Strain gauge based sensing hydraulic fixtures

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Abstract

Clamping errors in workpiece positioning decrease the outcome of machine tools. To avoid rejects, which occur due to failures in the clamping, a sensory clamping system is being investigated at the Institute of Production Engineering and Machine Tools (IFW). The aim is to provide hydraulic clamping elements with sensory capabilities to enable condition and process monitoring of the clamping system inside the harsh environment of a machine tool.

Firstly, this paper gives a general survey of the targeted application and the concept to achieve a sensory clamping system for the industrial use in series production. Then it focuses on the integration of strain gauges into the exemplary chosen hydraulic swing clamp. Hereby, it shows the qualification of strain gauges for the estimation of different objectives, like hydraulic pressure, piston position, and external loads. Therefore, methods for the identification of suitable positions for the strain gauge integration into the clamping element are being discussed on the basis of experimental results and simulations. Furthermore, a method to achieve higher sensor sensitivity by 71% to the detriment of the compliance by 1.3% is presented.

1. Introduction

Clamping systems hold the workpiece in a defined position in the working space of a machine tool. Hence, positioning errors directly influence process behavior and machining results. Approximately 40% of rejects arise due to dimensioning errors that are attributed to poor fixture design [1].

The design and fabrication of fixtures take up to 20% of the total manufacturing cost [1–3]. Their quality often relies on the designers experience and is based on his understanding of the product. To reduce this dependency, but still provide a reliable clamping, much research effort has been focused on computer aided manufacturing. A broad survey of recent research and trends in computer-aided fixture planning (CAFP) and design (CAFD) are given in [1,3,4]. Most of the CAFP/CAFD methods have the aim to determine accessible and collision free locations of fixture points that ensure part immobility under the application of external forces and moments. Boyle et al. conclude, that many of the CAFD approaches have been tested for simple workpieces, which are not representative for those encountered in industry. Thus, the effectiveness of the developed techniques cannot be stated with confidence [4]. On this account, despite the accurate effort in the phase of fixture planning and designing, malfunction or failure during machining cannot be excluded.

Nevertheless, to ensure a reliable and sustainable manufacturing, different developments were done to enable machine components to monitor the machining processes [5–7] and to interact with manufacturing processes by using mechatronic systems [8]. Nee et al. [9] present an intelligent fixture prototype, which is capable of improving machined workpiece quality by controlling the clamping intensity. For the measurement of the clamping force, a direct sensing method with piezo-electrical force sensors was used. The direct monitoring methods can achieve a high accuracy, but due to numerous practical limitations, e.g. missing robustness against lubrication, these are characterized as laboratory oriented techniques [10]. To enable suchlike applications in industrial environment, sensor systems are needed, that are more suitable for practical applications at machine shop level.

An advantageous approach is presented by Litwinski [11] by integrating an intelligent sensor system into already existing components of a machine tool. Hereby, a modular clamping system is being investigated within the Collaborative Research Centre 6531 in the project N1. The system determines the potential use and performance of a manual sensory clamping fixture for machine tools. Being a prototype of a basic research project and regarding the robustness it is not suitable for industrial use yet. The system is

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characterized by integrated sensors for measuring cutting forces as well as accelerations and temperatures. The collected information allow assessing the current process state and the detection of process faults. The use for process monitoring offers outstanding performance. Therefore, the system is being transferred from research to industry within the transfer project T02 of the Collaborative Research Centre 653.

The aim is to develop a hydraulic clamping system, which is typically used in series production, with sensing capabilities in cooperation with two partners from industry, a clamping technology manufacturer and a fixture construction service provider. Error conditions such as wear, overload, incorrect setting, and improper use should be recognized to enable process and condition monitoring. In addition, the sensor integration, high system robustness, power and data transfer to rotating systems, and the consideration of cost aspects set special requirements to the application in an industrial environment.

Chapter Section 2 of this paper gives an overview of the overall concept to realize a sensory clamping system. Then it focuses in chapter Section 3 on the integration of strain gauges into hydraulic swing clamps to provide the fixture with sensing capabilities and ends with a conclusion in chapter Section 4.

2. Concept of the sensing fixture

The development of the sensory clamping system is carried out on the basis of a representative application scenario. It deals with the hydraulic clamping for multi-axis machining of cast casing covers. The simplified system structure is shown in Fig. 1a. The exemplary hydraulic clamping fixture (see Fig. 1b) is an assembly, which consists of a fixture plate, three hydraulic swing clamps with appropriate supports, and one hydraulic work support. The supply of oil for the hydraulic clamping elements within the fixture is realized by drilled hydraulic lines inside the fixture plate.

The realization of a sensing clamping fixture will be achieved by the sensor integration into the hydraulic clamping elements. Intended measurement quantities are strains, accelerations, and temperatures. Every sensory clamping element possesses an embedded micro-controller based hardware for signal-preprocessing. This serves several purposes: the shortening of susceptible analog transmission paths by digitalization close to the sensors, and the connection to a common fieldbus to enable communication abilities. In this way, it is possible to expand the fixture by additional sensory clamping elements with little effort. The transfer of the sensor information to an industrial PC for central data processing is established by an additional fieldbus participant via radio link. For the communication with the PLC of the machine-tool, e.g. to send status information, the industrial PC is provided with a PROFIBUS-interface.

To enable the multi-axis machining the fixture has to be mounted on a rotary table. Therefore, a hybrid rotary coupling is used to supply the fixture with electric and hydraulic energy. This unit is a combination of a rotary coupling for hydraulic oil and induction coils for contactless energy transfer. A typical voltage of 24 V DC is used and converted into AC voltage for the primary induction coil by an embedded circuit board.

3. Sensor integration

This chapter deals with the sensor integration. First the monitoring objectives and error conditions are described in Section 3.1. After that, the concept for the sensor integration is shown in Section 3.2. In Section 3.3 the result of preliminary experimental analysis are discussed, which led to the development of the methods for signal improvement that are described in Section 3.4.

3.1. Monitoring objectives and error conditions

The main task of hydraulic clamping elements is to convert hydraulic energy into mechanical clamping force. Hence, the actual present oil pressure inside the clamping chamber influences it directly. This principle is well known and used in hydraulic clamping systems for setting the clamping force by controlling the operating pressure at the hydraulic pump to a desired level. During the period of use different error conditions, e.g. leakages at hydraulic...
connections and blocked-up hydraulic lines, arise and cause oil pressure differences in the hydraulics.

Further error conditions that are reducing the lifetime of clamping elements result from incorrectly set parameters at the hydraulic supply. On this account, excessive flow rates and pressures must be avoided. To guarantee an appropriate clamping force before processing, it is useful to monitor the oil pressure and the pressure build-up time at the clamping element. Exemplary curves for an ideal pressure build-up and impermissible deviations are illustrated in Fig. 2a.

Despite of an adequate designed hydraulic supply, further faults in the clamping situation occur due to external reasons like wrong geometries or interfering objects, e.g. milling chips at the clamping point. These effects are often accompanied by a varying piston position (see Fig. 2b). Therefore, the following section presents a sensor concept to enable space-saving pressure measurement and piston position estimation.

3.2. Concept for sensor integration

To provide the hydraulic swing clamp (see Fig. 3a) and the hydraulic work support (see Fig. 3b) with sensing abilities, strain gauges were integrated into the hydraulic clamping elements. The following considerations towards sensor placing are related to the swing clamp.

The used hydraulic swing clamp is a double-acting clamping element with a bottom flange. The piston is constrained by a mechanism to fulfill a defined swing movement during the first half of the total stroke. The rest of the downward movement is usable for clamping. The swing clamp can roughly be summarized into the main components: the clamping arm assembly, the piston with the piston rod and the cylinder as shown in Fig. 3a.

Referring to the investigations of Litwinski [11] and the experiences of the industrial partners the maximum strains while clamping a workpiece occur in the clamping arm assembly and the piston rod. Despite the achievable sensitivity, these components are not suitable for the sensor placing. One reason to avoid sensor application at the clamping arm is the fact, that standard clamping arms are rarely used in industrial practice. Due to the available space on the fixture plate, which is strongly limited in most cases of series production, clamping arms have often to be designed individually for different clamping tasks. Another reason concerns the reliability and robustness in harsh environmental conditions. For the sensor connection a flexible cable routing would be necessary, which is susceptible to damage. Therefore, the cylinder of the swing clamp is chosen for further investigation towards sensor integration. To protect the mounted sensors against mechanical and chemical influences, e.g. cooling lubricants and chips, a cylindrical protective cover can be used advantageously. Some considerations concerning the moveable components of the clamping element apply to the hydraulic work support, which will be discussed in detail in subsequent publications.

Fig. 4 illustrates the concept of sensor integration. For the estimation of suitable sensor positions the finite elements method was used to point out the stress distribution in a simplified geometry of the swing clamp. Therefore, different conditions were simulated.

One way to acquire the hydraulic pressure inside the cylinder is the measurement of strains, which are caused directly by hydraulic load. Therefore, it is reasonable to place the strain gauge (SG) in the region of the biggest local deformations due to the hydraulic pressure. For the acquisition of strains even at small strokes the strain gauge SG 1 is placed at the level of the top dead center (TDC) of the piston, see Fig. 4a.

The stress distribution in the clamping element, which results directly from the hydraulic pressure, varies with the executed stroke. Increasing strokes lead to an amplification of the strains in the lower part of the cylinder as depicted in Fig. 4b. Because of that, a strain gauge SG 2 placed at the level of the bottom dead center (BDC) can be used to estimate the position of the piston, e.g. to detect interfering obstacles between the clamping arm and the
clamping point of the workpiece. This can only be achieved by a simultaneous evaluation of both sensors to enable the distinction between strains, which result from pressure or the executed stroke.

With the evaluation of additional strain gauges further objectives are detectable. An exemplary fault, which occurs in actuated elements, is for instance a blocked oil line that restricts the correct functionality. This results in an increased pressure at the oil return and could be recognized with a strain gauge at the position SG 3 in Fig. 4c.

The last example, see Fig. 4d, shows the strain distortion, which results from an additional applied force at the top of the piston rod. Based on the principle of the bending beam, the external force effects a bending load to the cylinder and that leads to an increase of the stresses especially at the bottom part of the clamping element. On this account a strain gauge placed at the position SG4 has the biggest sensitivity toward external forces in comparison to the other marked positions. Furthermore, this example illustrates that the external force never affects only a separated region of the clamping element. The influence on the measured values of the remaining strain gauges is probably unavoidable. Therefore, to attain a substantiated calculation of the present loads or faulty states, it is necessary to conjunct the different sensor signals and ascribe them to their cause. For this purpose it is essential to gain knowledge of the complex stress distortions inside the clamping element, depending on varying conditions.

It is obvious that the number of detectable objectives can be extended by applying additional strain gauges. But in consequence, every additional sensor increases the production costs, the dimensions of the circuit board for the preprocessing and the failure probability of the sensory clamping element. Therefore, it is necessary to find a compromise between the maximum number of sensors and the monitorable objectives.

3.3. Preliminary experimental analysis

To verify the concept of sensor integration, experimental analyses were performed. At present, experimental results exist for the concepts according to Fig. 4a/b. Therefore, two full bridge strain gauges were applied to the swing clamp, see Fig. 5a. According to Fig. 4b the lower bridge SG 2 is adjusted at the level of the BDC and the upper bridge SG 1 twelve millimeters above the BDC, which complies with the range of the clamping stroke. In the experimental set-up the swing clamp is connected to a hydraulic circuit, which supplies the cylinder with controlled hydraulic pressures. The pressure in the circuit is measured by a common hydraulic pressure sensor and is acquired as an absolute reference quantity. The measurements were done with the operating pressures of 0 MPa, 1 MPa and 15 MPa.

3.3.1. Calibration

The offset and the amplification of the strain gauges are calibrated to the voltages of 0 V at the hydraulic pressure of 0 MPa and 7.5 V at 15 MPa. The calibration was done without a supporting workpiece, so the piston executed the maximum stroke until the BDC. Thus, the deformations inside the hydraulic cylinder result only from the inner pressure of the hydraulic oil and the interaction between the piston and the stroke-limiting bottom of the cylinder. The measured graphs in this scenario (see Fig. 5b) match very well, so that an indirect measurement of the hydraulic pressure is possible, if no other loads affect the stress distribution inside the cylinder. The advantage of the direct estimation of the hydraulic pressure at the clamping element compared to a hydraulic pressure measurement at the supply is demonstrated in the enlarged section. Even short-time local pressure drops during the swing and downward movement of the piston are measurable with the strain gauges. This feature enables e.g. the monitoring of the time that this piston needs to fulfill the swing and clamping motion. To achieve similar performance with a conventional pressure sensor, it would be necessary to install it very closely to the clamping element. That would lead to the disadvantage of a significant loss of constructional place.

3.3.2. Load collectives

In ordinary application the clamping elements are always exposed to load collectives. The minimum number of loads results from the hydraulic pressure inside the cylinder and the clamping force, which is acting at the contact bolt. For this purpose measurements were done with the set-up in Fig. 5a in which the contact bolt presses against a support. Fig. 5c shows exemplarily the result with the end position of the piston at seven millimeters above the BDC. In comparison to the graphs from Fig. 5b it is clear, that the varied load situation does effect the stress distribution at the lower strain gauge, and thereby the signal of SG2 decreases. But it has rarely an effect to the upper strain gauge.

To display the influence of the end position of the piston to the strain gauge signals, a measurement series with a stepwise varied height of the contact bolt, to achieve a clamping with different end positions of the piston, was performed. For every end position one measurement graph of both strain gauge signals was captured and an arithmetic mean at a constant level of 15 ± 0.01 MPa (see Fig. 5c) was calculated. These mean values are plotted as solid markers over the remaining stroke in Fig. 5d. The curves show the expected development. The variation of the end position does not affect the strains at SG 1, so the curve remains at a constant level. The curve of SG 2 decreases with a higher end position of the piston because of the growing distance to the influenced area of the hydraulic pressure (compare Fig. 4a/b). The measurements were repeated with a second set-up. Here, the orientation of the
strain gauges was rotated around the Z-axis by 90° (see Fig. 5d) to expose them to the direct flux of force. The result of this measurement is plotted in Fig. 5d as dotted markers and labeled with SG 1 and SG 2. The curves have similar trends to the curves of the previous set-up with the difference that their absolute amplitudes are shifted to a lower level. This effect results from the deformation of the cylinder due to the external clamping force at the contact bolt. The deformation partially superimposes the stresses at the cylinder surface, which are initiated from the hydraulic load.

3.4. Methods for signal improvement

The use of the additional strain gauge SG 2 (compare Figs. 4b and 5a) purposes primarily the indirect estimation of the piston position. This is a valuable quantity for the monitoring of a correct executed clamping. It can be used to check the existence of a workpiece or to verify the variations in allowances of casted workpieces.

3.4.1. Decrease of strain gauge dimension

The results in Fig. 5d point out that the amplitude of the sensor signal SG 2 depends on the executed stroke. But to use this dependency for the piston position estimation vice versa, an improvement of the correlation of SG 2 to the stroke is necessary. One disadvantage of the used full bridge strain gauges is their dimensions regarding the desired objective. To center the strain gauge at the levels of the piston for both extreme values of the clamping stroke, thus with a displacement of 12 mm, both strain gauges have to be placed very close to each other, see Fig. 5a. Thereby, the measured values are similar. To achieve a sharper separation the use of smaller strain gauges has been examined by additional measurements. Therefore smaller strain gauge half-bridges were applied to the opposite side of the cylinder but at the same level as SG 2. For the purpose of improved comparability, the SG-signals in Fig. 6 are scaled to normed values between zero and one. The comparison of both signals demonstrates that using a smaller strain gauge for the measurement of more local strains a higher correlation to the piston position is achievable. But this fact presupposes even more detailed knowledge about the strain distribution at the cylinder, which is mandatory for choosing suitable positions for the strain gauge application.

3.4.2. Finite-elements based strain gauge positioning

To gain knowledge about the strain distribution at the cylinder, the strains at the cylinder were simulated using the finite elements method for different load situations and with a detailed geometry of the hydraulic swing clamp. The load situations were varied according to the desired monitoring objective with three different parameters: the hydraulic pressure inside the piston chamber, an external load at the clamping arm, and different heights of the piston, see Fig. 7a. To identify positions at the cylinder, which are influenced most by one of the three parameters and hardly from...
the others, the strain distributions were compared with each other. For a better visualization of the simulation results in further figures the strain distributions of the three-dimensional cylindrical surface will be illustrated in two-dimensional diagrams, using the polar coordinates \( Z \) and \( \phi \), see Fig. 7b.

Besides the positions for the strain gauges integration, the orientation of the measuring grid has also a big influence on the measured signal. Therefore, the strain distributions were analyzed separately for tangential and axial strains. An excerpt with the main results is shown in Figs. 8 and 9.

Fig. 8 shows the strain distributions of tangential strains that result from the hydraulic pressure of 15 MPa inside the piston chamber for the highest (a) and the lowest piston position (b). The difference between both load situations is depicted in Fig. 8c. It has to be noted, that the correlation between the hydraulic pressure and the absolute values of the strains, which is not shown separately in the figures, is also depicted in the FEM-set-up and result visualization.

Fig. 8. Strain distributions at varying piston positions.

Fig. 9. Strain distributions at varying external load.

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explicitly, is linear. All three figures have eight local maxima that occur due to geometrical reasons and indicate positions at the cylinder surface, which are influenced most from the hydraulic pressure. Therefore, the application of strain gauges with tangential orientated measuring grids at the height of approx. 14 mm at the maxima in Section 2 are most suitable for the estimation of the piston position, because this section is most sensitive to piston position variation. The highest amplitudes, which result directly from the hydraulic pressure, are expected at the height of 30 mm. To achieve a sharper separation to Section 2, the positions for the strain gauges placing for the estimation of hydraulic pressure are defined to the higher level between 30 and 40 mm, see section 1 in Fig. 8b.

Fig. 9 shows exemplary strain distributions for tangential (three graphics at the bottom) and axial strains (three graphics on the top) at the highest clamping position of the piston for load situations without (a) and with an external load (b). In these calculations, the external load was applied by displacing the clamping arm by 0.1 mm in the negative Y-direction. At the top position, this load equals approximately a force in Y-direction of 3.5 kN and can result, e.g. from process forces which act at the workpiece. As is observable in Fig. 9c the highest changes of the strain amplitudes occur in axial direction and are located at the bottom of the cylinder at heights lower than 5 mm. Therefore, in order to achieve high sensitivity towards external loads like displacements and forces at the clamping arm, this section has been chosen for the application of strain gauges with axial orientated measuring grids. In this investigation, the change of strains in tangential direction is relatively low.

This simulation-based investigation shows that the absolute values and the orientations of the strains at the hydraulic cylinder strongly differ depending on the cause.

3.4.3. Influencing the flux of force by notch effects

A further step toward signal improvement concerns the increase of sensor sensitivity by influencing the force flux by the utilization of the notch effect [12]. A successfully implementation of this method to achieve a sensory Z-slide is demonstrated in [13]. Therefore, a notch geometry for the insertion into the clamping element was defined. With the application of strain gauges at the notch base, the local increase of stresses is exploited to improve the sensitivity of the integrated sensor. First simulation results with a simplified geometry of the swing clamp cylinder (see Fig. 10) indicates that for the illustrated case a local stress increase of 71% can be achieved. The negative effect in this case, the weakening of the swing clamp cylinder by increasing the compliance by 1.3%, is relatively low. Currently, FEM studies are carried out with a more detailed swing clamp geometry for the purpose of the optimization of the notch dimensions and the determination of further suitable positions on the clamping element for the integration of strain gauges.

4. Conclusion

The presented paper shows latest results from the development of a sensing fixture for the use in an industrial environment. The research is conducted within a joint research project with industrial partners.

At first, a general overview of the system structure and the description of the targeted fixture design are given. To provide the fixture with sensing capabilities the concept for the sensor integration is explained. It comprises the application of strain gauges at the hydraulic clamping elements. In order to measure different influences on the strain distribution several positions for the sensor placing are discussed.

The usability of integrated strain gauges for the indirect measurement of hydraulic pressure is verified on the basis of an experimental set-up with a hydraulic swing clamp. The measured signals demonstrate the dependency of the strain gauge locations on a further desired quantity, the clamping position of the piston, and thereby the capability for its estimation vice versa. To improve this correlation the beneficial use of smaller strain gauges is demonstrated experimentally. In addition, the identification of different strain gauge positions for the estimation of certain objectives is shown on the base of finite-element-analyses. To improve this estimation a method to increase sensor sensitivity by applying notches to the clamping element is presented. Based on finite element simulations the improvement of sensor sensitivity by 71% to the detriment of the compliance by 1.3% is achievable.

In further investigation, the proposed simulation-based methods will be verified experimentally and used for sensor integration to enable the monitoring of hydraulic pressure, force, and piston position with sensory hydraulic swing clamps.

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