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Does the User Behavior effect the Productivity of Hammer Drilling?

Analysis of the Influences of Feed and Lateral Force

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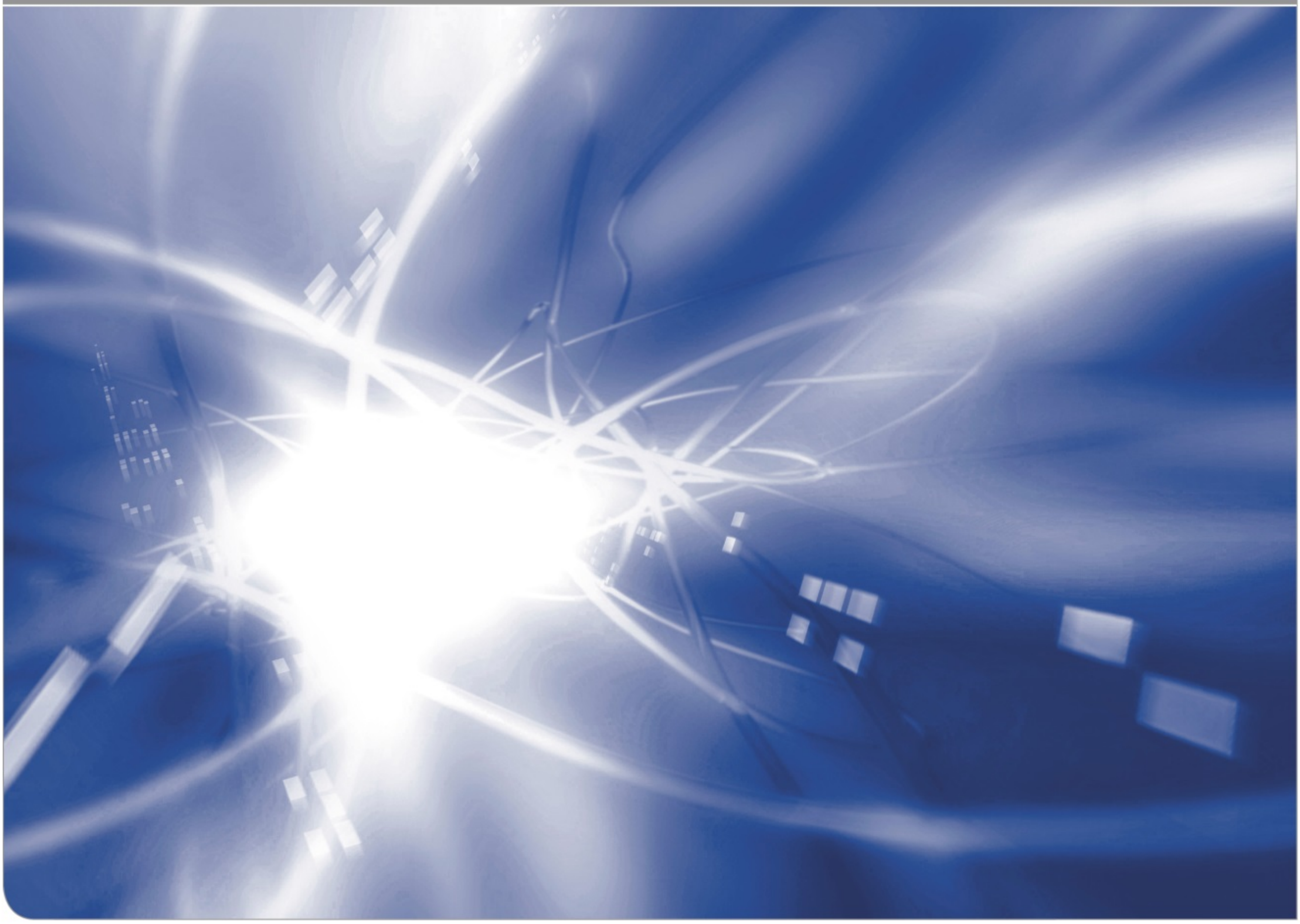
KIT SCIENTIFIC WORKING PAPERS 191



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Impressum

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2022

ISSN: 2194-1629

Does the User Behavior effect the Productivity of Hammer Drilling? – Analysis of the Influences of Feed and Lateral Force

Abstract:
The objective of this study was to investigate the relationship between feed and lateral force with productivity in hammer drilling. Necessary user forces and vibration caused by hammer drilling leads to user fatigue and long-term injuries. Through an increase in productivity, the stress duration and thus injuries caused can be reduced. The user, who influences productivity, applies lateral forces in addition to the feed force during hammer drilling. Their influence and interaction with the feed force on productivity has not yet been investigated. In this study, a total of 1152 boreholes were performed on an automated test bench. Along with the feed and lateral forces, the setup, consisting of hammer drill and drill bit model, was varied in order to investigate interaction effects as well as discuss transferability of the findings. The productivity was evaluated by the rate of penetration (ROP). It was observed that the ROP decreased with increasing lateral forces ($p < .001$, $r = 0.315$) and increased with increasing feed force. The detailed courses of these relationships were setup-specific. At low feed forces, the feed and lateral force interacted on the ROP. The investigated relationships indicate an efficient operating range depending on the user forces and setup used, which enables a reduction of the user's stress duration. The findings help engineers develop power tools that provide more efficient and hence less fatiguing work, making them more ergonomic for the user.

Keywords: power tool, rate of penetration, user forces, human-machine systems, user-centered design

Highlights:

- Lateral and feed force influence the productivity of hammer drilling
- The detailed influence of user forces depends on the hammer drill and drill bit
- Lateral forces should therefore be taken into account when developing power tools

1 Introduction

The construction industry is reporting higher demands than ever before in the last 20 years. In the USA, over $1.25 trillion was spent on construction work in 2019 (Wang, 2020). Other industrial sectors are also benefiting from this. In Germany, for example, the power tool industry has recorded a sales increase of over 25% in the last 8 years (Breitkopf, 2019). One of the most commonly used power tools is the hammer drill. Electric hammer drills are used for chiselling work and, depending on the size of the construction project, thousands of holes are drilled into mineral materials. An example of this would be the mounting of dowels or concrete screws. The aim of the manufacturers should therefore be to develop products that have the highest possible productivity.

During product development of power tools, a holistic view of the system - consisting of user, device and workpiece - and their interactions with each other is relevant (Aptel et al., 2002; Bruchmueller et al., 2019; Matthiesen et al., 2018). Since there is a strong physical interaction between the user and the device during the drilling process due to the flow of information and power (Fraser, 1980), the performance and reliability of the system are strongly influenced by the user. However, these interactions also cause the user to be placed under stress. The user stress that occurs during hammer drilling in the form of muscular exertion leads to muscle fatigue over a certain period of time. This muscle fatigue is influenced by task repetition and force (Ferguson et al., 2013). Muscle fatigue resulting from static posture reduces the user's cognitive attentional resources and could therefore have an effect on the quality of the work result (Stephenson et al., 2020). In addition, excessive vibration stress can lead to long-term illnesses, also known as hand-arm vibration syndromes (HAVS). HAVS are diseases that can occur in users of vibrating hand tools and include circulatory disorders (e.g. white finger disease), sensory and motor as well as musculoskeletal disorders (Weir and Lander, 2005). The probability and extent of HAVS depend on the intensity and duration as well as frequency of exposure.

Thus, an increase in productivity not only increases the economic efficiency, but also reduces the duration of the workload and thus the risk of fatigue and disease on the user. Looze et al. (2001) showed that in product development, increased productivity and reduced stress often go hand in hand. To increase productivity, both the power tool and the tool itself are constantly being further developed. The trend is towards user-centered design, in which the human is in the focus of the development design. In order to optimally develop the technical system for the user, the influence of the user must be known in addition to the influence of the technical system.

One parameter used to characterize productivity is the rate of penetration (ROP) (Botti et al., 2017; Rempel et al., 2019b; Uhl et al., 2019). The ROP describes the feed rate in drilling meters per time. So far, various studies have been conducted to explore the effects of different factors on ROP during hammer drilling. In addition to the user influence, the technical system, consisting of the hammer drill and the drill bit (Carty et al., 2017; Cronjäger and Jahn, 1985; Kivade et al., 2015; Rempel et al., 2019a; Rempel et al., 2017), and the workpiece properties, such as the concrete strength (Cronjäger and Jahn, 1985), have a decisive influence on the productivity of the drilling process. Other investigations consider the flow of forces from the striking mechanism of the hammer drill through the drill bit to the contact surface between the cutting edge of the drill bit and the workpiece (Gruner and Knoll, 2000; Hecker, 1983; Hecker and Riederer, 1985; Vonnemann, 1977). According to the approach of the holistic system view, an influence of the user on the drilling process has already been discovered (Botti et al., 2020; Uhl et al., 2020; Uhl et al., 2019). Moreover, the user's behavior or applied forces can be divided into active and passive forces (1982). The active user forces result in the feed force, which acts in the drilling direction, and the lateral forces, which act normal to the drilling direction (Uhl et al., 2019).

That active user influences, which have an effect on the drilling process and thus also on the ROP, have been observed for the past 40 years, especially for the feed force. Hecker (1983) investigated the factors influencing noise emission, and concluded on the basis of three individual runs that increasing feed force increases ROP. However, in Hecker's study, the small number of experiments means that one cannot assume the findings to provide statistical evidence. Furthermore, Rempel et al. (2019b) described that "The feed force differences (88 N vs 150 N) had little effect on ROP". In a comparison to an experiment by Botti et al. (2017) with the same experimental setup they observed an increase in ROP from 9.09 mm/s to 9.7 mm/s caused by the increasing feed force. Based on this, Botti et al. investigated the relationship between different feed forces and ROP for one hammer drill and drill bit setup. They described an increase in ROP of 7.2 to 8.5 mm/s associated with an increase in feed force from 95 N to 185 N and that no further increase in ROP was observed with a further increase in feed force to 211 N (Botti et al., 2020). Since Rempels et al. as well as Botti's et al. studies are based on only one drill bit and hammer drill model, transferability of these findings to other models has not yet been verified. In a study by Uhl et al. (2019) the influence of feed force on productivity was investigated using an automated test bench and the findings were summarized as follows: "With regard to the active influences of users, it could be shown that the rate of penetration increases with increasing feed force". However, Uhl et al. used a hand-arm model that does not adequately model human behavior and were only able to demonstrate this effect for two levels of feed force. Hence, he was not able to prove statistical significance. Furthermore, Kivade et al. (2015), through using an experiment with a jackhammer drill and 30 mm diameter integral drill bits in an ascending manner, observed that the ROP increases with applied pressure until a maximum is reached, where after it starts to decrease as the pressure continues to increase. The observed peak in ROP was explained here due to the increased pressure preventing a complete return stroke of the drill bit. As the pressure continues to increase, the drill bit reaches a possible "stall" condition (Kivade et al., 2015). Due to the different system components, this behavior cannot be transferred to electric hammer drills without verification.

Uhl et al. (2019) were able to show with three subjects that the forces generated by the user during hammer drilling cannot be reduced to the applied feed force alone, in which they demonstrated significant lateral forces caused by the user. For example, Uhl et al. were able to measure lateral forces with a median of up to LF = 16.2 N and a maximum of LF = 55.6 N during manual hammer drilling. In another study with 15 subjects, Uhl et al. (2020) confirmed that users apply lateral forces. The subjects applied lateral forces of 16.7 N at the median and 37.6 N at the 95th percentile over one bore. A single outlier reached a maximum of 73.1 N. Finally, Uhl et al. recommended further investigations on their influence on the drilling process.

The state of research shows that the active user influence on ROP regarding feed force had been investigated in several studies, but the exact relationship has only been examined in one study and only on one setup. Whereas lateral forces in manual hammer drilling have been demonstrated, but their influence on productivity and possible interactions with other influencing factors have not yet been researched. Momeni et al. (2017) wrote that small lateral motions exerted by skilled operators and varying the feed force can reduce borehole friction. If the detailed relationship between user forces, consisting of feed and lateral forces, on productivity were known, optimal operating points between user forces, productivity and user load could be identified. Thus, power tools could be developed that are best designed for user ergonomics. Therefore, the following research question shall be answered here:

- Which relationship exists between the active user forces, consisting of the feed and lateral force, and the productivity during electric hammer drilling?

In order to answer this research question, this study investigated the relationship between the feed and lateral forces with the productivity during electric hammer drilling. For this purpose, a robotic test bench including a hand-arm model was used to automate the drilling process while modeling various user forces. The data obtained was analyzed using the Bonferroni-corrected post-hoc tests. Since the state of research shows an influence of drill bit and hammer drill on productivity, a transferability of the results with different setups was examined. In addition to the main effects of the investigated relationship, interaction effects could also be explored.

2 Materials and methods

2.1 Experimental design

Two different hammer drills with SDS-Plus drill chucks were used to carry out the experiments. Each had an angular gearbox but differs in the design of the striking mechanism. The hammer drill from Bosch (model GBH 3-28 DRE, Robert Bosch Power Tools GmbH, Leinfelden-Echterdingen, Germany) (see point 4 in Figure 1), weighing 3.6 kg, generates 4000 bpm with an impact energy of 3.1 J via a tumbler bearing at a nominal speed of 900 rpm. The hammer drill from Hilti (model TE 30-AVR, Hilti Deutschland AG, Kaufering, Germany), weighing 4.2 kg, has a crank drive which generates 4500 bpm with an impact energy of 3.6 J at a nominal speed of 1100 rpm.

A total of three different drill bit models were used during the test runs. The drill bit with four cutting edges from Hilti (model TE-CX 10/22 MP8, Hilti Deutschland AG, Kaufering, Germany) (9) and the drill bit with two cutting edges from Alpen (model SDS-plus F4 Forte, ALPEN-MAYKESTAG GmbH, Puch bei Hallein, Austria) each had a diameter of 10 mm and a working length of 150 mm. These two drill bit models allowed a comparison to previous studies (Uhl et al., 2020). The validity of the investigated relationship was also verified for a hollow drill bit. The authors; however, were not aware of any hollow drill bits with a diameter of 10 mm. Therefore, a hollow drill bit with two cutting edges from Fischer (model FHD 14/250/380, fischerwerke GmbH & Co. KG, Waldachtal, Germany) with a diameter of 14 mm and a working length of 250 mm was used. Since there was no comparison between the absolute values of the drill bit types during data evaluation, the different drill bit diameters did not pose a problem. With the aid of an industrial Festool vacuum cleaner (model Absaugmobil CLEANTEC CTL 26 E, Festool GmbH, Wendlingen, Germany), the drilling dust was extracted from the hollow drill bit during the drilling process.

For the experimental procedure, a concrete block (concrete test body C 20/25, Rau-Betonfertigteile, Ebhausen, Germany) (5) with a minimum compressive strength of 25 N/mm² made of standardized concrete was used. The workpiece had dimensions of 2400x1200x200 mm³ and reinforcements with a diameter of 6 mm and a spacing of 150 mm. Reinforcement hits were prevented by the way the experiment was conducted. Based on the standard DIN EN 206-1 (2017), the strength class of the workpieces refers to a condition after 28 drying days. The workpieces meet the conditions defined in the standard ISO 28927-10 (2011) for workpieces.

The drilling runs have been performed on an automated test bench with a KUKA robot (model KR 500 R2830 MT, KUKA, Augsburg, Germany) (1). The hammer drill was connected to the flange of the robot via a hammer drill mount and a hand-arm model (HAM) (6), based on the study presented by Cronjäger et al. (Cronjäger et al., 1984; Jahn and Hesse, 1986). The HAM was designed for modeling translational movements in the drilling direction due to the installed plain bearings and suitably dimensioned spring elements. Movements perpendicular to the drilling direction are made possible by elastomers. During the course of the study, only movements were performed that were within the validity range of the HAM. A multi-axis force & torque sensor (model NET FT Omega 160-IP65, ATI, Apex, NC, USA) (2) was used to control the feed and lateral forces. The dust generated during drilling was extracted via a hose (8) attached to the robot. The setup of the test bench can be seen in Figure 1.

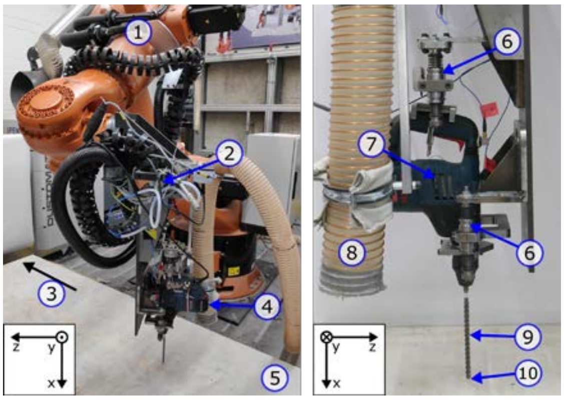

Figure 1: Automated hammer drill test bench incl. visualization of the tool coordinate system.

Two temperature sensors (model TJC100-ICSS-M050U-150, OMEGA Engineering GmbH, Deckenpfronn, Germany) were used to measure the hammer drill and drill bit temperatures. The measuring points of the temperature sensors are shown in Figure 1. The temperature of the hammer drill was continuously measured at the side ventilation slots (7). The temperature of the drill bit was measured between the drilling of each borehole at the tip of the drill bit (10).

2.2 Experimental procedure

Each borehole was drilled vertically downwards until a depth of 120 mm was achieved. In order to prevent possible binding of the drill bit due to lack of air flushing, a dust extraction phase was carried out at half of the drilling depth. The feed and lateral force as well as the hammer drill and drill bit model were varied during this process using a full-factorial experimental design created with MODDE (Modde Pro 12, Sartorius AG, Göttingen, Germany). In this design the hammer drill and drill bit model were considered as blocks. In order to reduce the setup times of the test bench and to avoid influences due to multiple assembly, all drillings were first performed with the hammer drill from Bosch and subsequently with the hammer drill from Hilti. Eight drill bits were used for each drill bit model, with each creating 48 boreholes at a time. Consequently, a total of 1152 drillings were carried out for this study. The factor levels of the feed and lateral forces were selected to represent realistic drilling processes on the basis of the measurement results of manual drilling tests (Uhl et al., 2019). These are listed in Table 1.

In order to reduce a possible influence of the inhomogeneity of the workpiece properties caused by the manufacturing process, such as the pouring direction (see point 3 in Figure 1), the positioning of the boreholes on the concrete block was randomized. In addition, reinforcement hits were prevented by suitably positioning the boreholes.

Table 1: Factor levels of feed force, lateral force, hammer drill and drill bit.

Factor	**Factor levels**					
Feed force [N]	80	110	140	170	200	230
Lateral force [N]	0	20	40	60		
Hammer drill model	Bosch GBH 3-28 DRE (Bo)	Hilti TE 30-AVR (Hi)				
Drill bit type	Helical, 2 cutting edges (He2c)	Helical, 4 cutting edges (He4c)	Hollow, 2 cutting edges (Ho2c)			

The hammer drill was not switched on until the workpiece was approached via an automated control of the power supply. In order to avoid an unwanted influence of the hammer drill and drill bit temperature on the measurements and an associated falsification of the results, a warm-up phase of the hammer drill was carried out before the experiment. This warm up phase was followed by a cooling phase between each drilling. Thus, the drill bit was cooled down to 60°C before the start of the next drilling. The temperature of the hammer drill was kept between 60 and 80°C during the test runs, since a low temperature of the striking mechanism has a negative effect on the ROP (Cronjäger and Jahn, 1985).

During drilling, the robot system converts the active user behavior in the form of the feed and lateral force in a force-controlled manner. A Proportional Integral (PI) control was used for the feed force and a Proportional (P) control for the lateral force. This resulted in a reset time until the target forces were reached. To prevent the drill bit from deviating to the side or breaking out, the target lateral force was only applied after 30 mm of drilling depth in the z-direction of the tool coordinate system. In order to avoid an exaggeration of the lateral force resulting from both spatial directions, the lateral force was controlled to LF = 0 N in the y-direction of the tool coordinate system. The HAM modeled the user vibration characteristics during the drilling process.

2.3 Data analysis

Evaluation range

The unprocessed raw signal of all measurements included the following phases of a test: approach drill bit to workpiece, start drilling, drilling step 1, dust extraction, drilling step 2, extraction (see Figure 2).

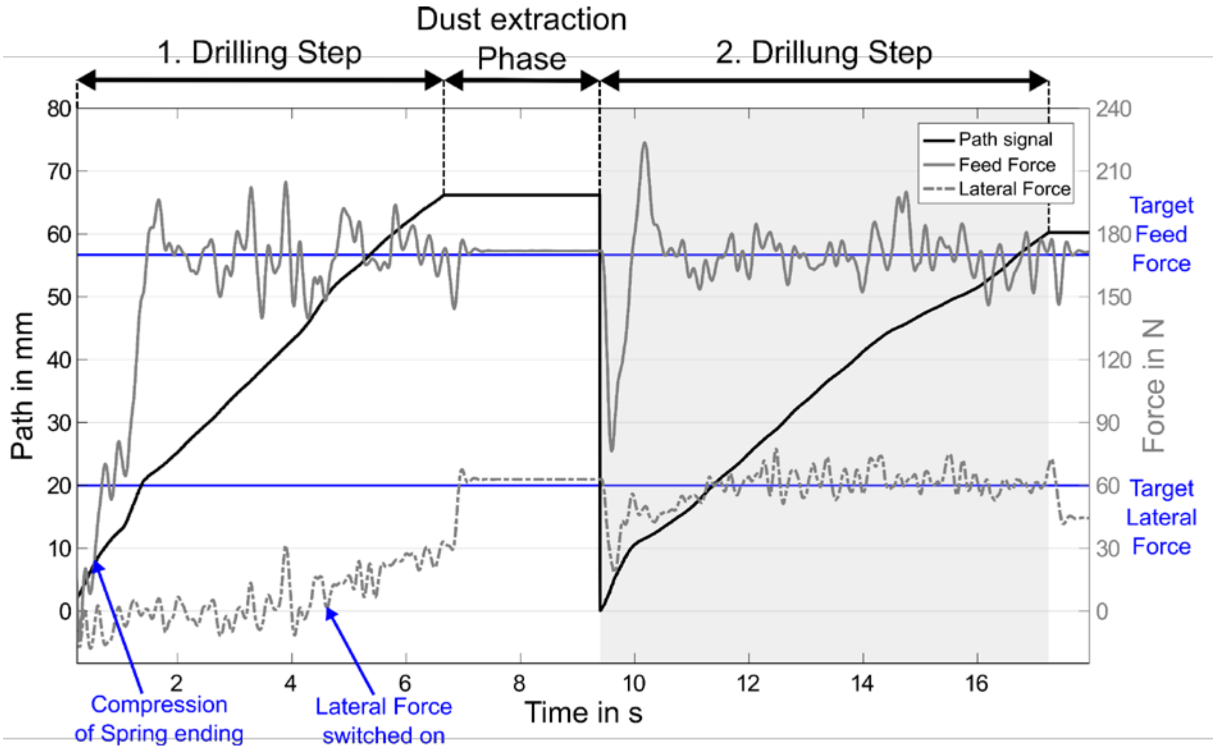

Figure 2: Raw signal of the feed (gray solid line) and lateral force (gray dotted line) as well as the path signal (black) of a borehole with the target values of the feed force of 170 N (blue) and the lateral force of 60 N (blue). Phases: 1. approach & drilling start, 2. first drilling step, 3. dust extraction phase, 4. second drilling step & evaluation range (gray).

In the start phase of the drilling process, the feed force (FF) setpoint is continuously built up due to the control speed. The spring deflection of the HAM, which is dependent on the feed force due to the spring rate, falsified the evaluation of the achieved drilling depth in the start phase, since this is determined via the signal of the executed position correction of the robot. In addition, according to the manufacturer, the operating range of the hammer drill lies above FF = 80 N. As already mentioned in 2.2, the lateral force was only applied from a drilling depth of 30 mm. The reset time caused by the control results in the fact that the feed and lateral force target values have not yet been reached at the beginning of the first drilling step.

For the analysis of the measurement data, only the ranges in which the target values of the feed and lateral force have been reached should be evaluated. Due to the control deviation resulting from the start of drilling and the control-related reset time, only the second drilling step was evaluated in the following analyses of the required measured values for all drillings. The instances of time for cutting the raw signal were determined based on the force signal accordingly. A low-pass filter with a cutoff frequency of 10 Hz filtered out high-frequency oscillations in the force signal, which were generated by the hammer strokes and subsequently occurring vibrations. The evaluated time range differed between the individual test runs due to different ROP values, but remained around 12 s, as can be seen in Figure 2. The processing of the raw signals and calculation of the measured values within the evaluation range were performed with Matlab (Matlab R2017a, The MathWorks, Natick, MA, USA). Furthermore, the dependent variables calculated in this way were graphically evaluated and statistically analyzed using SPSS (IBM SPSS Statistics 25, IBM, Amonk, NY, USA).

Productivity analysis

To determine the ROP, the drilling depth performed in the evaluation range was divided by the duration of the evaluation range t, as seen in (1). The motion s performed by the robot in the evaluation range in the feed direction was used to determine the drilling depth.

$$ROP = \frac{s_{end} - s_{start}}{t_{end} - t_{start}} \quad (1)$$

The aim of this analysis was to determine the relationship between the feed or lateral force and the ROP. Furthermore, it was of interest to investigate whether this relationship can be transferred to the individual setups, consisting of hammer drill and drill bit. To achieve the highest possible significance of the statistical tests, the data of all setups with a similar course were combined. If the setups had a similar course, but differed from each other by a clear deviation of the mean values, a z-transformation of the measurement data was performed.

When using a multifactorial ANOVA to determine whether the hammer drill and drill bit factors had an influence, each group consisted of eight samples. For these groups, the significant Levene test ($F(143,1003) = 1.479$, $p = .001$) indicated a disparity of variances. Consequently, non-parametric tests were performed to investigate a possible influence of the setups. The main effect of the hammer drill on ROP was determined using a Mann-Whitney U test, while the effect of the drill bit model was determined using a Kruskal-Wallis test. The main effects examined were finally evaluated using Cohen's (1992) effect size.

Moreover, the Kruskal-Wallis test was used to investigate the effect of feed and lateral force, and post-hoc tests were used to statistically evaluate the mean differences in productivity due to the individual factor levels. To address the problem of increased probability of alpha error, the Bonferroni correction was applied. The effect size of feed and lateral force on ROP was evaluated relatively. In the statistical evaluation of the measurement data, five test runs were not considered because the drilling process was interrupted during their execution. Mean values (M), median (Mdn), standard deviation (SD), and interquartile range (IQR) are given in the chapter 'Results'. P values < .05 were considered significant.

3 Results

3.1 Control accuracy & descriptive statistics

A control accuracy of the adjusted feed force of SD < 1.5 N was achieved for the test runs investigated. Vertical to the drilling axis, the standard deviation for the lateral force adjusted to the respective factor level was SD < 3.9 N, and for the lateral force adjusted vertically to 0 N, SD = 1.0 N. The exact values of the descriptive statistics can be seen in Table 2.

Table 2: Descriptive statistics of the user forces effectively generated with the control system.

Factor	Target force [N]	Mean force [N]	Standard deviation [N]	n
Feed force	80	79.6	1.3	191
	110	109.8	1.4	192
	140	140.0	1.3	191
	170	170.3	1.4	191
	200	200.4	1.4	192
	230	230.4	1.4	190
Lateral force$_{z\text{-DIR}}$	0	0.6	1.3	285
	20	21.3	1.7	287
	40	40.7	3.1	288
	60	60.3	3.8	287
Lateral force$_{y\text{-DIR}}$	0	0.0	1.0	1147

3.2 Influence of the hammer drill (Hi, Bo)

Using the Mann-Whitney U test, it can be shown that, for the boreholes investigated, the use of two different hammer drills has a statistically significant effect on the ROP determined (asymptotic Mann-Whitney U test: $z = 5.502$, $p < .001$). The effect size, according to Cohen (1992), was $r = 0.16$ and indicated a weak effect. Thus, drilling with the hammer drill from Hilti (Hi) had a higher ROP (Mdn = 8.5 mm/s, IQR = 3.3 mm/s) than with the hammer drill from Bosch (Bo) (Mdn = 8.2 mm/s, IQR = 3.5 mm/s), which had a lower impact energy and impact frequency (Bo: Mdn = 66.3 Hz, SD = 2.2 Hz, Hi: Mdn = 69.3 Hz, SD = 2.8 Hz).

3.3 Influence of the drill bit type (He2c, He4c, Ho2c)

In addition, a Kruskal-Wallis test confirmed that the determined ROP was influenced by the drill bit models ($\chi^2(2) = 663.575$, $p < .001$, $r = 0.761$). Subsequent post-hoc tests (Dunn-Bonferroni tests) showed that all three drill bit models examined were statistically significantly different. However, the post-hoc test also showed that the difference between the helical drill bit with two cutting edges (He2c) (D = 10 mm) and the hollow drill bit with two cutting edges (Ho2c) (D = 14 mm) ($z = 20.582$, $p < .001$, effect size according to Cohen (1992): $r = 0.75$) as well as the helical drill bit with four cutting edges (He4c) (D = 10 mm) and the hollow drill bit ($z = 23.733$, $p < .001$, effect size according to Cohen (1992): $r = 0.86$) was significantly larger than that between the helical drill bit models with two and four cutting edges ($z = -3.144$, $p = .002$, effect size according to Cohen (1992): $r = 0.11$). Thus, a strong effect was observed between the hollow drill bit with a diameter of D = 14 mm and the helical drill bits, which had a smaller diameter with D = 10 mm, while a weak effect was seen between the two helical drill bits. Accordingly, a higher median ROP occurred in the test runs with helical drill bits with four cutting edges (Mdn = 9.1 mm/s, IQR = 1.4 mm/s) relative to the test runs with hollow drill bits that have a larger drill bit diameter (Mdn = 5.5 mm/s, IQR = 1.8 mm/s), where a lower ROP was observed than in test runs with helical drill bits with two cutting edges (Mdn = 8.9 mm/s, IQR = 1.2 mm/s).

3.4 *Influence of the feed force (FF)*

In Figure 3, one can observe the mean values of the ROP over feed force (FF) applied to the boreholes for each setup, consisting of drill bit and hammer drill. Each point is based on approximately 32 boreholes. Additionally, Table 3 shows the results of the Kruskal-Wallis test and the post-hoc tests with Bonferroni correction for feed force. Note that the *p* values of the post-hoc test had already been Bonferroni-corrected by SPSS and therefore were checked against $p < .05$.

The curves of the ROP for the individual setups coincided with the results of the Mann-Whitney U and Kruskal-Wallis tests. Thus, the ROP of the hollow drill bit (D = 14 mm) were below those of the helical drill bits (D = 10 mm) and had an offset amongst the hammer drill models (Hi+Ho2c: Mdn = 6.1 mm/s, SD = 1.1 mm/s; Bo+Ho2c: Mdn = 5.1 mm/s, SD = 0.9 mm/s). Since these two curves; however, showed the same course of action for a feed force of FF = 110 N and higher, the measured values of these test runs can be evaluated together using a z-transformation for both the Kruskal-Wallis test and the post-hoc tests. The Kruskal-Wallis test confirmed a strong effect of the feed force on the ROP during hammer drilling for the test runs with the hollow drill bit ($\chi^2(5) = 162.083$, $p < .001$, $r = 0.653$). Furthermore, the results of the post-hoc tests with the hollow drill bit showed an increase in ROP with feed force in the majority factor of level comparisons ($p < .05$). For example, ROP increased continuously from 4.9 mm/s (FF = 110 N, SD = 0.5 mm/s) to 5.7 mm/s (FF = 230 N, SD = 0.9 mm/s) by 15.9% for the hammer drill from Bosch and from 5.8 mm/s (FF = 110 N, SD = 0.5 mm/s) to 6.7 mm/s (FF = 230 N, SD = 0.7 mm/s) by 16.3% for the hammer drill from Hilti, which possesses a higher impact energy.

In the case of the helical drill bits with four cutting edges, as in the case of the hollow drill bits, both an offset caused by the different hammer drill model (Hi+He4c: Mdn = 9.5 mm/s, SD = 1.1 mm/s; Bo+He4c: Mdn = 8.8 mm/s, SD = 0.9 mm/s) as well as a similar course of action of the curves can be observed. Thus, for helical drill bits with four cutting edges, the measured values of the test runs were evaluated together in the post-hoc test by means of a z-transformation. The Kruskal-Wallis test also confirmed a strong effect of the feed force on the ROP ($\chi^2(5) = 179.262$, $p < .001$, $r = 0.683$). The ROP for the helical drill bits with four cutting edges increases by 4.9% on average from 9.0 mm/s (FF = 110 N, SD = 0.8 mm/s) to 9.4 mm/s (FF = 200 N, SD = 0.9 mm/s).

Table 3: Results of Kruskal-Wallis test and Bonferroni-corrected post-hoc tests of feed force (FF) on z-transformed rate of penetration.

Kruskal-Wallis test statistics													
		Ho2c (n=380)			**He4c** (n=384)			**Bo He2c** (n=191)			**Hi He2c** (n=192)		
		df	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*	*df*	χ^2	*p*
		5	162.083	<.001	5	179.262	<.001	5	155.335	<.001	5	159.789	<.001
Multiple Comparisons													
FF_1 [N]	FF_2 [N]	*z*		*r*	*z*		*r*	*z*		*r*	*z*		*r*
80	110	**-5.913*****		0.53	**-4.209*****		0.37	**-4.920*****		0.62	**-5.509*****		0.69
	140	**-7.727*****		0.69	**-5.890*****		0.52	**-5.167*****		0.65	**-6.867*****		0.86
	170	**-8.954*****		0.80	**-6.367*****		0.56	**-6.607*****		0.83	**-5.999*****		0.75
	200	**-9.801*****		0.87	**-7.344*****		0.65	**-6.008*****		0.75	**-3.732****		0.47
	230	**-11.381*****		1.01	**-7.475*****		0.66	**-4.836*****		0.61	**-3.914****		0.49
110	140	-1.844		0.16	-1.681		0.15	-0.246		0.03	-1.359		0.17
	170	**-3.076***		0.27	-2.158		0.19	-1.687		0.21	-0.490		0.06
	200	**-3.904****		0.35	**-3.134***		0.28	-1.088		0.14	1.777		0.22
	230	**-5.513*****		0.49	**-3.266***		0.29	0.045		0.01	1.595		0.20
140	170	-1.227		0.11	-0.477		0.04	-1.440		0.18	0.868		0.11
	200	-2.044		0.18	-1.453		0.13	-0.841		0.11	**3.316***		0.42
	230	**-3.654****		0.33	-1.585		0.14	0.290		0.04	**2.953***		0.37
170	200	-0.812		0.07	-0.976		0.09	0.599		0.08	2.267		0.28
	230	-2.427		0.22	-1.108		0.10	1.719		0.22	2.085		0.26
200	230	-1.624		0.14	-0.131		0.01	1.124		0.14	-0.182		0.02

Note. Basis: n=1147, Bonferroni-corrected Post-hoc test, *p<0.05, **p<0.01, ***p<0.001

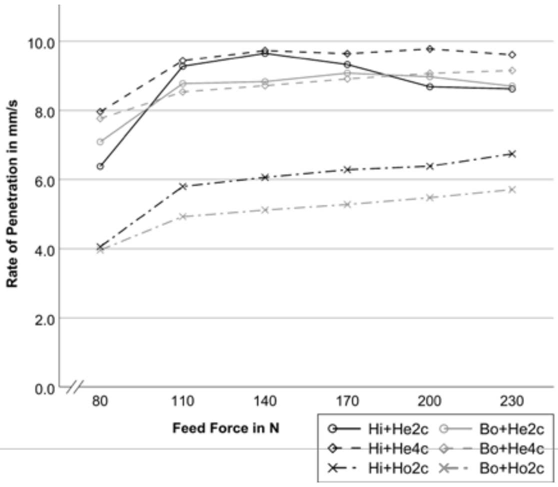

Figure 3: Mean values of rate of penetration (ROP) over feed force for the different setups, consisting of various drill bits and hammer drills, incl. approximation line. With a total of n=1147 boreholes, each point contains approx. 32 test runs.

In contrast, for helical drill bits with two cutting edges, the two curves differed due to an offset caused by the hammer drill model, which resulted in a differing action of their course. Thus, as can be seen in Figure 3, for helical drill bits with two cutting edges using the hammer drill from Hilti, a significant peak in ROP was observed at a feed force of FF = 140 N (FF_1 = 80 N & FF_2 = 140 N: z = -6.867, $p < .001$, FF_I = 140 N & FF_J = 200 N: z = 3.316, $p < .05$). Meanwhile, using the hammer drill from Bosch, a relatively constant progression of ROP was observed for helical drill bits with two cutting edges from a feed force of FF = 110 N (Mdn = 8.9 mm/s, SD = 0.8 mm/s). This was equally evident in the results of the post hoc tests, where no significant mean differences could be detected for helical drill bits with two cutting edges using hammer drill from Bosch in the range between FF = 110 - 230 N. The post hoc tests for helical drill bits with two cutting edges were carried out separately for each hammer drill model.

In Figure 3, a decrease in ROP can be seen for all setups investigated at a feed force of FF = 80 N, which is 27.5% on average. Based on the results of the post-hoc tests, it can be seen that for all setups, the ROP differed ($p < .01$) when comparing to a feed force of FF = 80 N. Figure 4 presents boxplot diagrams of ROP per factor level of lateral force for feed forces FF = 80 - 140 N. It can be seen that an increase in lateral force at a feed force of FF = 80 N decreased the ROP more than at higher feed forces.

In addition, by applying a fast Fourier transform to the housing acceleration measurements, a decrease in the impact frequency could be observed for all setups where the feed force increases. Table 4 shows the impact frequencies determined in this way for the extreme values of the applied feed force (FF = 80 N and FF = 230 N) for each setup. Across hammer drills, the median impact frequency drops by 2.5 Hz for the hollow drill bits, by 4.8 Hz for helical drill bits with two cutting edges and by 4.7 Hz for helical drill bits with four cutting edges.

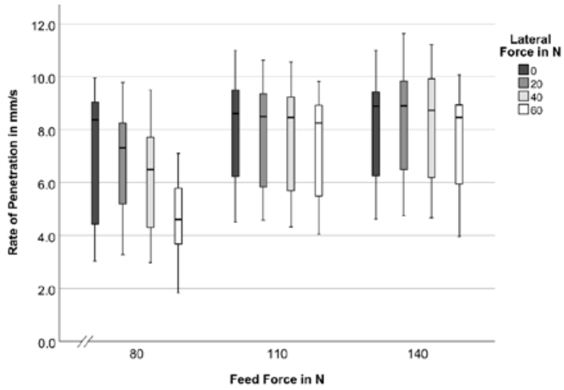

Figure 4: Boxplot diagram of rate of penetration for feed forces FF = 80 - 140 N per lateral force show greater influence of lateral force at 80N feed force.

Table 4: Median (Mdn) and interquartile range (IQR) of the impact frequencies for the different setups, consisting of various drill bits and hammer drills, determined by means of fast Fourier transformation for the extreme values of the applied feed force (FF). Each measured value contains approx. 32 test runs.

	Bosch (Mdn[a] = 66.3, SD[a] = 2.7)						**Hilti** (Mdn[a] = 69.3, SD[a] = 2.6)					
	He2c		He4c		Ho2c		He2c		He4c		Ho2c	
FF [N]	Mdn[a]	IQR[a]	Mdn[a]	IQR[a]	Mdn[a]	IQR[a]	Mdn[a]	IQR[a]	Mdn[a]	IQR[a]	Mdn[a]	IQR[a]
80	67.0	1.7	68.0	0.9	68.7	0.8	71.4	2.7	71.7	1.1	71.0	1.2
230	62.7	2.3	64.3	1.6	65.8	1.5	66.4	5.0	67.8	2.0	68.2	1.7

Note. [a]Value in the unit hertz [Hz].

3.5 *Influence of the lateral force (LF)*

Figure 5 shows the mean values of the ROP over the lateral force (LF) applied during the test runs for each setup. Each point contains the measured values of approx. 48 boreholes. The curves of the individual setups all show a similar course of action. Due to the offset between the individual curves, the measured data were z-transformed for statistical analysis using a post-hoc test. Table 5 shows the results of the Kruskal-Wallis test and the post-hoc tests with Bonferroni correction for lateral force. Note that the p values of the post-hoc tests had already been Bonferroni-corrected by SPSS and therefore tested against $p < .05$.

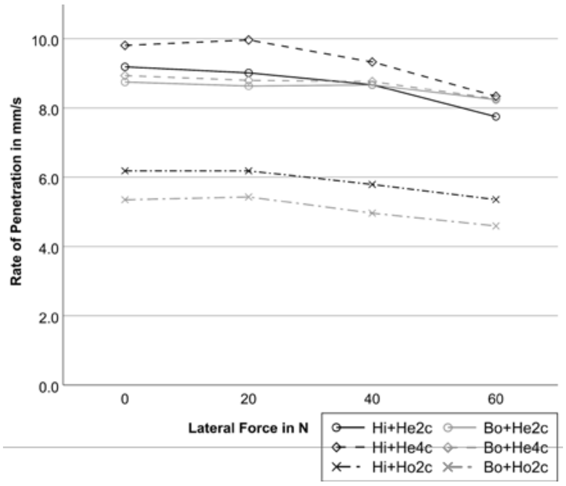

Figure 5: Mean values of ROP plotted against lateral force for the different setups, consisting of various drill bits and hammer drills, incl. approximation line. With a total of n=1147 boreholes, each point contains approx. 48 test runs.

Table 5: Results of Kruskal-Wallis test and Bonferroni-corrected post-hoc tests of lateral force (LF) on z-transformed rate of penetration across all test runs.

Kruskal-Wallis test statistics			
	df	χ^2	*p*
	3	113.887	<.001
Multiple Comparisons			
LF_1 [N]	LF_2 [N]	*z*	*r*
0	20	0.590	0.03
	40	**3.849****	0.16
	60	**9.474*****	0.40
20	40	**3.316****	0.14
	60	**8.952*****	0.37
40	60	**5.643*****	0.24

Note. Basis: n=1147, Bonferroni-corrected Post-hoc test, ***p*<0.01, ****p*<0.001

A Kruskal-Wallis test confirms that there is an medium effect of lateral force on ROP in hammer drilling ($\chi^2(3) = 113.887$, $p < .001$, $r = 0.315$). As can be seen in Figure 5 and proven using the post-hoc tests (see Table 5), for lateral forces of LF = 20 N and higher, with increasing lateral force, the ROP significantly decreased ($p < .01$) for all setups investigated. This decrease in ROP with an increase in lateral force from LF = 0 N to LF = 60 N averaged to be around 13.7%. Meanwhile, no significant mean differences were detected in this study in the range between LF = 0 N and LF = 20 N. However, when looking at the curves of ROP versus lateral force, it can be seen that for all hollow drill bits investigated as well as for the helical drill bits with four cutting edges using the hammer drill from Hilti, the ROP remained constant or slightly increased when the lateral force was increased from LF = 0 N to LF = 20 N. In contrast, the ROP tended to decrease for the other setups with such an increase in lateral force.

4 Discussion

The aim of this study was to investigate the relationship between feed as well as lateral force and the ROP, and thus the influence of the operating forces caused by the user on the productivity in hammer drilling. The use of different setups, consisting of various drill bits and hammer drills, resulted in a knowledge gain of the extent to which the researched relationships can be transferred to different setups.

4.1 *Basic influence of the hammer drill (Hi, Bo) and drill bit type (He2c, He4c, Ho2c)*

The study did not aim to investigate the influence of the hammer drill model or drill bit type on ROP. However, since the main effect of the hammer drill and drill bit type is a relevant influence, it is described here to better understand the results of this study. In addition, having two hammer drill models from different performance classes allow an investigation of the transferability of the results. Furthermore, possible setup-related interaction effects were considered in the discussion on the relationships between the feed and lateral forces with ROP.

The results of this study showed a significant but relatively weak influence of the hammer drill models used on the ROP. It should be noted that the hammer drill from Hilti has a higher impact energy and impact frequency than the hammer drill from Bosch. The motion generated by the motor is converted into impact energy in the striking mechanism of the hammer drill. This impact energy is transferred to the concrete via the drill bit on the drill bit head in order to knock material out of the bottom of the borehole and shatter it on the basis of the drill bit tip and the cutting-edge profile. The design of the striking mechanism as well as the mass ratios of the striking mechanism components have a decisive influence on the transfer behavior of the impact energy from the striking mechanism to the drill bit. In addition, this ratio influences which of the bodies come back into contact during wave reflection or recoil of the drill bit. In combination with a higher impact frequency, a higher transmitted impact energy therefore leads to an increase in the resulting drilling progress or productivity, which was evaluated here via the ROP (Cronjäger and Jahn, 1985; Gruner and Knoll, 2000; Hecker and Riederer, 1985). The beforementioned behavior resulted in the mean difference in ROP between the two hammer drill models used in this study.

Furthermore, the analysis of the measurement data showed that the drill bit model had both a weak and strong influence on the productivity of the test runs, depending on the model comparison. According to Hecker and Riederer, the design of a drill bit in terms of the drill bit head and helix shape has an influence on the drilling progress (Hecker and Riederer, 1985). The greater number of helical flutes that follows with the higher number of cutting edges allows for more efficient removal of the drilling dust. In combination with the model-specific cutting geometry a weak mean difference in productivity between helical drill bits with two and four cutting edges may result. Moreover, these observations are consistent with those of manual drilling test runs, in which Uhl et al. (2020) also demonstrated a difference. However, the relatively strong mean difference in ROP between the hollow drill bit (D = 14 mm) and the two helical drill bit types (D = 10 mm), in addition to the design differences, can mainly be explained by the difference in diameter. The larger the drill bit diameter is, the larger is the surface area of the cutting edge of the drill bit tip over which the impact energy applied to knock out the material is distributed in the bottom of the borehole. Thus, not only the resulting pressure between the drill bit tip and the bottom of the borehole decreases, but also the drilling progress achieved per stroke. The extent; however, of the diameter-independent effect of the hollow drill bit to the helical drill bit on the ROP was not investigated based on the results of this study.

4.2 *Influence of the feed force (FF)*

The results of this study show that the feed force applied by the operator had a significant influence on the productivity in hammer drilling evaluated by the ROP. This finding is consistent with the current state of research (Botti et al., 2020; Hecker, 1983; Uhl et al., 2019). Basically, the productivity in hammer drilling is largely dependent on the impact frequency and energy (Gruner and Knoll, 2000; Hecker and Riederer, 1985). Based on findings from the state of research that considers the influence of feed force on the impact frequency and energy, their relationship with ROP can be explained.

Hecker and Riederer (1985) investigated the displacement and acceleration profiles of the percussion components, and were able to observe a basic alternating percussion sequence during hammer drilling in which the damping element of the hammer drill housing does not hit the striker pin on every second percussion. This indicates that the percussion components are pushed together less during the second stroke. Thus, not only the impact energy transmitted from the striking mechanism to the drill bit but also the drilling progress decreased with this weaker stroke due to greater transmission losses (Gruner and Knoll, 2000). Depending on the feed force applied by the user, the hammer drill can swing back more or less after a stroke. This influences the return of the striker piston and finally leads to the fact that with greater feed force, the contact elements of the striking mechanism are closer together with the second weaker stroke. Therefore the impact energy transferred to the drill bit and thus the productivity increases (Gruner and Knoll, 2000).

Additionally, Vonnemann (1977) investigated the impulse course of the percussion process in hammer drilling and enables a hypothesis based on his findings for the influence of the feed force on productivity during hammer drilling. Based on the penetration hysteresis of the cutting edge into the workpiece, he identified four phases of material removal during a percussion caused by impulse reflections within the drill bit. Vonnemann described that during each penetration phase, the cutting edge must first penetrate a cushion with lower resistance before it reaches the bottom of the borehole. As the feed force increases, the energy part of the impulse that must be applied to penetrate the drilling chips could be reduced. Thus, a greater proportion of the impact energy can be used for the actual fragmentation of the concrete and the drilling progress can increase with greater feed force.

Last but not least, the motor speed of the hammer drill and the mechanically coupled impact frequency depend on the frictional resistance in the borehole. As the feed force increases, the frictional resistance between the drill bit head and the bottom of the borehole also increases. In addition, increased drilling progress results in an increase in the amount of drilling dust to be removed by the drill bit. In the case of a helical drill bit, the dust is carried from the bottom of the hole to the surface of the workpiece via the helical flutes. Hecker (1983) described frictional forces occurring in the borehole between the drill bit and the drilling dust. Thus, with increasing ROP, the increased volume of drilling dust to be removed can lead to increased frictional forces and, in extreme cases, even to clogging of the helical flutes beyond the compaction of the drilling dust. Clogging of the flutes would result in wedging of the drill bit and thus triggering of the slip clutch of the hammer drill. This did not; however, occur during the test runs. The values of the frequency analysis of the housing accelerations shown in Table 4 indicated that with increasing feed force, the impact frequency and thus also the mechanically coupled motor speed decreased for all setups used. Due to the suction of the drilling dust, the rotational speed and impact frequency decreased less for the hollow drill bits than for the helical drill bits.

Regarding these effects on the hollow drill bits with two cutting edges, the linear increase in ROP from a feed force of FF = 110 N (see Figure 3) can be explained by the energy transfer in the second weaker stroke and the contact of the drill bit with the concrete improving with the feed force, while the impact frequency decreased (see Table 4). Due to the suction function of the hollow drill bit, despite the increased volume of drilling dust to be removed with the feed force, it can be assumed that there is no relevant negative influence of additional frictional resistance on the ROP with this drill bit model.

In contrast, a superposition of the effects described led to the fact that in the case of the helical drill bits, the ROP dropped due to the additional frictional resistance caused by the removal of the drilling dust. Therefore, a significant peak of the ROP at FF = 140 N was observed for helical drill bits with two cutting edges using the hammer drill from Hilti (see Figure 3). This observation is consistent with that of the study by Botti et al. (2020) in which a peak in ROP was also observed for a helical drill bit with two cutting edges. Accordingly, the effects listed in this study are valid for their observations and specify the explanation listed by Botti et al. in which the peak is attributed to the fact that “the FF exceeding the power of the drill to generate the percussive motion” (Botti et al., 2020). The comparison to the state of research also confirms that the detailed course of the investigated relationships is system-specific. Thus, the differences in the observed high point by Botti et al. compared to the setups investigated in this study are due to the different drill hammer and drill bit models.

In contrast, a linear increase in ROP occurred for helical drill bits with four cutting edges starting at a feed force of FF = 110 N. This was lower than that of hollow drill bits with two cutting edges due to the additional frictional resistance caused by the removal of the drilling dust. However, a peak of the ROP could not be observed for helical drill bits with four cutting edges, since the frictional resistance depended on the respective helical shape or the helical volume of a drill bit, and this peak therefore presumably occurred beyond the investigated factor levels of the feed force. The course of the ROP over the feed force of helical drill bits with two cutting edges using the drill hammer from Bosch (see Figure 3) suggested a tendential peak in productivity. However, this could not be significantly demonstrated based on the results. Whether a high point of ROP also occurred with hollow drill bits as a function of feed force could not be judged from the results of this study. Additionally, Kivade et al. (2015) were able to observe a peak in ROP in jackhammer drilling for all integral drill bits studied. The "stall" condition described by Kivade et al. suggests that when a too large volume of drilling dust has to be removed, pre-stalling of the hollow drill bit could cause a dip in ROP. To what extent Kivade et al. findings can be transferred to the hollow drill bit in pneumatic hammer drilling remains to be investigated.

Further, the observation showed a strong drop in ROP at a feed force of FF = 80 N for all setups investigated (see Figure 3). At such a low feed force, the drill bit can continue to recoil due to the recoil of the drill bit after a blow. As a result, the striker piston is not sufficiently reset by the low feed force when it comes into contact with the hammer drill. Thus, during the subsequent stroke, the drive piston cannot transmit the impact energy to the drill bit via the striker piston. This results in an unstable drilling process, which leads to double hits. This results in a significant drop in ROP. From feed forces that are too low, the reliability of the drilling process is therefore no longer given.

A study by Botti et al. (2020) showed that in hammer drilling, the hand-arm vibration generated increases with increasing feed force and the maximum user exposure time per day thus defined according to the standard ISO 5349 (2001) decreases. If this relationship can be applied to the setups investigated in this study, it is recommended to drill at a feed force between FF = 110 - 140 N, especially for the helical drill bits, where a relatively small increase in ROP with feed force was observed. On the other hand, the greater increase in productivity for the hollow drill bits means that one could drill more meters over the course of a working day at higher feed forces despite less operating time. The results of this study show that the relationship between productivity and user forces is dependent on the hammer drill and drill bit model used. Therefore, the manufacturer's specifications are decisive for the optimum operating point.

4.3 Influence of the lateral force (LF)

In this study, an effect was demonstrated for all setups investigated at a lateral force of LF = 20 N, 40 N, and 60 N. Thus, with increasing lateral force at these factor levels, the ROP decreased significantly.

When applying a lateral force, the robot performed a motion normal to the drilling axis. However, since the lateral force was controlled to the target value to be applied after a drilling depth of 30 mm, the applied lateral motion caused the drill bit to bend and skew, as the front part of the drill bit is already in the borehole at that point. This in turn resulted in the drill bit shaft and the wall of the borehole to come in contact, which would result in additional friction. The additional friction reduced the resulting impact energy, which could be transferred from the drill bit head to the bottom of the borehole. In addition, the friction resistance reduced the motor speed of the hammer drill, and thereby the mechanically coupled impact frequency. In conclusion, productivity decreased with increasing lateral force, which was evaluated here on the basis of the ROP.

Furthermore, the additional friction in the borehole caused by the lateral force had a negative effect on the return of the striker piston, which is why the energy transmitted to the drill bit by the striking mechanism was reduced. In combination with a low feed force, at which the return of the striker piston is affected, the poor transmission behavior led to an operating point at which the reliability of the system in terms of its functional performance was no longer guaranteed. This hypothesis explains why, at a feed force of FF = 80 N, an increase in lateral force causes the ROP to decrease more than at higher feed forces (see Figure 4).

It should be noted that the factor levels of lateral force set in this study correspond to the lateral forces occurring during manual hammer drilling. For example, Uhl et al. (2019) showed in a study with subjects that the user unintentionally applies lateral forces when drilling vertically downwards, even under laboratory conditions. At high feed forces, these lateral forces amount to a median of LF = 16.2 N, but lateral forces of up to LF = 55.6 N were measured independently of the drilling direction (Uhl et al., 2019). Furthermore, in another study by Uhl et al. (2020), lateral forces were measured during manual hammer drilling with a median of LF = 16.7 N, a 95th percentile of LF = 37.6 N, and a maximum of LF = 73.1 N over one bore. Based on this study where no significant mean difference in ROP was demonstrated for a lateral force of LF = 20 N compared to LF = 0 N, a relatively small effect on ROP can be assumed when lower lateral forces are applied. However, for higher lateral forces such as the 95th percentile, a significant decrease in ROP can be expected. It should be noted that the study by Uhl et al. (2020) used professionals, who are experienced in hammer drilling, as test subjects. Moreover, under real working conditions, the user more often encounters situations with different boundary conditions than the laboratory conditions used in the study with professional subjects. It can therefore be assumed that greater lateral forces should occur under real working conditions, especially for a less experienced user.

For further development of drill bits and hammer drills, automated function tests are currently carried out in the industrial sector in which the lateral forces are not controlled or considered. Based on the results of this study, which demonstrated a relevant influence of lateral forces on the hammer drill process, it is recommended that realistic lateral forces be applied in automated function tests accompanying development.

4.4 Limitations

This study was carried out with an automated experimental setup and the HAM used was developed to represent the translational vibration characteristics of the human hand-arm system. Accordingly, the HAM used is not specifically designed to model lateral movements. Since the movements were force-controlled and the ROP as a measured value is independent of the HAM's vibration characteristics, it can be assumed that this did not lead to a distortion of the results. In addition, the effects shown were investigated while drilling vertically downwards. The drilling direction can affect the behavior of the hammer drill or striking mechanism and thus influence the relationships investigated. Therefore, the results of this study have to be validated by manual tests and the transferability of the findings to other drilling directions has to be further investigated.

The effects shown and proven were only investigated for the setups used in the chosen range of forces and subsequently do not carry any general validity. The comparison; however, to the state of research shows that the transfer of these results and hypotheses to other setups is quite probable. Nevertheless, the findings must be verified depending on the setup. Values of feed and lateral forces that deviate significantly from the investigated forces could lead to new findings on their influence on the ROP. However, these are outside the operating forces applied by humans according to the current state of research.

5 Conclusion and Outlook

The aim of this study was to investigate the relationship between feed and lateral force and the rate of penetration, thus allowing the influence of the operating forces caused by the user on productivity during hammer drilling to be found. The use of different hammer drills and drill bits enabled the transferability of the researched relationships to other setups and possible interaction effects to be investigated. For this purpose, 1152 drillings were carried out on an automated hammer drill test bench. The findings help engineers develop power tools that provide more efficient and less fatiguing work, making them more ergonomic for the user.

In summary, it can be stated that for all setups investigated, consisting of various drill bits and hammer drills, the feed and lateral force applied by the user had an influence on productivity in the form of rate of penetration during hammer drilling. Thus, productivity decreased by 14% on average when higher lateral forces were applied. Productivity tended to rise with an increase in feed force. Furthermore, it can be assumed that additional frictional resistance caused a setup-specific peak in productivity. An interaction effect at low feed forces of 80 N or smaller causes a sharp drop in productivity at lateral forces greater than or equal to 40 N (28% on average). A comparison of the results with the state of research shows that the findings are transferable to other hammer drill and drill bit models. The investigated relationships indicate an efficient operating range depending on the setup used, which enables a reduction of the user's stress duration.

Based on the findings in the study, the following investigations were recommended:

- Investigation of the researched relationships with other hammer drills models, drill bit types, and diameters
- Investigate whether a peak in rate of penetration also occurs with helical drill bits with four cutting edges and hollow drill bits under larger feed forces
- Explore the relationship between drill bit helix volume and rate of penetration
- Study with subjects to validate findings explored on the automated test bench
- Investigate various user feedback methods to efficiently manipulate user-induced operating forces

Funding:

This research was supported in part by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) through the financing of the test environment within the context of the proposal GZ: INST 121384/81-1 FUGG. The research results are solely the responsibility of the authors and do not necessarily represent the official views of DFG.

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