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IN-PROCESS MONITORING AND ANALYSIS OF DYNAMIC DISTURBANCES IN BORING AND TREPANNING ASSOCIATION (BTA) DEEP DRILLING

This paper presents an approach to monitor the dynamic disturbances of a BTA (boring and trepanning association) deep drilling system. High length to diameter ratios are the key characteristic of deep drilling processes compared to conventional drilling applications. Since length to diameter ratios of up to 150 for slender tool-boring-bar assemblies are common, the deep drilling process is sensitive to dynamic disturbances such as chatter and whirling vibrations. Whirling vibrations usually effect the shape of the hole and cause holes with several lobes. To gain a deeper understanding of the dynamic state of the process, a sensor application has been developed and was tested in practice. Experimental investigations on BTA deep drilling with continuous multi-sensory monitoring were conducted. The used setup allowed the determination of the frequencies of chatter and whirling vibrations during the cutting process by analysing the logged data using a continuous short-time Fourier transformation (STFT).

1. INTRODUCTION

From a holistic point of view, drilling is one of the most important processes in manufacturing technology. Considering a representative spectrum of work pieces in industry, drilling takes about 36% of the primary processing time of all machining operations [1]. One of the most common deep-drilling processes in solid drilling is Boring and Trepanning Association (BTA) drilling, which is also referred to as single-tube-system (STS) drilling. BTA drilling can be applied for boring (counterboring) and core drilling (trepanning) applications. It is possible to setup different operation modes with various combinations of cutting and feed movements of the workpiece and/or the tool. It can be performed either by rotating the boring bar-tool assembly and lock the spindle of the workpiece or lock the boring bar-tool assembly and rotate the workpiece or even by counter rotating both. In all this cases the feed motion is provided by a drive unit moving the boring bar-tool assembly.

The STS/BTA deep hole manufacturing process is a drilling method based on a special self-guided drill head [2] with an asymmetric arrangement of cemented carbide cutting

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inserts. Due to this arrangement, the resulting radial process forces are induced asymmetrically as well, therefore guide pads are used to support and guide the tool head in the bore hole being drilled. This self-guided application leads to a sliding movement of the pads along the lateral surface of the wall with additional levelling and smoothing effects on the surface microstructure [3]. The forming or burnishing process decreases the surface roughness and leads to higher surface quality. Compared to conventional drilling the STS/BTA principle is supplying cooling lubricant under pressure through an annular space between the bore wall and the boring bar to remove chips through narrowed chip passages on the tool head and the boring bar. Hence the chips do not scratch the finished bore hole surface like in conventional drilling processes. Furthermore, the coolant lubricates the cutting zone and tends to reduce friction between the guide pads and the workpiece. A high volume flow of the cooling lubricant is responsible for flushing the chips *via* the chip mouth and the boring bar.

The high length to diameter ratios in general are the key characteristic of deep drilling processes compared to conventional drilling application. The STS/BTA method is applicable for diameters in a range from roughly 6 mm up to 1500 mm. Since length to diameter ratios of up to 150 for slender tool-boring-bar assemblies are common [1], the deep drilling process is sensitive to dynamic disturbances such as chatter and whirling vibrations. In the present work an approach tackling the challenge of implementing a monitoring system for a STS process is presented. With this flexible sensor integration, it is possible to monitor all kinematic operation modes of cutting and feed movements in deep drilling.

1.1. DYNAMICS OF DRILLING

The mechanics of conventional drilling have been presented by Galloway [4] with the aim to predict the cutting forces and torque. Griffiths et al. [5, 6] presented a time invariant mathematical model to determine the cutting force system, the tangential pad forces and the friction coefficients for a single cutting edge and two pads tool head configuration. The drill tube is modelled as a flexible beam with a drill head at its free end. Therefore, the dynamic drilling system can be described with the following equations of motion,

$$[M]\begin{Bmatrix}\ddot{x}(t)\\ \ddot{y}(t)\\ \ddot{z}(t)\\ \ddot{\Theta}(t)\end{Bmatrix}+[C]\begin{Bmatrix}\dot{x}(t)\\ \dot{y}(t)\\ \dot{z}(t)\\ \dot{\Theta}(t)\end{Bmatrix}+[K]\begin{Bmatrix}x(t)\\ y(t)\\ z(t)\\ \Theta(t)\end{Bmatrix}=\begin{Bmatrix}F_x\\ F_y\\ F_z\\ T_c\end{Bmatrix} \tag{1}$$

where x and y are the lateral deflections, z is the axial and Θ the torsional deflection of the boring bar. According to the system description the mass, the damping and the stiffness matrices are represented by the symbols M, C and K. Apart form that, the external process forces acting on the drill tube include two lateral forces (F_x and F_y), one thrust force (F_z), and a torque (T_c). Such modelled systems depend on functions of the chip thickness, width of cut, material properties, the cutting insert vibration at the current time (t) and one tooth period earlier ($t-\tau$) [7]. Additional influences, especially in deep drilling, are the tool head geometry [8], the drilling depth, which leads to a shift in the natural frequency of the boring bar-tool head assembly [9], the stiffness and guidance of the stuffing box [10] and Lanchester dampers and the own weight of the boring bar. Several studies investigated the dynamic behaviour of deep drilling for STS/BTA and gun drilling applications. Thai [11], Chin [12] and Weber [13] presented analysis and time invariant models. Furthermore, detail investigations towards the dynamic behaviour of the bar in STS/BTA drilling were carried out by Chin et al. [12, 14, 15] and Perng [15].

1.2. CHATTER VIBRATIONS

Chatter in metal cutting has been an intensely discussed research topic for several years. According to Tlusty [16] the basic mechanism of chatter is a regeneration of waviness. This mechanism is caused by a vibrating tool leaving a wavy surface on the workpiece, which again excites the tool at the same frequency during the next tooth passage. Thus tool vibrations go along with dynamic interactions of the cutting forces and cause a time-delayed, regenerative torque and thrust on the tool. The cutting force will grow and the vibrations will turn unstable if the phase difference between the current tool motion and the prior surface is in an inappropriate range. While in conventional drilling torsional-axial chatter is very dominant due to the geometric structure of twisted drills, chatter vibrations in deep drilling typically occur due to torsional vibrations and are in the proximity of the natural frequency of the tool-boring bar.

First studies towards regenerative chatter vibrations in conventional drilling have been conducted by Tobias and Fishwick [17]. Bayly [18] developed a single degree of freedom model to study the torsional-axial chatter in drilling. The working group of Altintas et al. [19–22], conducted significant research in the field of time domain simulation with nonlinearities in drilling process. Additionally they developed stability diagrams and included model with process damping effects. Despite all the research work to predict cutting forces and stable or unstable process phases by modelling, the role of the chisel region is still difficult to describe and has been simplified.

Investigations from Weinert et al. [9, 23, 24] have been conducted with the focus on the development of process dynamics during the STS/BTA method. Therefore, they analysed the drilling torque signals recorded during the process and observed that chatter and non-chatter phases may alternate. Additionally they observed that the modes involved in chattering might change during the process due to the change of the system condition as a function of the drilling depth. The experiments have been conducted with a locked boring bar-tool assembly and a rotating workpiece. Based on experimental data from Weinert et al., Raabe et al. [25] developed a statistical-physical model to simulate the chatter vibrations as regenerative effects.

1.3. WHIRLING / SPIRALLING

Before starting with the technological aspect of whirling or spiralling in drilling, a few words should be pre-mentioned according to the nomenclature. In the literature, a different wording is used for the phenomena of low frequency regenerative vibrations, which are responsible for generating holes with helical multi-lobe formations. In conventional drilling, this mechanism is called whirling whereas in deep drilling it is called spiralling or rifling mark generating phenomena. Effectively, all these terminologies describe process instabilities during drilling with polygonal shape effects towards the bore hole. These holes can run into critical shape tolerances like roundness and the cylindricity and are having a consequence towards the produced component quality. Incidentally, the diameter may be within the tolerance if it is measured between two direct opposite points because the resulting polygonal shape is mathematically a curve of constant width, which are depicted in Fig. 1a.

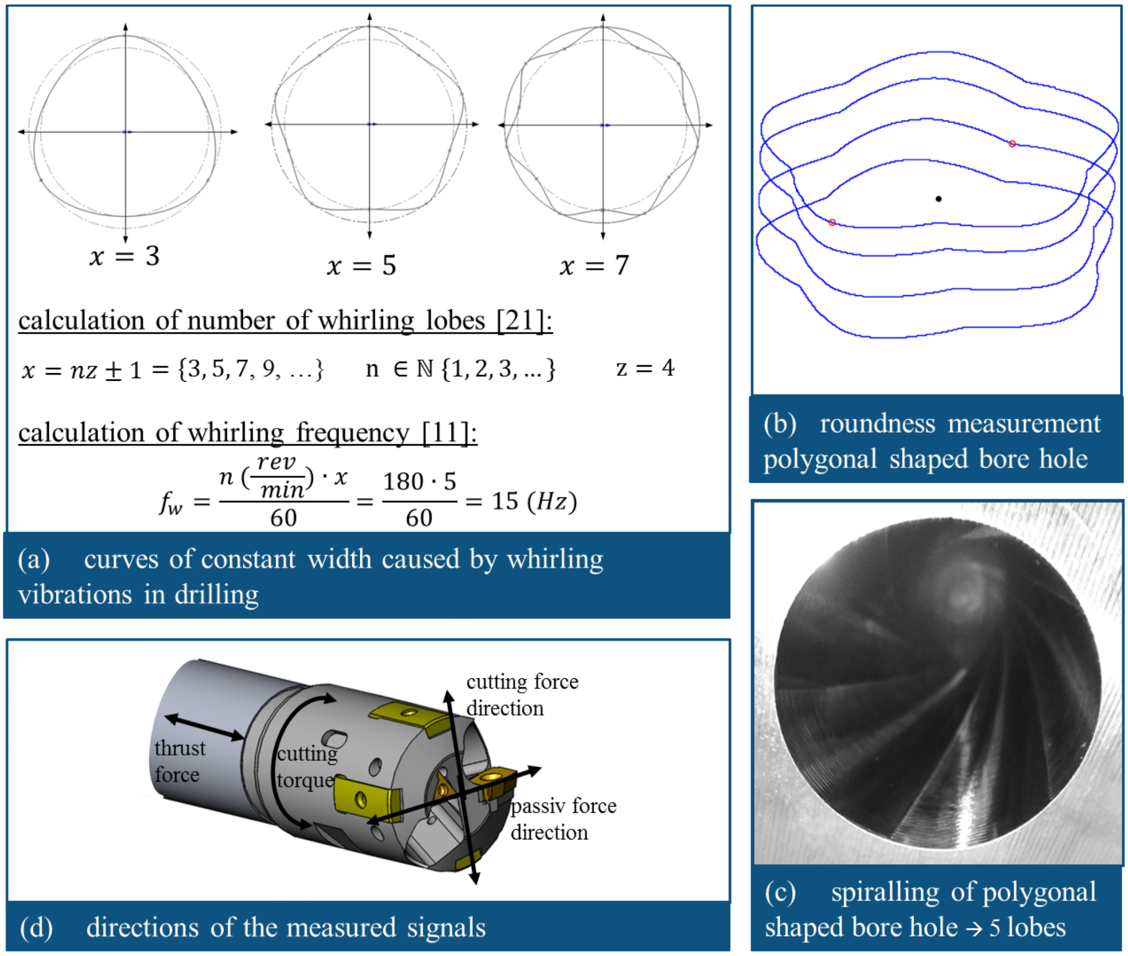

Fig. 1. (a) Curves of constant width caused by whirling vibrations in drilling, (b) roundness measurements of polygonal shaped bore hole, (c) picture of spiralling of a polygonal shaped bore hole, (d) measurement directions of the monitoring system

From investigations in gun drilling [26] it was demonstrated that whirling vibrations occur due to the static unbalance of the process forces acting on the tool head. Stockert [27] was one of the first who investigated the effect of the tool design parameters on whirling vibrations for STS/BTA drilling. In studies towards the process stability he also distinguished between three different origination points of whirling vibrations. One is directly at the beginning of the process, the second is reproducible and occurs at the same drilling depth and third arises randomly. Gessesse et al. [28] presented for the second type of whirling incidents a study were such vibrations show associations with bending modes of the boring bar. Whirling disturbances are able to arise when the frequency of the rotation or its higher orders coincide with the eigenfrequency of the bending mode of the boring bar. Consequently, whirling generates vibrations with frequencies of the rotational speed and its higher orders [29]. Studies on investigations on the eigenfrequencies of the boring bar have been published by Chin et al [6] and Perng [15]. Due to the constant varying drilling depth, it leads to shifts of the eigenfrequencies caused by the changing support situation. This subject has also been elaborated by Gessesse et al. [10] and Webber [30]. Efforts in terms of modelling the STS/BTA process and its vibration instabilities were conducted by Al Wedyan [31], Chin et al. [12], Matsuzaki [8] and Raabe [25]. Based on experiments, they built models to predict critical process frequencies were instabilities may occur.

2. EXPERIMENTAL SETUP

Significant research work has been conducted on modelling the mechanics of drilling. Therefore, the different phenomena of dynamic disturbances in drilling have been discussed with different and separated theoretical models. Nevertheless, in reality axial, lateral and torsional vibrations arise simultaneously when drilling a bore hole. Therefore, predictions are still difficult to make for dynamic process disturbances.

To gain deeper insight into the process and generating the basis for avoidance techniques it becomes necessary to set up a holistic process monitoring system. Consequently, it is mandatory applying sensory equipment to the BTA machine. A simplistic overview of the used setup for this investigation is depicted in Fig. 2.

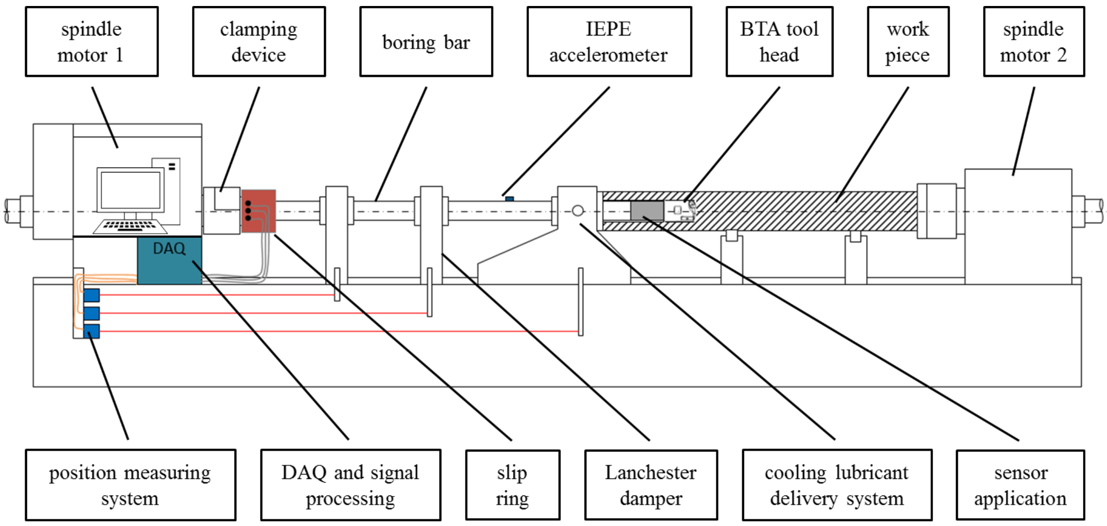

Fig. 2. Principle of the STS/BTA machine with sensor application positions

One focus of our investigation is to determine the dynamic disturbances of the process, which are induced by the interaction of dynamic cutting forces and the structure of the boring bar. As it can be seen in Fig.2, the measuring equipment was implemented onto the boring bar. In previous investigations [3, 13, 24, 30, 31] different monitoring systems for STS/BTA processes have been developed and discussed. Usually the sensory applications were mounted at the rear end of the boring bar just before the boring-tube chuck. It is obvious that this approach decreases the challenges that come along with the high-pressure oil environment and the minimised installations size due to the limited annular space between the wall of the bore and the boring tube. Weinert [23] presented a modified BTA-tool head to accommodate acceleration sensors but stated that this application is just feasible for experimental purposes. One issue for this statement is that tool heads have to be replaceable for reasons of tool wear or adjusting the cutting inserts and guiding pads. This circumstance renders creating sufficient power supply and signal transfer problematic.

This was considered in the present monitoring application and hence the sensor was mounted at the front end of the boring bar, right after the connection thread towards the BTA tool head to be very close to the cutting process. Thus, it is a very flexible system and it is possible to use BTA tool heads from different commercial suppliers. The sensor integration is based on strain measurement devices to detect the cutting torque, the thrust force and the bending moments in cutting force and passive force direction, as depicted in Fig. 1d. The location of the sensors is chosen to minimise the influence of the Lanchester damper towards the sensor signal which is pivoted on a steady rest. A measurement device for detecting the cutting torque is mounted at the rear end of the boring bar to compare and determine the measurement results. The current signals of the force measurements have been calibrated with a multicomponent dynamometer (Kistler Type 9129AA) to convert the unit to newton and newton metres.

Additionally surface micromachined capacitive (MEMS) accelerometers (ADXL001 ±250 g) have been installed close to the tool head to measure the rotational acceleration around the centre axis of the tool. The dislocation of the boring bar is detected with eddy current sensors, which were mounted 150 mm after the end of the bushing of the coolant supply unit. In this paper, we will focus our discussion on the force measurement data.

With the used BTA machine, it is possible to perform the previous described kinematic variants of the procedure. Especially for drilling operations, where the boring bar-tool assembly rotates it is challenging to transfer data to the stationary data acquisition platform. To overcome this challenge, a slip ring with gold-plated contacts has proved to be suitable.

The specimen material, with which the test has been conducted, was nonmagnetic, austenitic Mn-Cr-steel with a high nitrogen content, see Table 1. For the cutting tests, BTA drilling tools with two indexable inserts and three exchangeable guide pads with a diameter of 72 mm have been used. The used carbide cutting inserts were coated with a TiN layer. The modified boring bar with a total length of 4 m was connected to a CNC BTA deep drilling machine

Table 1. Chemical composition of tested workpiece material in %

C	Mn	Cr	Mo	N	Ni
max 0.06	20.50–21.60	18.30–20.00	min 0.50	min 0.60	min 1.40

3. EXPERIMENTAL RESULTS

One major point of interest regarding the monitoring system is to detect the tool wear of the cutting inserts. With this information it might be possible to give statements about the actual status of the cutting inserts as a function of the drilling depth, workpiece material, process parameters and volume flow of the coolant supply.

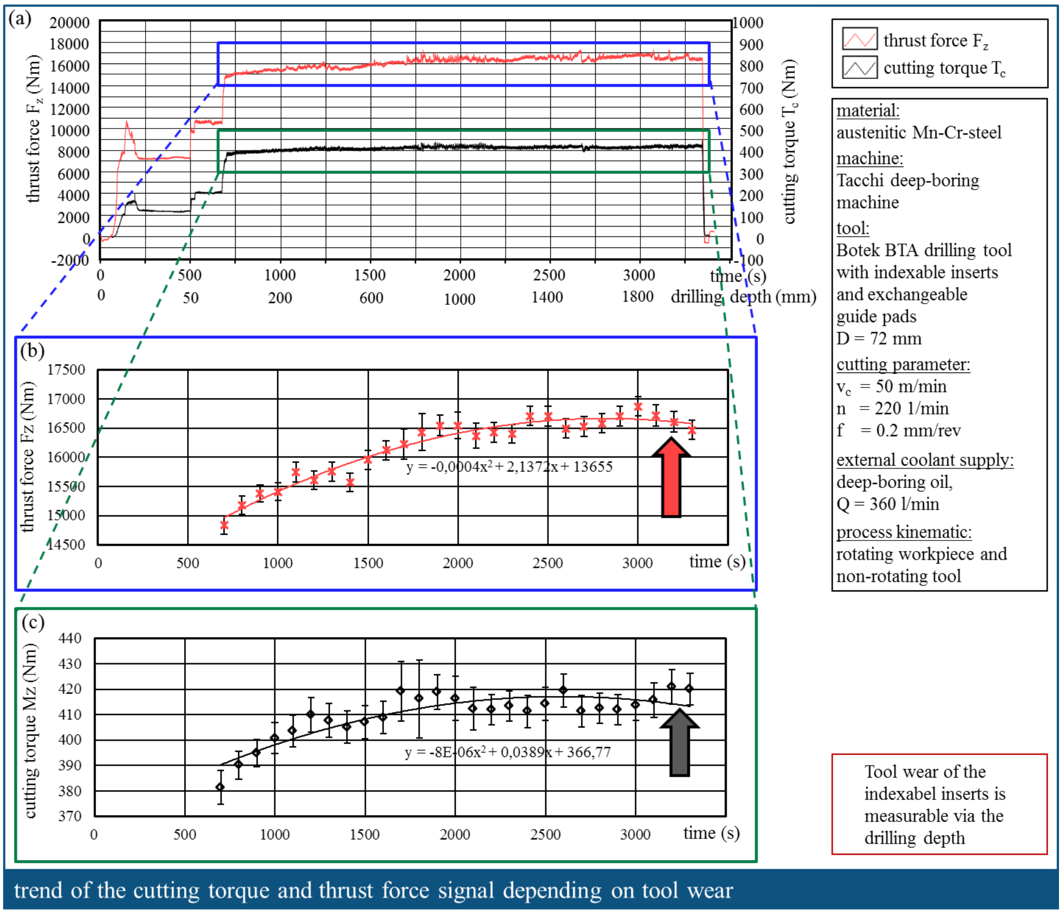

Fig. 3. (a) Time domain signal of cutting torque and thrust force, (b) mean values of the thrust force via drilling depth, (c) mean values of the of cutting torque via drilling depth

In preliminary trials, we tested new cutting inserts and compared the measured signals to the signals that were acquired with cutting inserts with extensive states of wear. Additionally, several combinations of process parameters have been tested with feeds between 0.1–0.2 mm/rev and cutting speeds in the range of 30 and 50 m/min. These tests proved that the thrust force and the cutting torque, conducted with the worn inserts were constantly higher than the signals recorded with the new cutting inserts.

After these promising trial results, cutting tests with higher drilling depths have been conducted. As an example for these tests, the time series analyses of the cutting torque and the thrust force are depicted in Fig. 3. This experiment was carried out with stationary tool and rotating workpiece. The process starts with the so called initial phase, where the tool head is guided in a starting bush. By leaving the bushing, the tool head is self-guided and after approximately 70 mm drilling depth, the feed was gradually increased to 0.2 mm/rev and then kept constant to a drilling depth of about 2 m. As it can be seen in Fig. 3a no significant dynamic disturbances occurred during the whole process.

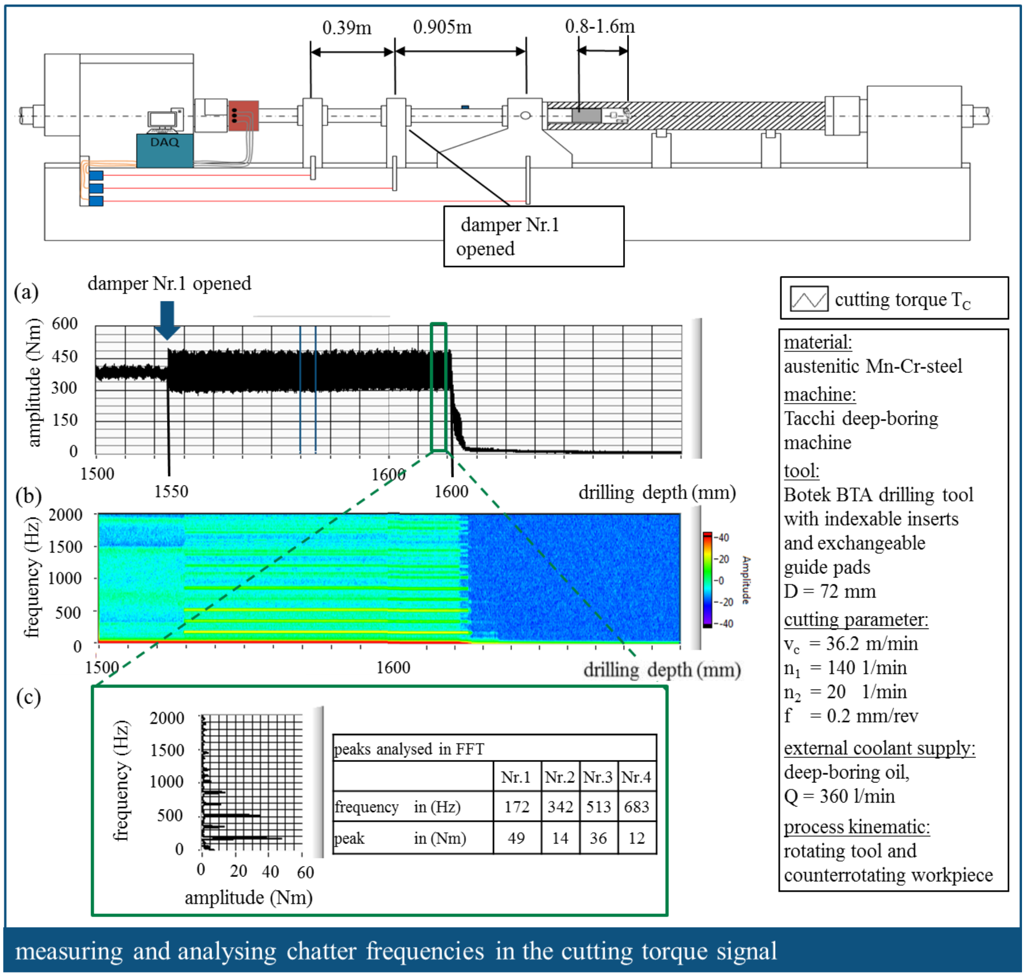

Fig. 4. (a) Time domain signal of cutting torque, (b) STFT of signal of cutting torque, (c) FFT of cutting torque with dominant frequencies, with chatter occurrence in the signals

The increase of the cutting torque (black line) and the thrust force (red line) over the drilling depth is depicted in Fig. 3c and 3b, respectively, which represent the development of the signal mean over the process time. Both signals show significant increase of the mean value via the drilling depth, more precisely with an 8–10% increase of the thrust force and 5–7% increase of the cutting torque. Consequently it is possible to measure an increase of cutting torque and the thrust force in relation to the tool wear and the drilling depth.

3.1. DETECTING AND ANALYSING CHATTER VIBRATIONS

According to the holistic monitoring of the process also the actual position of the Lanchester dampers is measured by laser distance sensors. In deep drilling, these dampers have two areas of application. One is the geometric alignment and the support of the boring bar against deflections caused by the horizontal arrangement and the other one is damping chatter frequencies. The principle of balancing torsional vibrations is based on an inertia ring that is typically tuned to the first torsional natural frequency of a shaft.

It is proposed to use vibrations dampers when the tool is rotating [32], so tests have been conducted with such a set-up to provoke the tendency of the system towards chatter vibrations. The parameters have been selected so that the boring bar-tool assembly rotates with 140 rpm and the workpiece counterrotates with 20 rpm. During these cutting tests chattering naturally occurred due to the drilling depth dependency of the deep drilling system. A transition of a stable into an instable cut due to an amplitude shift in the time series signal of the cutting torque is depicted in Fig. 4. At a drilling depth of 1550 mm the signal noise rises significantly. In Fig. 4b, the time frequency spectrogram of the short-time Fourier transform (STFT) is presented. It can be seen that the density of the spectral power is intensified for chatter frequencies represented by the green horizontal lines. The dominant frequencies measured during the chatter phase are presented in the table given in Fig. 4c, where 172 and 513 Hz are dominant. The frequencies in the range of 170–173 Hz, 341–343 Hz and 512–514 Hz have also been detected during chatter disturbances at rather different drilling depths ranging from 500 to 1500 mm. This circumstance and previous investigations [24] show that these frequencies, which are harmonics of the 172 Hz, appear with periodicity when chatter occurs.

Additionally, the tests have also been conducted with a BTA tool head from a different supplier. The tool head diameter was also 72 mm wide; however the macroscopic arrangement of the cutting inserts is different because this type is equipped with three indexable cutting inserts and three exchangeable guide pads. In a cutting test with the same configurations and process parameters also the frequencies of 170–173 Hz, 341–343 Hz and 512–514 Hz have been detected during instable chatter phases. Furthermore, these frequency measurements have also been detected in signals of the MEMS accelerometers. Additionally, these numbers of frequencies also arise during instabilities in drilling with clamped tool set-up and a rotating workpiece with 160 rpm. Interestingly, the higher harmonic 512 and 1539 Hz are the pre-dominated frequencies in the spectral analysis.

3.2. DETECTING AND ANALYSING WHIRLING/ SPIRALLING

Whirling or spiralling is also a dynamic phenomenon in drilling, which should be avoided in stable cutting processes. Following the investigations of Gessesse et al. [28] and Weber [28], a similar approach has been chosen to intensify the likelihood of spiralling during the process. Despite operating the cutting tests at critical speeds, modifications of the guide pads, seen in Fig. 5, have been conducted because the resulting cutting speed would be too high for the tool diameter of 72 mm and the workpiece material. Nevertheless, with the adapted tool setup and counterrotating bore kinematics, spiralling arose during the process. The resulting bore hole of this test is depicted in Fig. 1c where the helical multi-lobe formation can be seen at a glance. In this investigation, five lobes have been measured by tactile roundness measurements of the specimen and coincided with the prediction formula of Sakuma [33].

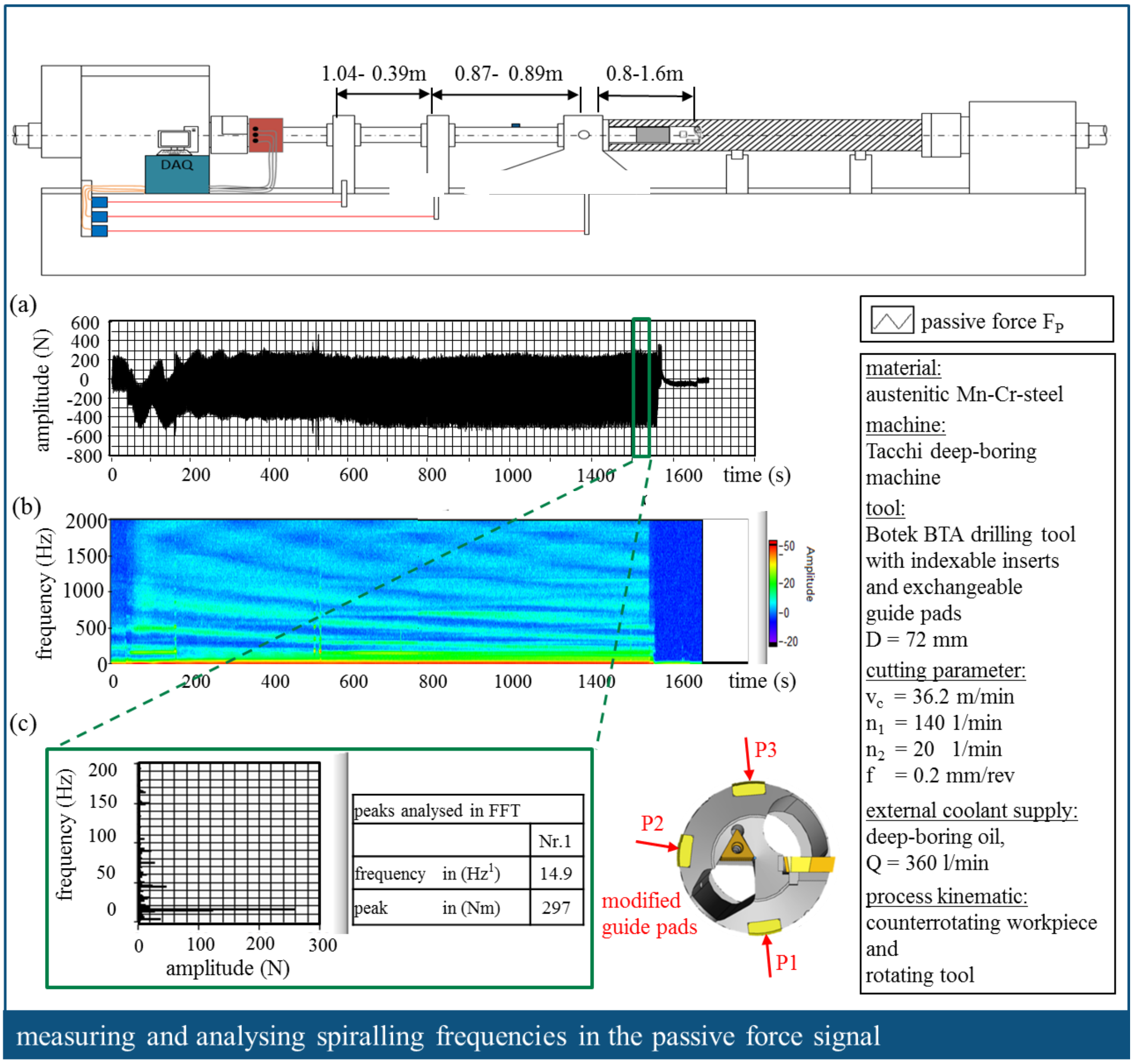

Fig. 5. (a) Time domain signal of normal loads in passive force direction, (b) STFT of signal of normal loads in passive force direction, (c) FFT of normal loads in passive force direction with dominant frequencies

As spiralling is related to the coincidence of bending modes and multiples of the rotation frequency [11], strains caused by bending moments are measured. One is in the direction of the cutting forces which are perpendicular to the rake face of the cutting inserts and the other one is shifted 90 degrees into the direction of the passive forces. The measured signals are thus equivalents to the normal forces in these directions. In Fig. 5, the measurements according to the spiralling bore hole in Fig. 1c are shown. In the STFT over the drilling depth from 800 to 1600 mm, transition shifts in the frequencies of the spectral power density can be seen at a glance. After about 400 seconds of recording time, also an increased intensity of the spectral power can be seen for lower frequencies than 500 Hz. To get a deeper insight, an FFT-based spectral analysis was used to analyse the vibration signals. The dominant frequency in this dynamic signal is about 15 Hz which is in fact the fifth order of the frequency of the rotational speed and corresponds to the helical five-lobe formation of the bore hole.

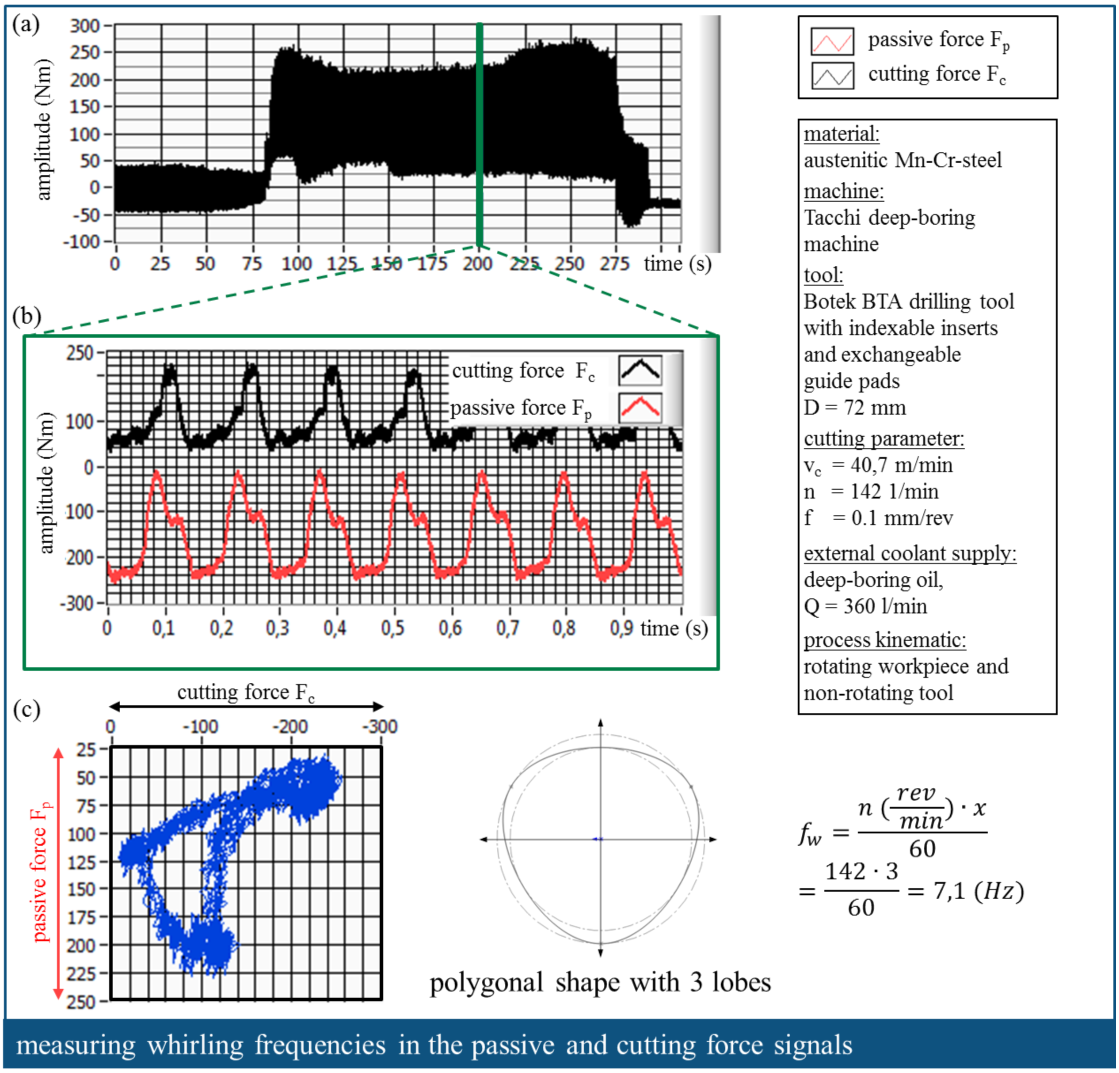

Fig. 6. (a) Time domain signal of normal loads in cutting force direction, (b) periodic behaviour of normal loads in cutting and passive force direction (c) orbit plot of cutting and passive force direction

In the current investigations, spiralling was also generated in cutting tests with a stationary tool and a rotating workpiece, as can be seen in Fig. 6. During this process, a three-sided borehole was generated. Compared to the experiment depicted in Fig. 5, the principle of correlations between the dominant measured frequency and the order of the frequency of the rotational speed, applies here as well. In Fig. 6b the time signal of two bending forces are shown. During spiralling these two signals show quasiperiodic behaviour with a phase shift of $\pi/2$. By arranging the two signals in an orbit plot, a two-dimensional image of the resulting loading effects onto the boring bar is generated. This diagram reflects the loading shaft centre motion during the cutting process. It is evident that the reflecting orbit plot shows a triangular shape, which has certain similarities to a Reuleaux triangle. During constant cutting phases without spiralling, the signal in the cutting force direction shows non-periodic characteristics. Besides, the orbit plot does not show relevant geometric shapes.

4. CONCLUSION

An approach for monitoring dynamic disturbances of the BTA deep hole boring system has been developed successfully to gain deeper insight to the process dynamics. A holistic, continuous multi-sensory process monitoring system is needed for the generation of data and information on the process itself. The basis for further investigations is developing avoidance techniques regarding dynamic instabilities. One major driving force of this investigation was to create a monitoring system with a flexible sensor integration guaranteeing to monitor all possible kinematic operation modes of cutting and feed movements in deep drilling. An additional approach aimed at the application of the sensors close to the cutting process to minimise the influence of the Lanchester damper and the cooling lubricant delivery system towards the sensor signals.

In cutting tests, the system has been tested to detect two major dynamic instabilities in deep drilling which are chattering and spiralling. The system was tested under different kinematic process operation modes, with different BTA tool heads, as well as different cutting parameters. Here, the monitoring system showed promising results to give clear statements about the process condition.

Further experiments will aim at drilling depth dependent chatter disturbances and the dominant frequencies. Additionally, the formation mechanism of spiralling and its adequate detectability is an issue for ongoing research. This can serve as basis for real time avoidance techniques of spiralling or whirling vibrations in deep drilling.

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