Contact-based Collision Detection – A New Approach to Avoid Hard Collisions in Machine Tools

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Abstract

Among all process disturbances, collisions cause the highest repair costs and the longest downtime periods. In some situations the collision cannot be predicted by the numerical control unit. Hence, the machine tool has to be stopped as fast as possible whenever load limits on the tool are exceeded in order to avoid consequential damage. A new approach for faster reaction is the detection of the first contact as the beginning of a collision. Considering this approach it is of particular importance to make a distinction between a collision contact and the contact caused by the beginning of a manufacturing process. The following paper discusses sensor principles which allow the fast detection of a contact between a milling tool and the work piece. Furthermore, the analyses of different contact situations are described in detail. Essential information about the actual machining process, such as rough machining or finishing, are taken into consideration as well as external sensor signals. The described approach provides a new method for process monitoring in machine tools. Splitting the application into two parts – contact detection and signal processing – allows a faster reaction on collisions depending on the overall situation.

Keywords:

Process Monitoring, Milling, Collision Prevention

1 INTRODUCTION

The requirements of production machines regarding their productivity and quality are rising continuously. In order to accomplish these demands, more and more machines are equipped with monitoring systems which observe the actual state of the machine components and the machining process itself. A reliable process safety along with high machining speeds and accuracy are an essential property of machine tools. A possible disturbance of the process is marked by a collision between moving and non-moving objects in the workspace. These collisions generally lead to high repair costs and long downtimes.

A survey with different users and machine tool manufacturers was conducted by the WZL in summer 2005. The objective of this survey was to find out the most common reasons for collisions in machine tools. As possible causes for hard as well as for soft collisions, handling errors by the user or the programmer were mentioned most often. The following errors were implied mainly as reasons for hard or soft collisions:

- the wrong definition of the applied tool,
- the installation of an incorrect tool,
- failures during preparation of a manufacturing process such as the zero offset.

Among this designated errors the definition of the zero offset turned out as the most common source for hard collisions. In case of zero shift errors the tool or the main spindle collides with the work piece at high speed and further damages are unavoidable. Other reasons for collisions were also named in the survey [1], e.g. errors caused by the machine or numeric control itself. However, the interviewees agreed almost unanimously, that such errors are very uncommon.

In Figure 1 a hard collision was provoked by a zero offset error. A drilling tool collides with the work piece at 10 $^{m}/_{min}$. During the first milliseconds the increasing force at the contact point bends the tool within the elastic flexibility range (t = 8 ms). After the non-elastic bending stage (t = 16 ms) the tool breaks (t = 23 ms). This experiment outpoints that a hard collision has to be detected during the first milliseconds. Taking into consideration the high masses and inertia of today's machine tools, an emergency stop may not avoid further damages if it is initiated more than five milliseconds after the first collision contact. Damages of the tool and particularly of machine components, such as main spindle bearings, are the consequences.

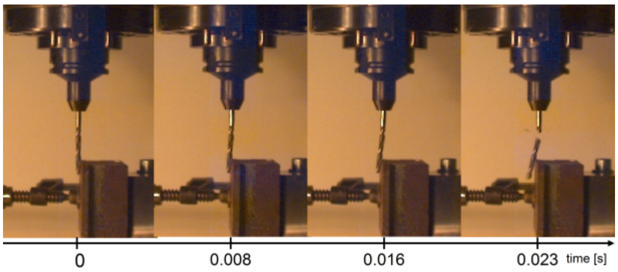

Figure 1: Collision of a drill tool at a feed speed of 10 m/min.

2 COMMON STRATEGIES TO DETECT AND AVOID COLLISIONS

Nowadays, two concepts for collision protection in spindle-nut-drives are widely established. One concept is based on mechanically releasing safety clutches, the other comprises systems which are fully integrated into the NC-control or additional sensor based collision monitoring systems.

2.1 Sensor based collision monitoring systems

External sensor based systems are usually used in machine tools because they operate independently from NC sample times. In collision situations it is of particular interest to detect the passing of defined thresholds as fast as possible. Hence, the applied sensors are installed as close as possible to the tool centre point [3]. The applied sensors are often acceleration or force sensors as well as piezo resistive wire strains. Generally, these systems do not use any NC internal information to analyse collision situations. However, sensor based collision monitoring systems cannot avoid a collision but only detect one. Once detected the main focus is on how to stop the machine as fast as possible. While manufacturing processes with low velocities allow such a collision monitoring strategy, other methods are required to monitor processes with high feed rates.

2.2 Control integrated collision monitoring

The objective of today's collision monitoring systems is not only to detect a collision as fast as possible but also to avoid a collision situation. Therefore, new approaches use information about the machine tool in the numeric control as e.g. defined zero offset, tool compensations and NC commands [4], [5]. These systems calculate the position of critical components to each other before they actually reach these positions. Therefore, they are able to avoid collision situations between machine components. Nevertheless, the NC is still "blind" regarding the installation of the correctly chosen or programmed tools, the work piece or clamping elements. Most collision situations are provoked by user errors. A simple error while stocking the tool changer's magazine or imprecise zero offset may result in a hard collision. The consequences are the loss of machining accuracy or even long downtimes to replace the damaged components.

2.3 Comparison of NC control internal and external sensor reaction times

As mentioned above, it is of particular interest to detect a collision as fast as possible. Thus, different sensor applications have been researched. This analysis provided a basis for a fast and secure detection of collision situations. Nowadays, users of monitoring tools have a strong interest in integrated and continuous systems. Hence, the first priority for a collision monitoring system is to include it in the NC. As described in [2], [7] and [8] NC integrated signals provide an excellent basis for process monitoring applications regarding backlash and guide way roller path damages as well as tool breakage in real time.

However, since the speed of detection is of critical importance, these control integrated signals do not necessarily provide an adequate signal resolution. They are normally recorded in the position cycle time which is currently limited to one millisecond in the Siemens 840D powerline. In Figure 2 the development of different force signals during a hard collision with a feed drive velocity of $9\ ^{m}/_{min}$ is represented. The feed drive force was calculated through the feed drive current and the characteristic feed drive constant. Furthermore, a force platform was installed to log the forces occurring during a collision between the tool and the work piece.

Comparing the two force signals the externally recorded force signal increases much faster than the control internally logged signal. Comparison of the signal progressions in detail (right part of Figure 2) yields that the externally recorded force signal starts rising immediately after the collision starts. As a matter of fact, there must be a programmed threshold which has to be crossed. Only then, the monitoring system may react to the collision situation. Considering that the external sensor has reached approximately 3500 N after the 6 ms it takes the internal current signal to show any reaction at all. It is obvious that monitoring the current signal may not be an adequate method to avoid further collision damages. Even externally logged signals such as the feed drive force will not avoid further damages to the spindle nut system or the bearings, as a threshold has to be defined, too. In case of high velocities, the threshold will be reached very fast. However, Figure 3 illustrates that in case of low feed velocities the defined threshold will never be reached or at least very late. Therefore, most collision monitoring systems use externally installed sensors, such as acceleration sensors or piezo resistant sensors. Particularly, it is difficult to decide during a manufacturing process, if the threshold is reached by a desired process or by a collision. Hence, new methods have to be found to detect and avoid collisions effectively.

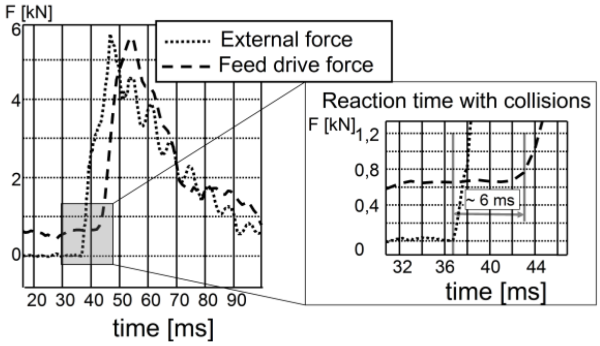

Figure 2: Reaction times of different sensor applications.

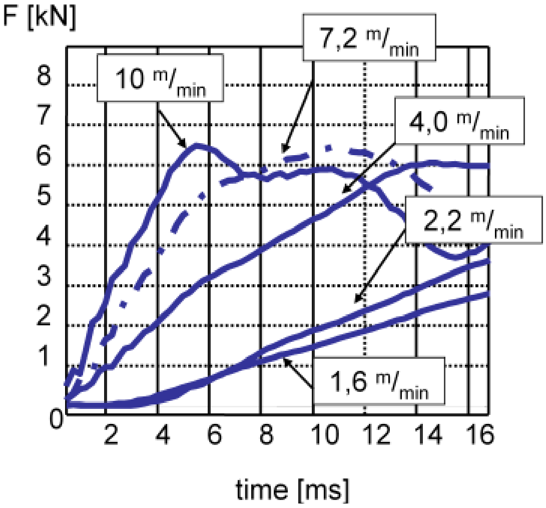

Figure 3: Force development at different feed speeds.

3 CONTACT BASED COLLISION MONITORING

To avoid or at least minimise collision damages a new approach is described in this paper. This new approach is based on the detection of the first contact at the beginning of a collision. The electrical contact would for instance indicate the first touch prior to significant forces. However, with this approach it is of particular importance to distinguish between a collision contact and the contact caused by the beginning of a manufacturing process. Thus the system under consideration is divided into six modules shown in Figure 4. It describes the operating mode of the contact based collision detection system. A contact sensor detects the first touch between the tool and another component of the machine. Immediately, the decision logic receives a signal and analyzes the contact situation with regard to the actual machining situation. If the contact initiates a collision the machine tool has to be stopped at least by internal NC emergency stop. If the current feed rate is too high so that control internal emergency stop does not prevent damages to the machine components and especially to the spindle nut, the rotating parts are to be uncoupled by an electronically activated clutch. Afterwards an external brake system decelerates the linear axes. The configuration as well as the actual state of the collision monitoring system will be realised by the module “user interface”.

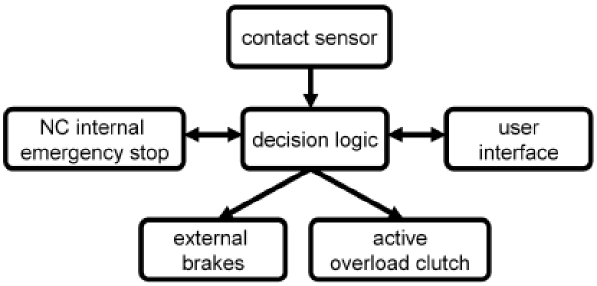

Figure 4: Structure of the presented collision monitoring system.

The following section detail the modules “contact senor” and “decision logic”. Primarily, the challenge of collision prevention is to recognise a dangerous situation as fast as possible. The described approach provides a new method to process monitoring in machine tools. Splitting the application into two parts – contact detection and signal processing – allows a faster reaction to collisions depending on the overall situation.

3.1 The decision logic module

As mentioned before, the contact sensor will not decide if the signal contact is the beginning of a collision or simply defines the manufacturing start. This is the function of the decision logic. Thus, it is of particular interest, that the logic obtains information about the complete process.

One way to distinguish between these situations is the analysis of process signals and generated signal patterns. In addition to the common process signals – like position, velocity and acceleration – the algorithm considers geometrical and material characteristics of the applied tool as well as detailed information about the current state of processing. Considering e.g. the easiest case of rapid feed motion, any detected contact indicates a collision situation. Hence, the machine has to be stopped as fast as possible. To avoid high damages to the spindle nut the rotating parts are to be uncoupled by an electronically activated clutch. Subsequently, an external brake system decelerates the linear axes.

The signal patterns are generated by the digital drive signals which are communicated to the decision logic by the numerical control. Additionally, current machine data and information about the installed tool are supplied. The technology data, the feed rate v_f and the rotational speed of the main spindle n_{MS} are related to each other through the feed per tooth FPT (f_z) and the number of cutting edges z. The worker prepares the manufacturing process by defining the feed rate v_f and the spindle rotation speed n_{MS} depending on the material and the installed machine tool.

$$\frac{v_f}{n_{MS}} = f_Z \cdot z \tag{1}$$

During the machining process the digital drive signals like the actual position as well as the reference values and the rotational speed are acquired by the logic module. Using these signals a reference and an actual *FPT* can be calculated continuously. Furthermore, the reference values are known prior to the actual signals. This allows a calculation of a reference FPT some milliseconds in advance. Thus, the reference FPT and the current FPT are compared to a FPT depending on the current tool data. If a FPT exceeds a maximum value this is an indication for an overly high feed rate.

3.2 The contact sensor module

The function of the contact sensor is the identification of an object in the path of the tool and the main spindle. As explained in the introduction, the tool normally is involved in collisions. Therefore, the development of a contact sensor has to include the tool as a part of the sensor itself in order to avoid collisions. At least the sensor needs to know about the applied tool and its geometry. As shown in Figure 6 later on an electrical contact offers a good and fast opportunity and an improvement in collision detection. Nevertheless, this sensor principle requires a physical contact between the tool and an installed object. For that reason other principles also have to be considered. Among these are:

- the ultrasonic and
- the capacitive sensor principle.

The following paragraphs will explain these two principles as well as the electrical contact sensor.

Use of an ultrasonic sensor

The use of ultrasonic sensors has several advantages. Regarding the time lag between the first detection of an object and the first physical contact, the ultrasonic sensor detects the object much earlier than an acceleration sensor (Figure 5). The ultrasonic sensor is installed in z-direction and identifies altitude differences between the tool and the test bed bottom.

Detecting an object, the ultrasonic sensor not only sends a detection signal, but also returns the actual distance.

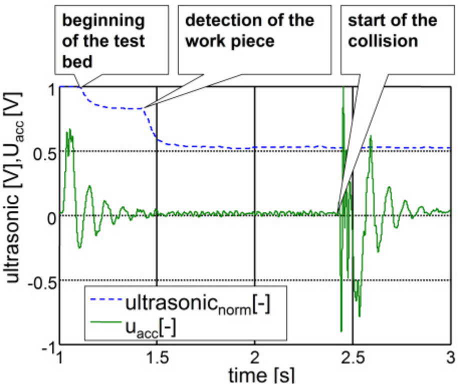

Figure 5: Detection of an object in the movement of the test tool compared to an acceleration sensor.

Taking into account the tool data and the installation position of the sensor, the decision logic is able to calculate if the detected object might collide with the applied tool. Considering the actual position and the distance to the detected object, the decision logic is also capable of making a decision about a possible collision. As the sensor only detects altitude differences but is not able to give further information about horizontal position the application requires several sensors installed around the main spindle.

Capacitive sensor using electrical contact

The explained solution using the ultrasonic sensor does not include the tool. However, one of the errors which provoke collisions is the wrong definition of the tool data or the installation of an incorrect tool. Therefore, the electrical insulation of the tool or the main spindle offers new and faster detection possibilities for a contact including the endangered machine components. Connecting the isolated components to a voltage source, a simple touch will suffice to recognise a contact between the moving and the static parts of the machine tool.

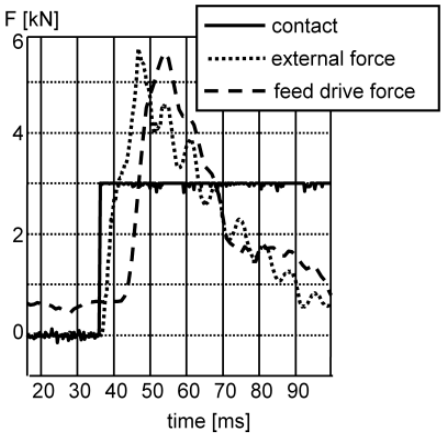

Figure 6: Collision with electrical contact signal.

Figure 6 shows the trend of forces during a collision and the adapted electrical contact signal. Obviously, the electrical contact is the first to indicate the beginning of the collision and does not need any threshold. Therefore, the decision logic is immediately triggered.

The electrical contact demands a physical contact. However, collisions with high velocities may not be avoided, as the stopping distance is longer than the elastic bending range of the machine tool. Hence, damages will not be avoided but only limited. To gain a little more time, the next step will be realising the capacitive sensor principle with the tool as active capacitor charger. Considering the insulation a contact will be identified as well. Since the capacity of a capacitor is inversely proportional to the charger's distance and proportional to the dielectric constant a possible contact can be measured. First experiments are made with a commercial distance sensor based on the capacitive principle. It was installed next to the tool and one could detect an object in axial direction with a distance of approximately 8 mm. the radial detection of objects was determined to 4 mm. The simulation results are shown in Figure 7. It shows that a contact can be anticipated about 2 mm before the physical contact (simulation conditions: C_{ISO}=1 nF, L= 35 µH).

4 SUMMARY

This paper presents a new approach to detect and avoid hard and soft collisions caused by user errors. The described proceeding is divided into several modules, two of them are explained. The contact module senses the first contact between two components of a machine. Thus, the decision logic will be activated much faster than conventional sensor applications would do. Although a contact does not immediately signify a collision, in some situations a contact is not allowed and therefore the emergency stop will be triggered faster than with conventional monitoring systems.

While the contact module is not able to choose whether the contact indicates a collision or not, the decision logic combines different signals to signal patterns. Using the look-ahead functionality of today's numeric controls, actual signals as well as reference signals are used to calculate the actual FPT. By comparing these signal patterns to a look up table depending on the actual tool data, a decision about the type of contact can be made at the very same moment.

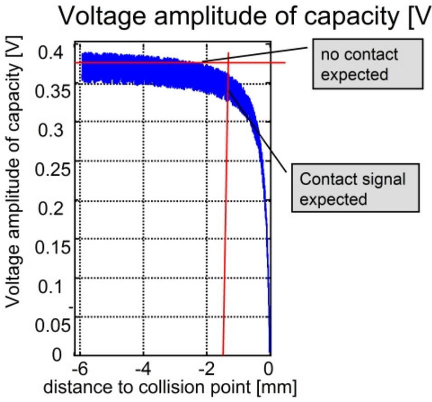

Figure 7: simulation results of the capacitive sensor principle

At the present stage the experiments with the electrical contact demonstrate a significant improvement regarding the reaction time. Furthermore, the capacitive principle might provide even better reaction times. However, the accuracy of the capacitive sensor principle has to be improved and guaranteed. At the present stage the repeatability of the capacitive measurement is their main short-coming for reasons of humidity, chips and other environmental effects. Additionally, the decision logic evaluates process signals. To enhance the logic module, the look-ahead functionality and the transfer behaviour of feed drive axes have to be considered.

5 ACKNOWLEDGEMENT

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