art in Drilling Process Monitoring

The essential objective of process monitoring described in literature, is to reliably identify machining process deviations and problems or anomalies occurring during machining such as excessive tool wear, tool fracture, collisions, process instabilities (e.g. chip clogging) at an early stage during manufacturing and consequently being able to initiate adequate actions.[5, 6, 7]. With the introduction of CNC machine tools into production in the mid 1970s, research was performed heading for an unattended drilling process, by detecting tool breakage. In the beginning, mainly force and torque sensors were applied and tested in lab environment [8]. Later, acoustic emission sensors (AE) were applied which have the potential to pick up chippings an tool fractures much better than by force and torque sensors alone [7, 9]. During the last decade, the speed of data processing has increased drastically. It is now possible, to process data from different sensor types simultaneously and to apply artificial intelligent methods such as neural network, fuzzy logic in real time [10]. By the turn of the century, the third generation of systems entered the market using improved ways of communication between NC and PLC via Profibus, Interbus or DeviceNet. These systems could now be integrated into the controller architecture of the machine tool [9]. Having direct access to controller information, monitoring systems were now able to manage more complex tasks in the field of machine-tool and work-piece control [11]. The monitoring strategies used, are signal-or feature-based processes in the timeline. Deviations or anomalies in the drilling process are detected by comparative measurements. These systems are intended to detect tool breakage and excessive tool wear. Commercial monitoring systems for drilling predominantly process the effective power consumption of the spindle during machining. In cases where a high installed spindle power meets an overall very low effective power consumption driven by the drilling process, the accuracy of these systems is limited. Based on their experience, users in the industry are still skeptical about monitoring systems. According to a survey conducted under SIMON project (Japan, U.S., and Europe), less than 29% of the machine-tool manufacturers and app. 38% of the end-users are satisfied with existing monitoring solutions. The reasons they gave are inadequate reliability, wrong alarms and operator errors [12].

2. Monitoring of drilling operations in aero engines

In scientific research it could be demonstrated, that, by applying sensors near the cutting zone, the drilling processes can be successfully monitored with respect to tool wear, tool fractures, chatter, overload and collisions. Process data picked up by a combination of force/torque sensors and acoustic emission sensors seem to be sensitive enough to pick up major anomalies. For the commercial exploitation of these results in jet engine manufacturing the following fundamental tasks can be defined:

(1) Establish a link between monitoring data and cyclic life of life-limited parts to utilize the potential of process monitoring for component safety.

(2) Develop a robust monitoring solution for drilling jet-engine hardware which fits into the production system of aero engine manufacturing.

Today, digital connections between numerical controllers, spindle and motion drives enable access to data originating directly from the actuating elements of a machine-tool in high accuracy. Open controller architecture makes it possible to access all relevant data via standardized software modules and hardware interfaces.

In comparison to applying additional sensors, like acoustic emission or force sensors, as close as possible to the cutting zone, the approach in this article is to use data supplied by the CNC-Controller, acquired from the spindle and the motion drives. These data are to be processed with the ambition, to extract information about the excellence of the hole-making process. A specific challenge is the handling and processing of data in limited quantity and quality.

2.1. Performed Cutting Tests

Inconel718 rings, machined from a lot of original high pressure turbine disks are machined on the 5-axes machining centre MIKRON UCP1050 equipped with SIEMENS Sinumerik 840D controller. Tools, machining strategies, and parameters are applied as in production.

Machining was performed in a two-step drilling process consisting of roughing with a solid-carbide spiral drill (diameter = 8.20 mm, 2 flutes) and subsequent finishing with a solid-carbide face-cutting reamer (diameter = 8.50 mm, 6 flutes). The tool batch used for the machining tests contained both new and re-sharpened tool, as they circulate in regular production. Cutting conditions for roughing and finishing were chosen in combinations of cutting speeds $v_c = 20$ m/min and $v_c = 30$ m/min with a feed per tooth $f = 0.035$ mm and $f = 0.025$ mm, respectively. During the machining tests, emulsion (5%) was applied during roughing, both as conventional (low pressure) flooding and with high pressure (50 bar) through the tool. Finishing was performed with conventional flooding only.

A profibus client was installed on machine tool. The client consists of an industrial PC, which was equipped with a profibus card and hooked up to the profibus. The advantage of this configuration is that the client can easily be configured by a wide range of operation systems (e.g. Windows or Linux), the data processing can be performed with a wide range of commercial products. (e.g. Labview, Matlab, etc.), and data can be accessed in an easy way via USB interface.

By using compile cycles, process data representing effective spindle power, torque of the spindle and the effective power of the feed drive were collected by an OPC-Server installed on the machine-tool controller SIEMENS Sinumerik 840D under the shell of WinXP-SP2. In addition to that, the active NC-sequence was recorded. The recording rate of the OPC-Server in the experimental environment was app. 10 samples/second for each channel. The data was transmitted via LAN to a client-PC.

3. Comparison of sensor signal quality

3.1. Hardware and software platform

The first and fundamental task within this work is to evaluate suitable means of controller-based data logging to access this internal data. It has not been proven yet, whether this data is usable to monitor the excellence of metal cutting processes and the integrity of high stressed work-pieces applied in aero engine manufacturing.

As an important prerequisite to satisfy this task, it is necessary to define a representative hard- and software platform that can be accessed in a flexible and structured way. In scientific literature, this platform is defined very generally as so-called "open controller architecture". Unfortunately there is no universal definition for this term and therefore the interpretation of open controller architecture can vary [11]. Consequently, a more precise definition is needed. Prischow [11] judges the extent of "open controller architecture" by four main criteria: portability, extendibility, interoperability and scalability. In the context of this paper, "open controller architecture" is understood as "providing sufficient inherent support for capable soft- and hardware devices in digital numerical controllers of machine tools for the purpose of accessing data in real-time, which carries enough information content to judge the excellence of metal cutting operations with a special focus on the integrity of the work-piece".

Within the product family of machine tool controller systems (MTCS) with open controller architecture, SIEMENS SINUMERIK 840D has the biggest commercial relevance today. Therefore this type of controller was considered to be a promising candidate for the research task. The MTCS of SIEMENS SINUMERIK 840D consists of a Windows PC providing the Human Interface (HMI) and the Numerical Controller Unit (NCU). The NCU basically consists of a so-called Numerical Controller Kernel (NCK), a Programmable Logic Controller (PLC) and other modules that provide basic functions such as data-storage and alarm-generation. NCK components (e.g. interpreter, interpolator) process NC commands in real-time [13]. NCU and NCK are connected with a multi-point-interface-bus (MPI-bus) which physically is a fieldbus based on the profibus topology and protocol. Open HMI-architecture in this controller is achieved by DDE and COM interfaces that can be accessed by client-server-commands through Visual Basic or Visual C++. Open NCK architecture is achieved through so-called “compile-cycles“. Compile cycles are small C++ programs that can be called out at defined events within an NCK processing cycle. Via so called “bindings“ it is possible to access all NCK addresses [14].

It is evident that this architecture provides various means of logging internal data from the machine tools. In addition, SIEMENS provides detailed documentation of its MTCS and its interfaces, which makes it easy to transfer commands and data.

Therefore this platform was chosen to explore possible correlations of controller data with tool wear and surface integrity of the work-piece. But before investigating the data obtained from internal sources in detail, the initial research task was to investigate, compare and select suitable means of communication with this controller system.

3.2. OPC Data Logging

OPC is the common abbreviation for “OLE for Process Control“. It provides a universal means for the exchange of data between different hardware without the need to know the exact internal design of each device under consideration [14]. This is achieved by providing a common bi-directional abstraction level as outlined in Fig. 1.

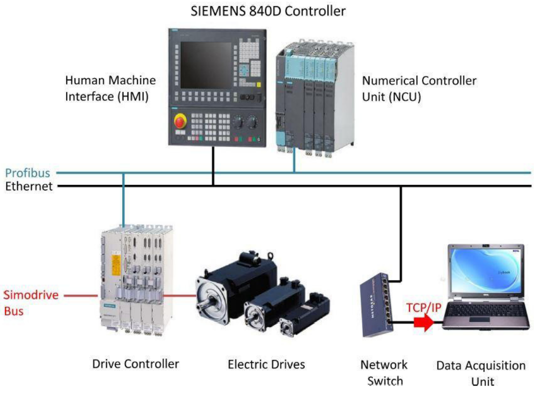

Fig. 1. Test configuration for OPC datalogging

Since commercial OPC software is not tailored to the needs of cutting process monitoring, a universal OPC server provided by SIEMENS with the symbolic name “OPC-SINUMERIK Machineswitch V2.4.98“ was installed and configured to the requirements of the experimental setup. A corresponding client (laptop) was configured to log both the effective power of the spindle and the effective power of the motor moving the z-axis. In a first step, the data was simply stored on the hard drive of the HMI and subsequently accessed with a USB flash drive.

In a second step, “near real-time-access“ was achieved with an additional executable programme. This programme was installed as a background service on the HMI and was configured to read and send OPC data to an external client connected to the HMI via Ethernet.

During the tests, the data rate was identified as a limiting factor for subsequent data processing. The maximum data rate was found to be around 10 samples/second. This is in compliance with the data rate of other OPC applications installed in manufacturer automation.

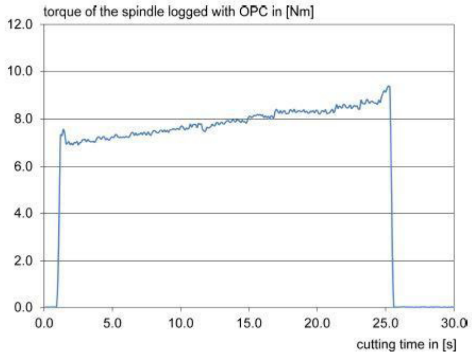

Fig. 2. OPC pattern of a pattern of a twist drill. New tool condition

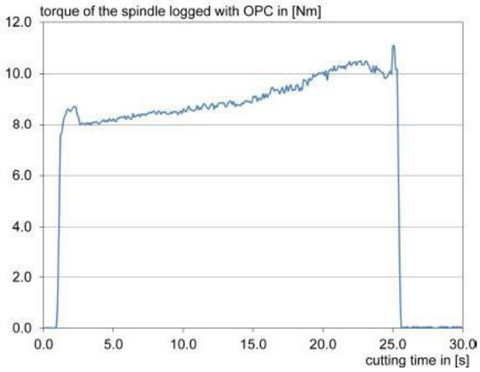

Fig. 3. OPC pattern of a pattern of a twist drill. Worn tool condition

Representative torque data generated during drilling and finishing and logged from the spindle by OPC are outlined in Fig. 2 to Fig. 3. These patterns require less interpretation. A significant change in amplitude can be observed between a new and a worn too for both drilling with a twist drill as well as for finishing with face cutting tools. It has to be considered that the torque logged via OPC is calculated by the machine tool controller. Input data is the effective power and the parameters of the motor(s) installed. Furthermore, it is important to consider that the machine tool applied for the OPC data logging were not calibrated prior to the cutting tests

Summarizing the most important results from the machining tests with OPC enabled, it can be stated that OPC can be considered a good source for data with respect to spindle torque and torque proportional to the feed force. It has to be taken into account that the data rate with OPC is limited and data originating from the z-axis must be judged with the knowledge about the mechanical set-up of the respective of axis. Under the machining setup chosen for this work, which delivered a data rate of about 10 samples/second, a considerable difference between the OPC pattern created by sharp and dull tools within a drilling and a finishing cycle was observed. It is obvious that this data is not suitable to log signals representing phenomena that occur in a frequency above 5 Hz. From its concept, OPC data logging adds no additional hardware to the machine tool and can be performed independently of the numerical controller's hardware platform.

3.3. Siemens Tracer and DAU

Although numerical controllers communicate digitally with their periphery, they also provide some special analogue ports. These ports are used for setup, diagnosis and service. SIEMENS Sinumerik controllers provide a so-called “DAU“port. In addition, Siemens Sinumerik provides a so called “Trace-Function“, which can be configured to log multiple data from rotary and translator machine tool axes in a digital format. The trace function is an excellent tool for post process data analysis up to a sample rate of app. 1000 samples/second. Unfortunately the trace function“ is not usable for real-time process monitoring. Consequently, within this work only the analogue DAU port was tested for its usability to log data during machining. The configuration for data logging is outlined in Fig. 4

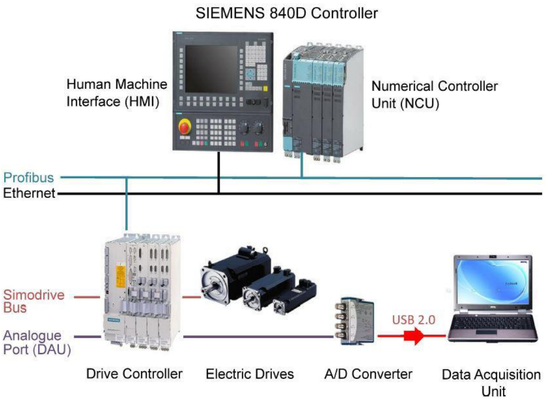

Fig. 4. Test configuration of DAU data logging

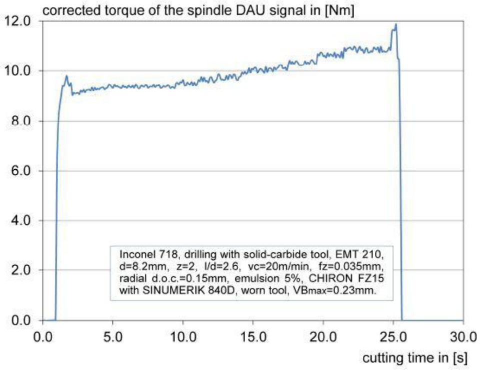

Fig. 5. Reconstructed DAU signal

Example plot obtained from drilling tests are provided in

Fig. 5. To allow real-time data processing during the tests it was necessary to convert the analogue data received from the DAU port to digital data. This data was sent to the USB port of a data acquisition PC applied for data processing. The limitation of this solution is that only one channel (e.g. effective power of the feed drive) can be submitted via DAU. In a series of cutting tests implausible data was recorded within a cutting cycle. During a more detailed investigation of the processing of internal data, it became evident that this port is configured to automatically adjust its measuring range to minimize signal deviations caused by the limited resolution of the 8 bit D/A converter that supplies the analogue signal. Considering the corresponding algorithm, it is possible to calculate back to the original signal.

In summary it can be stated DAU data logging is limited to one recordable channel at a time. This channel can be configured to the individual monitoring need. But it is not possible to switch this pre-selected channel during processing. In theory, the data rate is only limited by the maximum data rate of the internal D/A converter and the external A/D converter. But it has to be kept in mind, that the internal D/A translation are performed with an 8 bit converter. This converter offers $2^8 = 256$ different signal levels. If the machining process causes an elevated level of signal dynamics, DAU data needs to be continuously screened for plausibility and pre-processed. To avoid misinterpretation or perhaps false alarms, the algorithm of switching between measurement ranges must be known and considered for the interpretation of the signals. On the other hand, this method needs only a very limited instrumentation which is completely outside of the cutting zone.

3.4. Fieldbus Data Logging

Fieldbus systems are used to connect different devices on different command levels (e.g. sensors, actors and controllers on the slave level) with numerical controllers and workstations on the master level with one serial connection. The devices within the master level communicate via token passing procedure. The token is a sequence of bits that travels continuously through the master ring topology. The device that holds the token can communicate with the profibus devices. At SIEMENS this token is called compile cycle. SIEMENS already supplies compile cycles for different purposes including monitoring. For this work a compile cycle was used, that is commercially available and can be applied both for the so-called “PowerLine“ and the “SolutionLine“ series of an 840D controller. This compile cycle is called “Tool and Process Monitoring”. This specific compile cycle can read up to 8 configurable addresses within one interpolator cycle. A logging client was installed to the topology of the profibus in the machine tool for the configuration of the machine tool for fieldbus data logging. In order to make data storage and transmission as convenient as possible, a small embedded PC was installed.

Representative plots obtained from the configuration outlined in Fig. 6 are provided in Fig. 7 and Fig. 8. The sample rate that can be achieved depends on the interpolator (IPO) cycle. With the hardware installed in the machine tools MICRON UCP1050 approx. 100 samples/second +/-5 samples/second was achieved. According to new information provided by SIEMENS, sample rates of up to 2 kHz can be achieved on the newest controllers if the very latest compile cycles are applied. But so far, these new compile cycles have been reserved for SIEMENS applications and tasks.

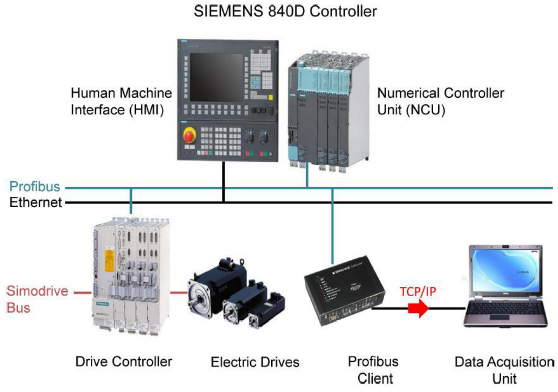

Fig. 6. Test configuration of fieldbus data logging

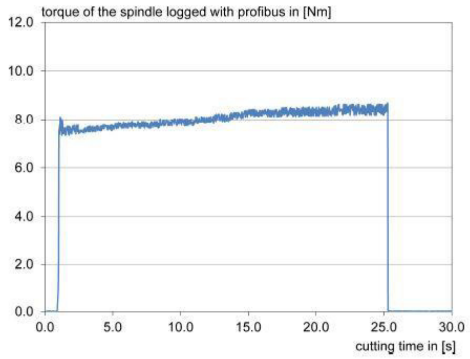

Fig. 7. Profibus pattern of a twist drill. New tool condition

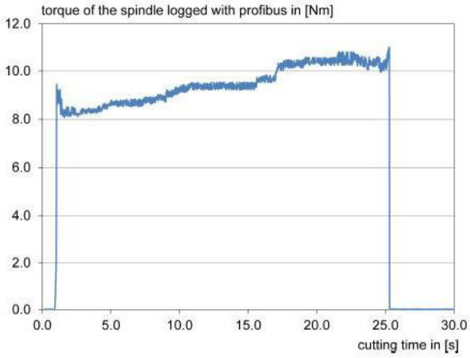

Fig. 8. Profibus pattern of a twist dril. Worn tool condition.

In order to compare the quality of the fieldbus data with the data obtained from a dedicated force measurement system, an additional KISTLER rotating dynamometer type HS-RCD 9125A was linked to the test machine. Since it is not possible to apply coolant through the RCD, the comparison was made for finishing. This is the most sensitive and important machining step when working on a very low level of cutting forces.

The signal patterns of profibus and RCD recordings are similar, see Fig. 9. Differences in signal level could be adjusted by calibration. It is obvious that profibus data with 100 Hz sample rate cannot provide the same level of details as compared to RCD data with 1000 Hz. Possibilities for signal analysis in the frequency domain with the profibus data and the compile cycle applied is limited to 50 Hz according to Shannon's theorem.

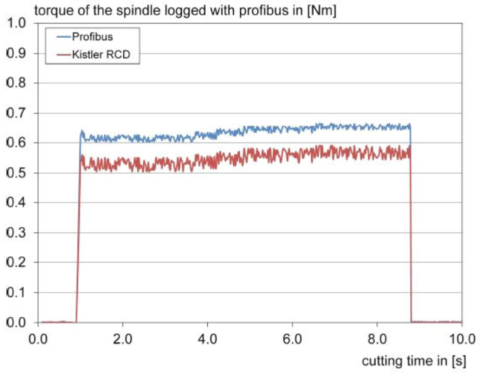

Fig. 9. Comparison between Profibus and RCD data face-cutting finishers, new tool condition;

With respect to the capabilities of profibus data logging performed within the conditions of this work, it can be stated that this data can be logged with only small modifications to the machine tool. The data is extracted and transmitted to the monitoring unit in a completely digital form. This rules out conversion losses and minimizes signal interference with other sources of electric and electromagnetic signals near the machine tool. With the compile cycle applied, the sample rate was 100 samples/second. Compared to external sensors, profibus data logging can be installed in a way that does not expose data logging devices to the harsh environment of chip-making processes at all. On the other hand, signal dynamics can only be picked up to a level of 50Hz, which is much less than the capabilities of many external sensors (e.g. for acceleration, force or acoustic emission). Compared to force data obtained from an RCD, profibus data still has an acceptable quality, especially in the time domain.

4. Conclusion

For this scientific work, SIEMENS Sinumerik controllers qualify themselves as an excellent hard- and software platform with“open controller architecture“. Comparing OPC data logging, DAU data logging and profibus data logging with respect to data quality, sample rate and real-time behaviour, profibus data logging appears to be the favourable choice. Compared to the price of many dedicated external sensors, all three methods to log internal data provide data access with small investments on a high level of integration. Internal data logging, as it is performed within this work, does not change the properties of the metal cutting system, which makes this technology applicable for existing “frozen“ processes that are widely applied in the jet-engine industry..

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