

# Optimizing Drilling Parameters: A Novel Cyclical Motor Control Concept to Adjust the Impact Energy Independently of the Frequency for Impact Mechanisms

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# **Optimizing Drilling Parameters: A Novel Cyclical Motor Control Concept to Adjust the Impact Energy Independently of the Frequency for Impact Mechanisms**

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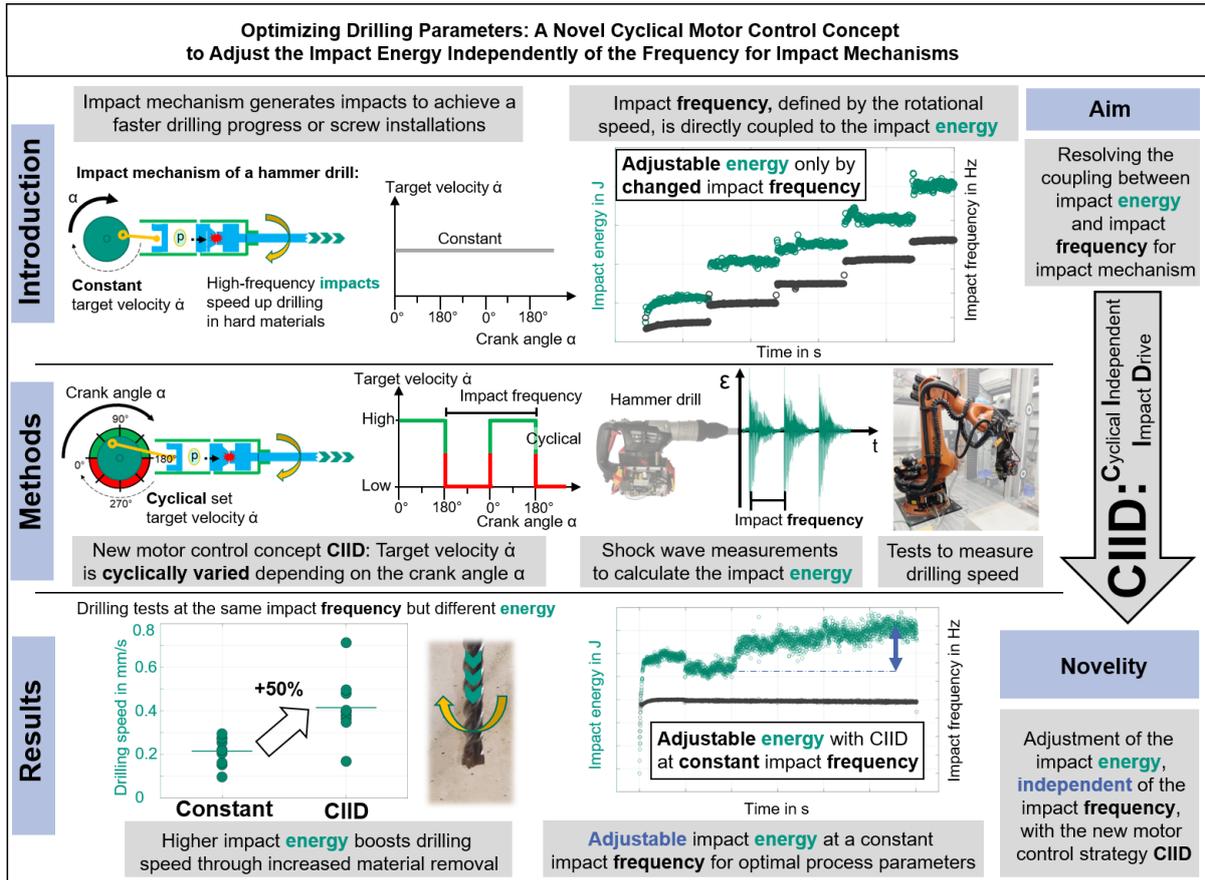
### Abstract

Hammer drilling is widely used to drill holes in hard materials. For high productivity, the impact mechanism generates impacts to remove the hard material to be drilled. The parameters of impact energy and impact frequency mainly influence drilling productivity. Further optimization requires more ways to influence the drilling parameters. Presently, however, the impact energy cannot be changed independently of the impact frequency. This paper investigates a new cyclical motor control concept to influence the impact energy independently of the impact frequency. The new control concept changes motor velocity in a highly frequent and cyclical manner as a function of the motor angle to adjust the impact energy by changing the timing of the impact mechanism. So far, this timing has only been adjusted by changing the impact frequency. An experimental study was carried out to measure the motor control concept's effect on the impact mechanism's timing and impact energy. The new control concept allows for an independent variation of the impact energy and impact frequency. An automated drilling study revealed that this increases drilling productivity. By means of the new concept, impact energy and drilling productivity can be further optimized. It may also be applied to improve productivity of other impact systems, such as impact wrenches.

Keywords: Impact drilling, drilling productivity, concrete, control approach, process analysis, construction

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**Graphical Abstract**

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## 24 **Optimizing Drilling Parameters: A Novel Cyclical Motor Control**

### 25 **Concept to Adjust the Impact Energy Independently of the**

### 26 **Frequency for Impact Mechanisms**

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#### **1. Introduction**

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Hammer drilling is a hybrid machining process, where drill bit rotation is superimposed by impacts. The impacts are generated by an impact mechanism with a known amplitude and frequency [1]. In hammer drills, the impacts are transmitted from the impact mechanism through the drill bit to crush the material [2]. This results in a fast drilling productivity in hard and stony materials. Besides the drill bit velocity, drilling productivity is influenced mainly by impact energy and impact frequency [3,4]. The drill bit's rate of penetration (ROP) measures drilling productivity [mm/s] [5]. For hammer drilling, the single impact energy is measured according to the measurement procedure EPTA 05/2009 [6,7]. Increasing the ROP to improve productivity is a major research interest [8–10]. This paper investigates a novel motor control concept to influence single impact energy independently of the impact frequency, the goal being to optimize drilling parameters with impact mechanisms.

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Changing the single impact energy to optimize the ROP is a common approach. Impact mechanisms differ in design. Due to the different designs, these different machines also differ in their single impact energies. Todorov et al. (2010) modified design parameters to optimize the single impact energy. Various masses and geometries of impact mechanism components were changed in the study. Improvements in single impact energy of less than 10 % were achieved. They stated that the relation between the investigated design parameters is strongly non-linear [11]. At a specific impact frequency, optimums exist for certain design parameters [12]. Yan et al. (2016) used simulations and experiments to investigate the design parameters of the impact mechanism in terms of productivity. Their optimized

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46 design was found to be improved by less than 5 % [13]. Due to the elastic-plastic material fragmentation  
47 resulting from impacts, the single impact energy effect on drilling productivity is non-linear [14]. This  
48 effect must be taken into account in the experimental evaluation of the effect of single impact energy  
49 on drilling productivity.

50 Besides changing the design of an impact mechanism, there are two methods to change the  
51 single impact energy using mechanical actuators [15]. The first method is adding high-frequency  
52 switching valves to weaken the single impact energy by changing the air flow. The second method is to  
53 change the length of the piston, an important design parameter of impact mechanisms, during operation.  
54 This changes the timing of the impact mechanism and, hence, the single impact energy [16]. Both  
55 methods require additional mechanical parts. This limits their use in impact mechanisms, as these  
56 additional mechanical parts are highly stressed and hence, unreliable in operation. For this reason, these  
57 two methods are not applied in common commercial impact mechanisms.

58 Impact energy and impact frequency are strongly correlated in impact mechanisms [12]. The  
59 common method to change impact energy is to change the impact frequency. This is done by changing  
60 the motor velocity that powers the impact mechanism. Only with this method can the impact energy be  
61 changed by the motor control alone. It is used in commercial impact mechanisms, as no additional  
62 mechanical parts are required. This means that impact energy cannot be changed independently of the  
63 impact frequency by the motor control alone. Different drilling applications have different optimal  
64 drilling parameters (e.g. impact frequency, impact energy, and drill bit diameter) in terms of  
65 productivity [17]. Li et al. stated that it was a problem in their study to adjust the impact frequency  
66 independently of the impact energy [17]. The non-separable coupling between impact energy and  
67 impact frequency limits therefore drilling productivity in this machining process.

68 Hammer drilling is a common task in construction. Holes are drilled to install anchor bolts,  
69 concrete screws, and wall plugs. A single construction job of a sound wall, for example, can require  
70 drilling 25,000 holes [18]. They are usually drilled manually with hammer drills. In the US,  
71 approximately 1.6 million workers regularly use hammer drills at work[19]. Reducing drilling time

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72 consequently is a promising approach to increasing productivity and reducing costs in construction [20].

73 Increasing productivity in the construction sector is highly relevant, as construction industry has a share

74 of about 6 to 9 % in a country's gross domestic product (Arditi and Mochtar, 2000; Chitkara, 2004).

75 Increasing drilling productivity with optimal drilling parameters reduces drilling time and

76 additionally protects construction workers. During the drilling process, the worker is exposed to harmful

77 vibrations. These can lead to occupational diseases, such as the white finger syndrome [21–23]. The

78 vibration of hammer drills is measured according to the standards ISO 28927-10 and ISO 5349-1 and

79 specified with the  $a_{hv}$  value [24,25]. The higher  $a_{hv}$  is, the more harmful is the vibration emission for the

80 construction worker. Every manufacturer of hammer drills has to specify this value. The  $a_{hv}$  value is

81 limits the permissible daily working time. Low vibrations protect construction workers in the long term,

82 thus maintaining labor productivity. Vibration emission is an important boundary condition that must

83 be taken into account in hammer drill investigations [18,26].

84 Utilizing low-frequency and ultrasonic vibrations has proven to be effective in minimizing burr

85 formation and extending the lifespan of cutting tools when drilling materials like aluminum and glass

86 fiber-reinforced plastics [27,28]. Experimental findings by Chern and Liang for vibration cutting

87 revealed that using a frequency of 100 Hz significantly reduces the presence of burrs in intersecting

88 holes [29]. Vibration frequency and amplitude were identified to be relevant parameters to improve the

89 inner surface roughness, with the amplitude being comparable to the impact energy [29].

90 A similar procedure is vibration-assisted drilling. It is used in medicine for bone drilling to

91 reduce frictional heat generation [1]. Drilling into the bone can be performed using a low-frequency,

92 high-amplitude approach (5–20 Hz and 100–500  $\mu\text{m}$ ). The effect of vibration-assisted drilling on

93 temperature is non-trivial and depends on the used drilling parameters of frequency and amplitude.

94 Increasing the frequency in vibration-assisted drilling while reducing the amplitude promotes the

95 generation of frictional heat. Vice versa, decreasing the frequency and increasing the amplitude reduce

96 both contact time and frictional heat generation. Selecting the vibration parameters requires careful

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97 consideration to minimize any potential thermal damage caused by the vibrations. It is therefore  
98 important that frequency and amplitude can be set independently of each other. [1]

99         The timing of the impact mechanism is relevant to the impact's amplitude, which is specified  
100 by the single impact energy [13]. If the timing of the impact mechanism could be changed while  
101 maintaining a constant impact frequency, the single impact energy could be changed as well [16]. Yan  
102 et al. explained that the impact mechanism in a hammer drill produces a cyclical load on the motor at  
103 impact frequency [13]. The novel motor control for impact mechanisms presented in this study is  
104 derived from this hypothesis. It implies that the motor powering the impact mechanism would have to  
105 act as a drive and as an actuator of the impact mechanism with a cyclically varying torque depending  
106 on the motor angle.

107         Lee et al. 2013 ran simulations to investigate changes in motor velocity and torque as a function  
108 of the motor angle. The approach was to influence the timing in the impact mechanism of an impact  
109 wrench. A hammer drill, however; differs significantly from an impact wrench. A hammer drill  
110 generates translatory impacts, whereas an impact wrench generates rotatory impacts with different  
111 kinematic characteristics and a different number of moving parts. The study by Lee et al. 2013 is limited  
112 to impact wrenches and simulation. Their results could not be confirmed experimentally. [30]

113         It has been shown experimentally that drones can be steered by cyclical acceleration and  
114 deceleration depending on the angle of the rotor during one rotation [31,32]. The complicated control  
115 mechanics with a swashplate is no longer necessary. In contrast to an impact mechanism, the rotor of a  
116 drone has a constant torque and only a very low inertial torque. This allows the rotor to be accelerated  
117 and decelerated in a targeted manner during one rotation. The impact mechanism of a hammer drill has  
118 a much higher inertial torque and a non-linear behavior [11]. It is therefore uncertain whether the timing  
119 of the impact mechanism can be influenced by motor control affecting the single impact energy.

120         The aim of this paper is to investigate whether a high-frequency cyclical motor velocity control  
121 can adjust the impact energy independently of the impact frequency for impact mechanisms. This will  
122 help optimize drilling parameters to increase drilling productivity. Existing approaches to influencing

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123 the single impact energy by the motor control are limited, as they will also affect impact frequency.  
124 Two experiments were conducted to answer two research questions. The first research question is: “Can  
125 a cyclical motor control concept adjust the single impact energy independently of the impact  
126 frequency?”. The second research question is: “Does a cyclical motor control have an effect on drilling  
127 productivity and vibration in hammer drilling?”. The experiment to answer the first research question  
128 was conducted according to the EPTA 05/2009 test procedure . The second research question was  
129 investigated by an automated drilling study.

## 130 2. Method

131 In the first subsection, the impact mechanism and the novel motor control concept investigated  
132 to influence the single impact energy independently of the impact frequency are presented. To test the  
133 control concept, a commercially available hammer drill is modified as an experimental prototype. This  
134 is shown in the second subsection. To answer the first research question, the effect of the motor control  
135 concept on the single impact energy was evaluated using the test procedure EPTA 05/2009. It is  
136 introduced in the third subsection. An automated drilling study was conducted to evaluate the control  
137 concept's effect on drilling productivity and answer the second research question. This is presented in  
138 the fourth subsection. Data evaluation and statistical analysis are presented in the fifth subsection.

### 139 2.1. New Cyclical Motor Control Concept for Impact Mechanisms

140 To generate impacts, an impact mechanism in hammer drills utilizes a combination of four  
141 mechanical parts: Piston, striker, impact bolt, and drill bit. The piston is driven by a crank mechanism  
142 inside a sealed cylinder. The crank moves at a defined target velocity and is driven by the motor. The  
143 air between the piston and the striker acts as a progressive spring. The piston exerts the force  $F(\alpha)$  on  
144 the striker via the air spring and accelerates it. For the impact, the striker hits the impact bolt. This  
145 impact is transferred as a shock wave to the drill bit and causes material crushing in the borehole. Due  
146 to the impact, the striker bounces off the impact bolt and is pulled backwards by the piston due to  
147 negative air pressure in the sealed chamber. The striker is accelerated forwards again as the crank rotates

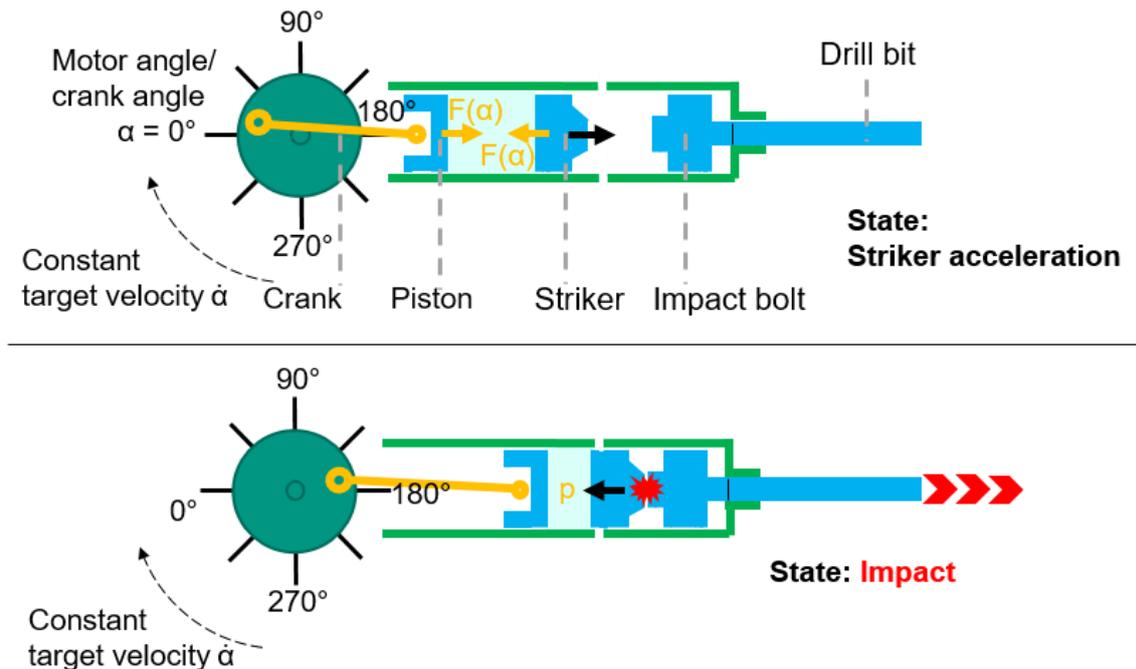
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148 further and the next impact occurs. A cyclical load acts on the piston due to the non-linear air spring.

149 This process and the relevant parts are shown in **Figure 1**.

**Figure 1**

The crank is attached to the motor and controlled to have a constant target velocity. The piston exerts the force  $F(\alpha)$  on the striker via the air spring and accelerates it. The striker hits the impact bolt and the impact is created. This impact is transferred via the drill bit to the material and causes material to be removed. During the impact, the striker bounces off and is pulled towards the piston due to negative pressure. The striker is accelerated forwards again by the force  $F(\alpha)$  during the next rotation and the cycle starts again.



150 The cyclical control concept is based on the control concept for flight drone motors, as  
 151 presented by Paulos and Yim (2015). As the aim of the control concept is the independent adjustment  
 152 of frequency and energy for impact mechanisms by a cyclical control, the concept in this paper is  
 153 referred to as “Cyclical Independent Impact Drive” (CIID). While Paulos and Yim used a cyclical  
 154 torque control, we used a cyclical velocity control of the motor, since the hammer drill load is non-  
 155 linear, which might affect the stability of the operation. The target velocity  $\dot{\alpha}$  of the motor controller  
 156 was changed cyclically as a function of the angle  $\alpha$ . The rear dead centre was defined as the angle  $\alpha =$   
 157  $0^\circ$ . The coordinate system is shown in **Figure 1**. Within one crank and, hence, one motor revolution,  
 158 two target velocities are set, a high target velocity and a low target velocity. At high target velocity, the

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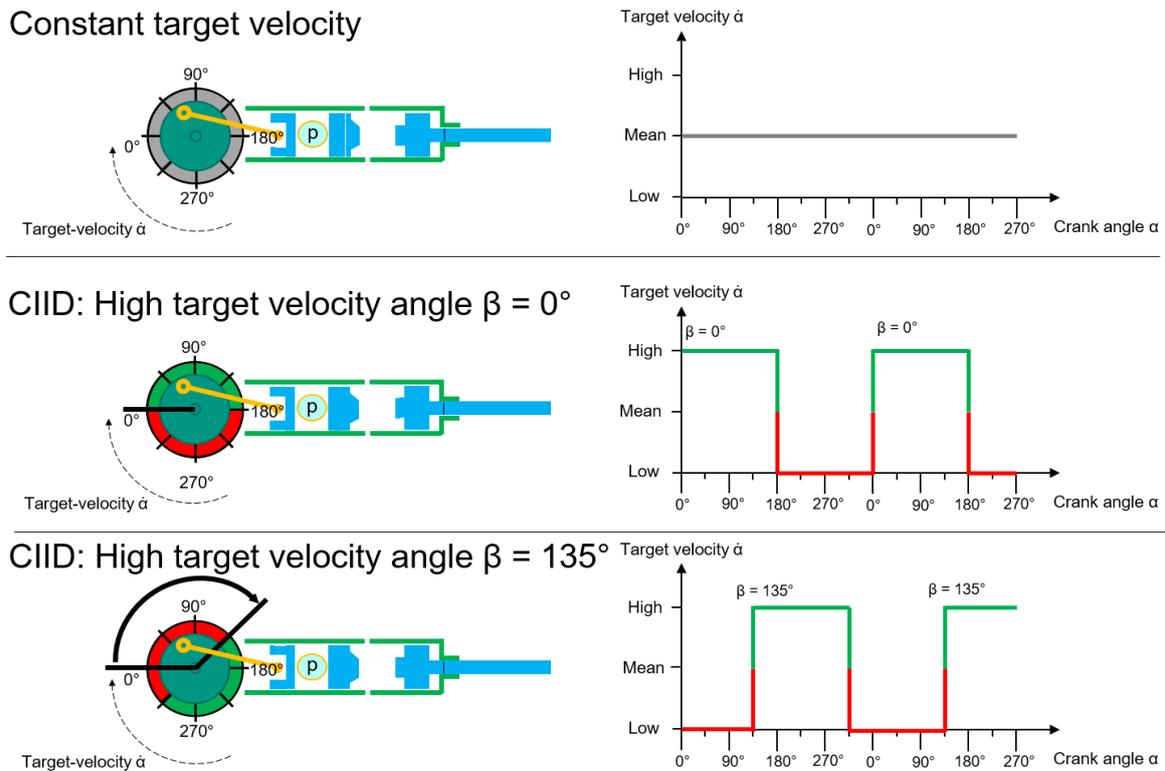
159 piston is accelerated, whereas the piston decelerates due to the load torque during the low target velocity  
160 phase. The motor was not braked actively with this motor control concept.

161 The angle  $\beta$  was defined as the start angle of the high target velocity phase. With the angle  $\beta$ ,  
162 the timing of the impact mechanism can be changed. The angle  $\beta$  was changed with the motor concept  
163 to achieve different single impact energies. The high (green) and low (red) target velocities are  
164 transmitted to the motor controller during  $180^\circ$  of the motor angle  $\alpha$ . One impact per crank revolution  
165 occurred. The resulting impact frequency was found to be between the impact frequencies  
166 corresponding to the high and low target velocities. In this study, the low target velocity was always  
167 selected to be zero to achieve high effects. The real velocity differs from the target velocity, as the  
168 system needs time to adjust to the new target velocity. The motor control concept with two different  
169 settings for the high target velocity angle  $\beta$  is presented in **Figure 2**.

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**Figure 2**

The “Cyclical Independent Impact Drive” (CIID) concept is compared to a constant target velocity. The motor is coupled to the impact mechanism. The motor’s target velocity  $\dot{\alpha}$  was varied depending on the motor angle  $\alpha$ . The angle for a high (green) and low (red) target velocity was varied with the angle  $\beta$  to achieve different single impact energy levels with the motor control at a constant impact frequency. Changing the angle  $\beta$  changes the timing of the impact mechanism. The aim is to change the impact energy independently of the impact frequency.

170 **2.2. Modified Hammer Drill DualDrive to Test the CIID Control Concept**

171 Commercially available hammer drills are powered by one motor. The impact mechanism and  
 172 drill bit rotation are coupled to a gearbox. For this reason, the impact mechanism and drill bit rotation  
 173 interact mechanically. This complicates the investigation of the impact mechanism in the drilling mode.  
 174 To investigate the new motor concept not only in the impact mode, but also in the drilling mode with  
 175 drill bit rotation, a hammer drill of the type Bosch GBH 4-32 (Robert Bosch Power Tools GmbH,  
 176 Leinfelden-Echterdingen, Germany) was modified. . To eliminate mechanical interactions, the impact  
 177 mechanism and drill bit rotation were decoupled mechanically and driven by a separate motor each. As  
 178 the modified hammer drill has two motors, it is referred to as “DualDrive” hammer drill in this study.

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179 When the impact mechanism generated the impacts, the corresponding motor was used for cyclical  
180 target velocity setting only. The other motor was controlled to have a constant target velocity for drill  
181 bit rotation.

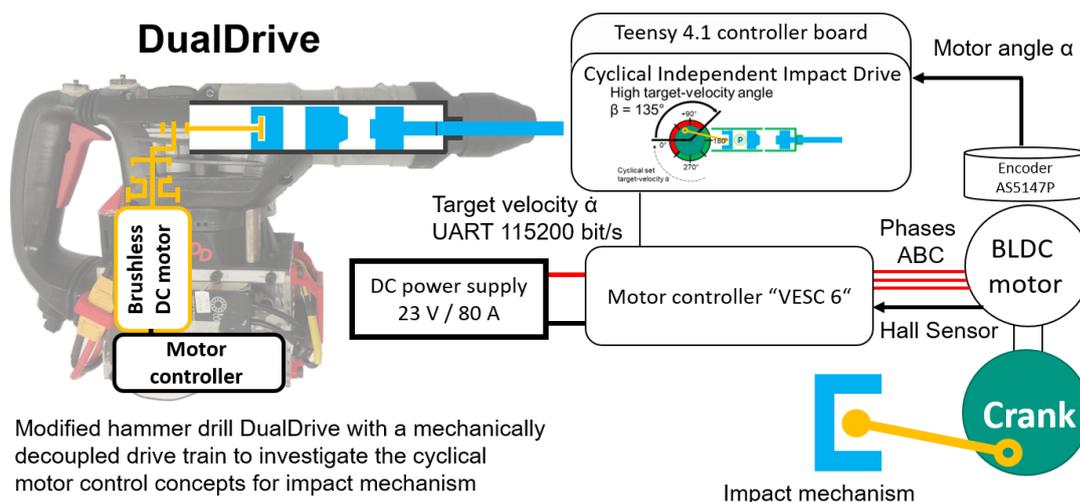
182 Motors with high nominal power and motor controllers with high nominal currents were used  
183 to provide a large power reserve for the investigation of the new control concept. The hammer drill had  
184 a rated electrical input power of 900 W. In the modified hammer drill, a BLDC external rotor motor  
185 with a rated power of 1820 W, seven pole pairs, and a KV value of 270 drove the impact mechanism  
186 (Brushless Sensor Motor ESC 3-8S 270Kv 1820W). The new BLDC external rotor motor for the drill  
187 bit rotation had a nominal electrical power of 2000 W (NTM Prop Drive Series 50-50 580Kv 2000W).  
188 The two motors were FOC-controlled (field-oriented). The two controllers had a nominal current of  
189 80 A and a maximal current of 150 A (VESC 6 MkV, Trampa Boards Ltd, Nottingham, United  
190 Kingdom). These controllers were selected to provide high currents for cyclic accelerations, combined  
191 with a low weight. The motor controllers were powered by a power supply unit with a voltage of 23 V  
192 (model EA-PSI 9080-120 2U, EPS Stromversorgung GmbH - Electronic Power Supplies, Augsburg,  
193 Germany).

194 The current velocity of the impact motor is transmitted to the motor controller with the three  
195 hall sensors. A 32-Bit Teensy 4.1 board (Teensy® 4.1 Development Board, PJRC.com LLC.,  
196 Sherwood, OR, USA) transmits the target velocity to the motor controller via the UART interface. This  
197 target velocity is varied cyclically depending on the motor angle  $\alpha$ . For this reason, the current motor  
198 angle  $\alpha$  was measured with the encoder AS5147P (AS5x47P motor board, ams AG, Premstaetten,  
199 Austria). Depending on the current motor angle  $\alpha$  and the high target velocity angle  $\beta$ , the 32-Bit Teensy  
200 4.1 board sends the target velocity to the motor controller. The 32-Bit Teensy 4.1 board and the control  
201 program have a sufficiently short cycle time to cyclically transmit the target velocities to the motor  
202 controller. The weight increased slightly as a result of the modifications, but was still within the range  
203 of hammer drills in this category (Original: 4.7 kg, DualDrive: 5.4 kg). Since the drive train was

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 204 modified only, the impact mechanism remained original. The modified “DualDrive” hammer drill with  
 205 the motor control concept is presented in **Figure 3** and was validated prior to this study [33].

**Figure 3**

A hammer drill was modified to test the CIID control concept. Two new motors, two motor control boards, and a Teensy board were used to implement the new control concept. The control scheme is shown in the right part of the Figure.



206 An efficient drilling operation with a high productivity is only possible with a stable impact  
 207 frequency. Hence, this is the boundary condition for the control concept and leads to a conflict of  
 208 objectives for the motor control parameters. A fast control can react quickly to changes, which benefits  
 209 the cyclic adjustment of the target velocity. Due to the non-linear impact mechanism load, however, it  
 210 may also result in an unstable motor control. A slow control reacts slowly to the cyclical change of  
 211 target velocity. The motor would hardly react to the imposed high-frequency change in target velocity.  
 212 A slow motor control would have no effect on the single impact energy. However, the slow control  
 213 ensures a very stable operating point at a constant impact frequency, which was found to be of major  
 214 importance in a preliminary study. The parameters of this control are listed in the appendix.  
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### 217 **2.3. Test Setup and Procedure to Measure the Single Impact Energy**

218 The new motor control concept was evaluated by its effect on the single impact energy. The  
219 measurement procedure EPTA 05/2009 “Measurement of the single impact energy of rotary hammers  
220 and breakers” is presented in this subsection based on Nalbach, 2009 and Yampol’skii and Vanaev,  
221 2018 [6,7].

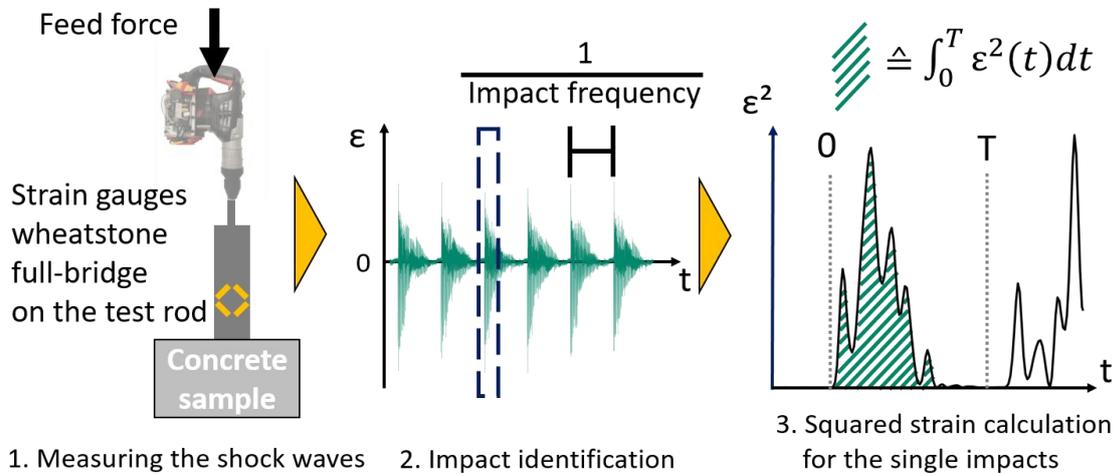
222 To measure the single impact energy, a long test rod is required instead of a drill bit. The  
223 hammer drill was operated in the impact mode without drill bit rotation. The test rod was long enough  
224 to measure the entire shock wave at the strain gauge position without noise. The noise occurs when the  
225 test rod end reflects the shock wave and the reflected wave is measured by the strain gauges again. To  
226 measure the impacts without noise, the prior impact must be fully damped, which is done by preloading  
227 the test rod and hammer drill against a concrete block. With every reflection, part of the shock wave  
228 was transmitted to the concrete. The impact was fully dampened when the next impact occurred. The  
229 test rod was made of 34CrNiMo6 and hardened to  $(57 + 3)$  HRC at a length of 660 mm and a diameter  
230 of 20 mm. Plastic deformation of the test rod did not occur during the experiment. Strain gauges were  
231 attached to the test rod in a full-bridge configuration (Type 3/350XY13, Hottinger Brüel & Kjaer  
232 GmbH, Darmstadt, Germany). The strain gauge signal was sampled at a frequency of 500 kHz with an  
233 LTTpro V4 measurement system (Labortechnik Tasler GmbH, Würzburg, Germany). The signal was  
234 low-pass filtered with a 4th order zero-phase Butterworth filter at a cut-off frequency of 100 kHz to  
235 reduce signal noise. The high measurement frequency was required, as shock waves move very fast  
236 through the test rod at sound velocity of steel (approx. 5180 m/s). This measurement procedure is  
237 shown in **Figure 4**.

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**Figure 4**

EPTA 05/2009 test procedure for measuring the single impact energy in this study. A long rod was inserted into the hammer drill. Strain gauges were applied to the long rod to measure the strain of the hammer drill impacts without noise. From the measured strain, the single impact energy was calculated using formula 1.



239            The strain of the single shock wave resulting from the individual impacts was measured. With  
 240 formula 1, the single impact energy was calculated taking into account the measured strain  $\epsilon$ , the test  
 241 rod's cross-sectional area  $A$ , the acoustic impedance  $I$ , and Young's modulus  $E$ .

$$\text{Single impact energy} = \frac{A * E^2}{I} \int_0^T \epsilon^2(t) dt \quad (1)$$

242            The hammer drill was held by an operator and pressed down during the tests. This ensured a  
 243 stable operating point, as a minimum feed force is required for an impact mechanism to work properly.  
 244 A scale was used to check whether the required minimum feed force was maintained. Each trial covers  
 245 60 seconds of operation. During these 60 seconds, single impact energies and impact frequencies of six  
 246 motor control concepts were measured.

247            In each test, a constant target velocity was set for ten seconds at first. This represents the current  
 248 state of the art in how impact mechanisms are driven. The values measured are the references for the  
 249 single impact energies achieved with the new motor control concept. After ten seconds, the motor  
 250 control switched to a cyclical set target velocity that was maintained for ten seconds at the high target

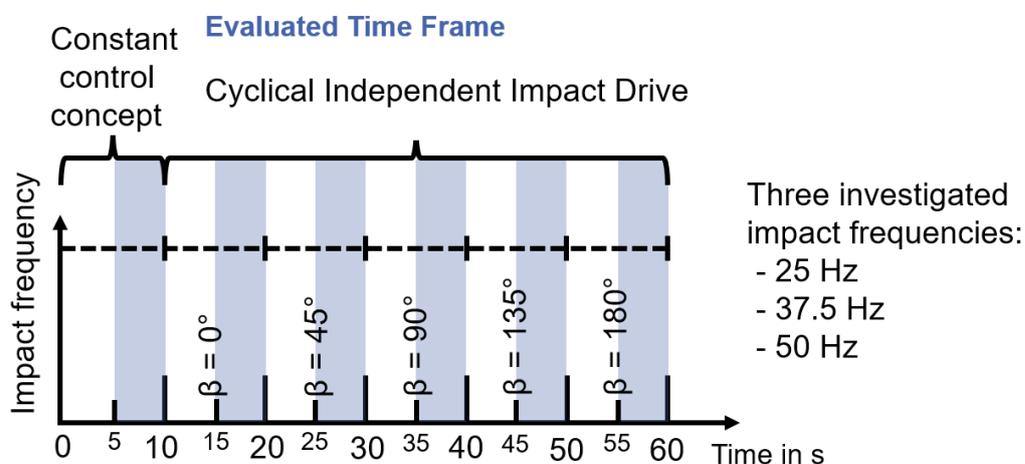
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251 velocity angle  $\beta = 0^\circ$ . Then, the angle  $\beta$  was changed to  $45^\circ$ . The angle  $\beta$  was increased by  $45^\circ$  every  
 252 ten seconds until the test was completed after 60 s.

253 Todorov et al. stated that the first impacts should not be included in the evaluation of the single  
 254 impact energy, as these impacts are influenced by the transition to a constant operating point of the  
 255 impact mechanism [12]. At the beginning of a test, the impact mechanism needs a few seconds to  
 256 achieve a constant operating point. For this reason, only the last five seconds of every control concept  
 257 were evaluated (blue range in **Figure 5**). The investigated motor control concepts and the evaluated  
 258 time frames are given in **Figure 5**.

**Figure 5**

The six motor control concept settings investigated at the three impact frequencies of 25 Hz, 37.5 Hz, and 50 Hz and the evaluated time frame (blue).



259 The operating range of an impact mechanism has mainly been characterized by the impact  
 260 frequency so far. That is why we investigated the motor concept at three different impact frequencies:  
 261 25 Hz, 37.5 Hz, and 50 Hz. The motor velocity and the motor angle were measured by the motor  
 262 controller to evaluate the influence of the control strategy on the real motor velocity and the timing of  
 263 the impact mechanism. In addition, current consumption during the tests was measured by the motor  
 264 controller. The motor controller has a specified recording frequency of 200 Hz.

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#### 267 **2.4. Drilling Study to Investigate the Effect on Drilling Productivity and Vibration**

268 To test the effect of the CIID motor control concept on vibration and productivity, an automated  
269 drilling study was conducted in a test rig presented by Uhl et al. [26,34]. Three different motor concept  
270 settings were tested at with the same impact frequency in this drilling study. The first setting covered a  
271 constant target velocity. For the second and third settings, the highest and lowest single impact energies  
272 were picked at the same impact frequency. The corresponding angles  $\beta$  to reach the highest and lowest  
273 possible single impact energies were evaluated. To ensure unbiased results, the experimental design  
274 included randomization in the order of the three factor combinations. 30 holes were drilled in this study.  
275 Additionally, the positions of the drilled holes were randomized across the concrete block to minimize  
276 any potential trend effects. Each factor was investigated with ten drilled holes.

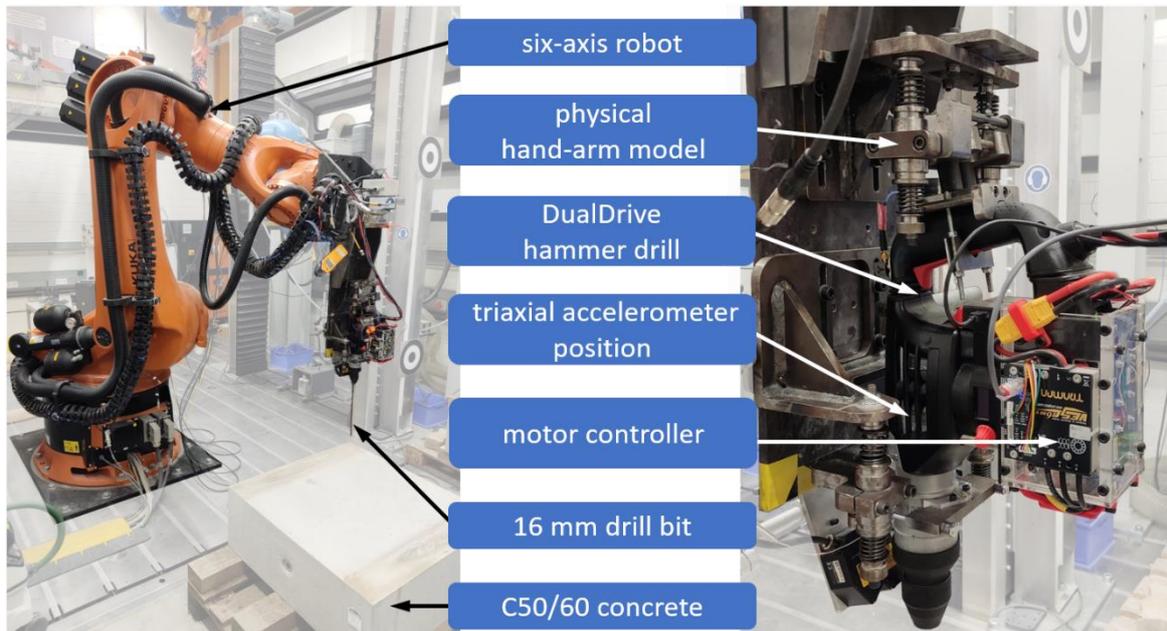
277 All drilling tests were performed at an impact frequency of 25 Hz. Although this impact  
278 frequency was smaller than the hammer drill's nominal impact frequency, it was chosen, because the  
279 variance in impact frequency could be minimized. A small variance in the drilling tests is required to  
280 be able to detect significant effects. A specified concrete sample of C50/60 with the dimensions of  
281 800x800x300 mm<sup>3</sup> was used to reduce the test variance (Rau-Betonfertigteile, Ebhausen, Germany).  
282 The drill bit rotation was controlled to have a constant velocity of 271 rpm. This represents the hammer  
283 drills associated drill bit velocity to the impact frequency of 25 Hz.

284 To further reduce test variance, a six-axis robot was used to drill the holes with the hammer  
285 drill (model KR 500 R2830 MT, KUKA, Augsburg, Germany). The robot controlled the required feed  
286 force to be constant at 200 N. This ensures a constant hammer drill operating point [20]. The hammer  
287 drill was clamped to the robot using a hand-arm model. This is a mechanical spring-damper system that  
288 models the mechanical influence of the human hand-arm system on the test bench and allows for a  
289 translational motion in drilling direction. Use of a hand-arm model allowed us to evaluate the vibration  
290 emission in an automated test rig (Jahn and Hesse, 1986). Vibration emission was evaluated using the  
291  $a_{hv}$  value based on ISO 28927-10 and ISO 5349-1 [24,25]. To measure vibration emission, a triaxial

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 292 sensor was attached to the main handle at the position recommended in ISO 28927-10 (model 356A02,  
 293 PCB Piezotronics, Depew, NY, USA). The test rig for automated drilling studies is shown in **Figure 6**.

**Figure 6**

Test rig for automated and reproducible drilling tests used in this study to measure the drilling productivity and vibration emission.



294 The control and data acquisition were performed at a record frequency of 12.5 kHz with an  
 295 ADwin-Pro II system (Jäger Computergesteuerte Messtechnik GmbH, Lorsch, Germany). To drill the  
 296 holes, a DeWalt DT9680 QZ-SDS+FHC 16 mm x 150 mm drill bit was used. The holes were drilled  
 297 down to a depth of 45 mm. The drilling progress was evaluated using the robot's tool center point  
 298 position. The drilling productivity was assessed based on the ROP according to formula 2. For this, the  
 299 required drilling progress was divided by the drilling time. The drilling depth of 15 mm was used to  
 300 establish a constant operation of the robot, impact mechanism, and hand-arm model, as this is required  
 301 to evaluate the ROP [34]. The progress was evaluated in the range from 15 mm to 45 mm. To obtain  
 302 the ROP, the required drilling progress was divided by the drilling time.

$$ROP = \frac{45 \text{ mm} - 15 \text{ mm}}{t(s = 45 \text{ mm}) - t(s = 15 \text{ mm})} \quad (2)$$

303 **2.5. Data Evaluation for Single Impact Energy and Drilling Productivity**

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304 The impacts were identified in each of the six evaluated blue ranges shown in **Figure 5**, For  
305 each impact, the single impact energy and impact frequency were calculated. The mean value and  
306 standard deviation were calculated for each range. These values are relevant to rate the stability of the  
307 operating point. The mean current consumption and the standard deviation were calculated as well.

308 Data analysis was carried out with Matlab R2022b (Matlab R2022b, The MathWorks, Natick,  
309 MA, USA). SPSS was used for statistical analysis (IBM SPSS Statistics 25, IBM, Armonk, NY, USA).  
310 To determine the differences of the motor concepts, variance (ANOVA) was analyzed. A homogeneity  
311 of variance is required to perform the ANOVA analysis. Levene's test was used to check the results  
312 for variance inhomogeneity. If variance inhomogeneity was found in the data, Welch's analysis of  
313 variance was applied. ANOVA or Welch's analysis of variance can only show that a difference exists  
314 between the groups. To show the effects for individual groups, post hoc tests were used. The Bonferroni  
315 test and the Games-Howell test were chosen to reveal differences and effects between the individual  
316 groups. The Bonferroni test is very selective, but requires variance homogeneity. The Games-Howell  
317 test requires neither variance homogeneity nor the same sample size in the test group [35].

### 318 **3. Results**

319 The tests for independent adjustment of single impact energy and impact frequency with CIID  
320 are reported in the first subsection. The effect of the CIID motor control concept on drilling  
321 productivity and vibration (second research question) is reviewed in the second subsection.

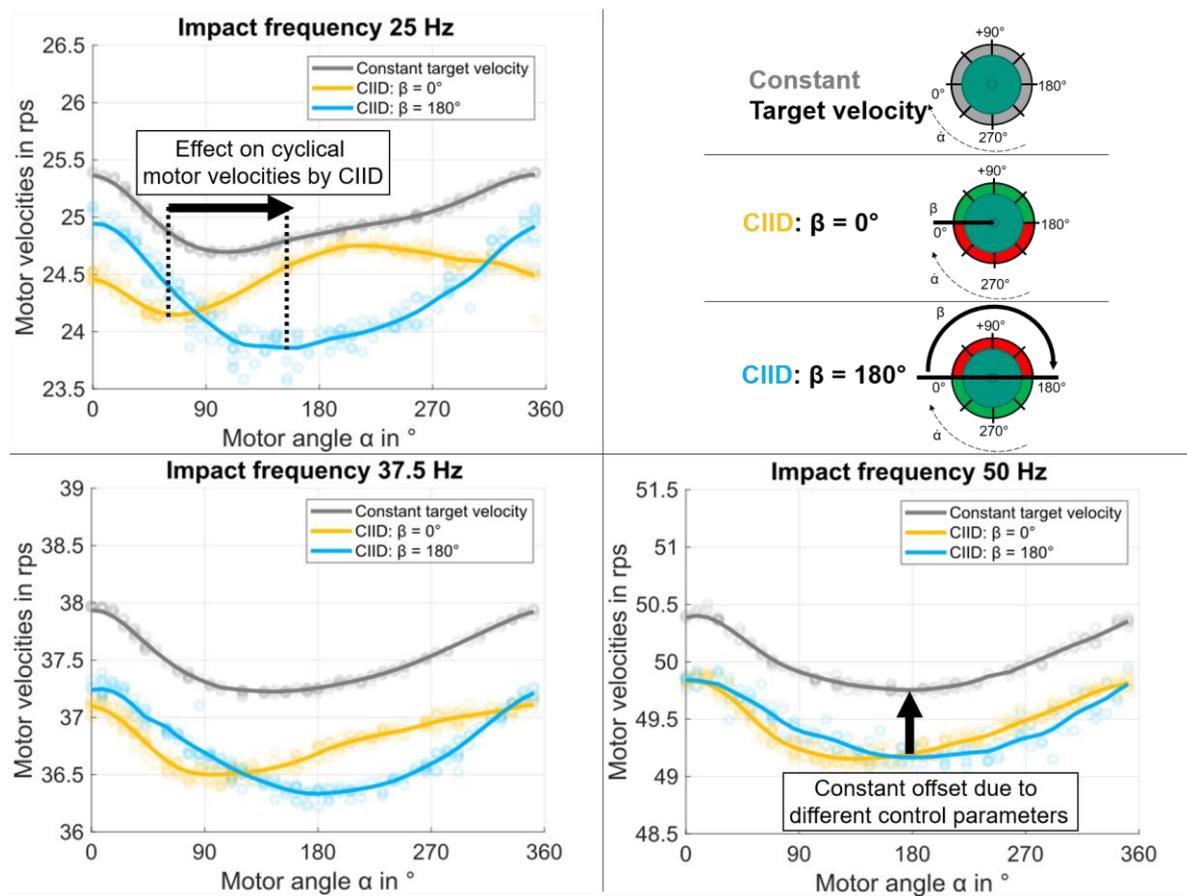
#### 322 **3.1. Cyclical Independent Impact Drive Effect on Single Impact Energy**

323 CIID aims to change the impact energy independently of the impact frequency. The target  
324 velocity of the motor was changed cyclically to change the timing of the impact mechanism.  
325 Consequently, the effect of the motor control concept on the actual motor velocity was investigated. In  
326 **Figure 7**, the measured motor velocities are plotted versus the motor angle  $\alpha$ . The angle  $\alpha$  ranges from  
327 zero to 360 degrees, which represents one mechanical motor revolution. **Figure 7** shows the motor  
328 velocities measured for the constant target velocity, two CIID settings ( $\beta= 0^\circ$  and  $\beta= 180^\circ$ ), and three

Independent impact energy and frequency adjustment  
 329 investigated impact frequencies based on the velocities measured in the respective time ranges (see  
 330 **Figure 5**).

**Figure 7**

Measured motor velocities in revolution per second (rps) plotted versus the motor angle  $\alpha$ . Each plot contains more than one motor revolution, which results in a scattering of measurement values. The single measurement points are shown as faded points. The mean values are plotted as lines. All measured motor velocities change cyclically, even at a constant target velocity (grey). The CIID motor control concept (yellow and blue) enables cyclic variation of motor velocities.



331 The pale dots represent the measured values. As the motor rotates multiple times in the  
 332 evaluated time range, each plot covers more than one motor revolution. This results in a scattering of  
 333 measurement values. The lines represent the mean values of the respective motor angle  $\alpha$ .

334 It can be seen that the actual motor velocities changed cyclically with the motor angle  $\alpha$ .  
 335 Although a constant target velocity (grey) was applied, the velocity still changed cyclically. The motor  
 336 velocities measured with the CIID control concept were slightly lower than those measured at a constant

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337 target velocity. For the lowest impact frequency of 25 Hz investigated, the velocities differed  
 338 significantly for different high target velocity angles  $\beta = 0^\circ$  (yellow) and  $\beta = 180^\circ$  (blue). Whereas the  
 339 control concept with  $\beta = 0^\circ$  produced the highest velocity at around  $210^\circ$ , the control concept with  $\beta =$   
 340  $180^\circ$  reached the highest velocity at around  $10^\circ$ . In contrast to the velocities at the lowest impact  
 341 frequency of 25 Hz, the velocities curves at 50 Hz differ slightly only. The control concept with  $\beta = 0^\circ$   
 342 reached the lowest velocity at around  $135^\circ$ , while the control concept with  $\beta = 180^\circ$  produced the highest  
 343 velocity at around  $180^\circ$ . For both concepts, velocity was highest at a motor angle of  $0^\circ$ .

344 To analyze the independent adjustment of impact energy and impact frequency with CIID, these  
 345 values were calculated. All values measured during the tests of the six different motor control concepts  
 346 at three different impact frequencies are given in Table 1.

347 **Table 1**

348 Impact energies, impact frequencies, and motor currents measured for the three different investigated  
 349 impact frequencies of the different motor control concepts and settings. For each measured value, the  
 350 mean values and variances were calculated.

| Motor control concept<br>Start angle $\beta$ | Impact frequency 25 Hz |                   |                    |                    |                     |                     |
|--|------------------------|-------------------|--------------------|--------------------|---------------------|---------------------|
|  | Constant<br>-          | CIID<br>$0^\circ$ | CIID<br>$45^\circ$ | CIID<br>$90^\circ$ | CIID<br>$135^\circ$ | CIID<br>$180^\circ$ |
| N  | 123                    | 121               | 121                | 120                | 121                 | 120                 |
| Mean impact energy                           | 0.59 J                 | 0.46 J            | 0.38 J             | 0.45 J             | 0.61 J              | 0.70 J              |
| Std. impact energy                           | 0.01 J                 | 0.02 J            | 0.03 J             | 0.02 J             | 0.01 J              | 0.02 J              |
| Mean impact frequency                        | 24.60 Hz               | 24.12 Hz          | 24.13 Hz           | 24.12 Hz           | 24.05 Hz            | 23.91 Hz            |
| Std. impact frequency                        | 0.03 Hz                | 0.25 Hz           | 0.23 Hz            | 0.06 Hz            | 0.04 Hz             | 0.14 Hz             |
| Mean motor current                           | 3.24 A                 | 3.09 A            | 3.04 A             | 2.99 A             | 3.12 A              | 3.17 A              |
| Std. motor current                           | 0.09 A                 | 1.43 A            | 1.49 A             | 1.33 A             | 1.26 A              | 1.07 A              |

| Motor control concept<br>Start angle $\beta$ | Impact frequency 37.5 Hz |                   |                    |                    |                     |                     |
|--|--------------------------|-------------------|--------------------|--------------------|---------------------|---------------------|
|  | Constant<br>-            | CIID<br>$0^\circ$ | CIID<br>$45^\circ$ | CIID<br>$90^\circ$ | CIID<br>$135^\circ$ | CIID<br>$180^\circ$ |
| N  | 184                      | 181               | 181                | 182                | 181                 | 181                 |
| Mean impact energy                           | 1.65 J                   | 1.51 J            | 1.43 J             | 1.42 J             | 1.60 J              | 1.75 J              |
| Std. impact energy                           | 0.03 J                   | 0.04 J            | 0.04 J             | 0.04 J             | 0.04 J              | 0.05 J              |
| Mean impact frequency                        | 36.92 Hz                 | 36.22 Hz          | 36.28 Hz           | 36.31 Hz           | 36.23 Hz            | 36.15 Hz            |
| Std. impact frequency                        | 0.05 Hz                  | 0.20 Hz           | 0.15 Hz            | 0.12 Hz            | 0.15 Hz             | 0.23 Hz             |
| Mean motor current                           | 6.98 A                   | 6.69 A            | 6.73 A             | 6.97 A             | 7.12 A              | 7.22 A              |
| Std. motor current                           | 0.46 A                   | 2.83 A            | 3.01 A             | 2.80 A             | 2.58 A              | 2.43 A              |

| Motor control concept<br>Start angle $\beta$ | Impact frequency 50 Hz |                   |                    |                    |                     |                     |
|--|------------------------|-------------------|--------------------|--------------------|---------------------|---------------------|
|  | Constant<br>-          | CIID<br>$0^\circ$ | CIID<br>$45^\circ$ | CIID<br>$90^\circ$ | CIID<br>$135^\circ$ | CIID<br>$180^\circ$ |
| N  | 250                    | 247               | 247                | 245                | 245                 | 244                 |
| Mean impact energy                           | 2.95 J                 | 2.67 J            | 3.20 J             | 3.29 J             | 3.40 J              | 3.55 J              |
| Std. impact energy                           | 0.06 J                 | 0.09 J            | 0.11 J             | 0.11 J             | 0.12 J              | 0.12 J              |
| Mean impact frequency                        | 49.99 Hz               | 49.36 Hz          | 49.25 Hz           | 49.15 Hz           | 48.99 Hz            | 48.83 Hz            |
| Std. impact frequency                        | 0.10 Hz                | 0.24 Hz           | 0.21 Hz            | 0.23 Hz            | 0.26 Hz             | 0.28 Hz             |
| Mean motor current                           | 14.22 A                | 13.82 A           | 14.20 A            | 14.14 A            | 14.22 A             | 14.20 A             |
| Std. motor current                           | 0.30 A                 | 2.66 A            | 3.17 A             | 3.24 A             | 3.30 A              | 3.40 A              |

## Independent impact energy and frequency adjustment

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Impact frequencies for CIID were slightly below those reached at a constant target velocity. In contrast to this, CIID resulted in higher and lower impact energy values, depending on the angle  $\beta$ , than those reached for a constant target velocity. Scattering of the impact energies and motor currents measured for all CIID control settings were higher than that of the values measured at constant target velocity.

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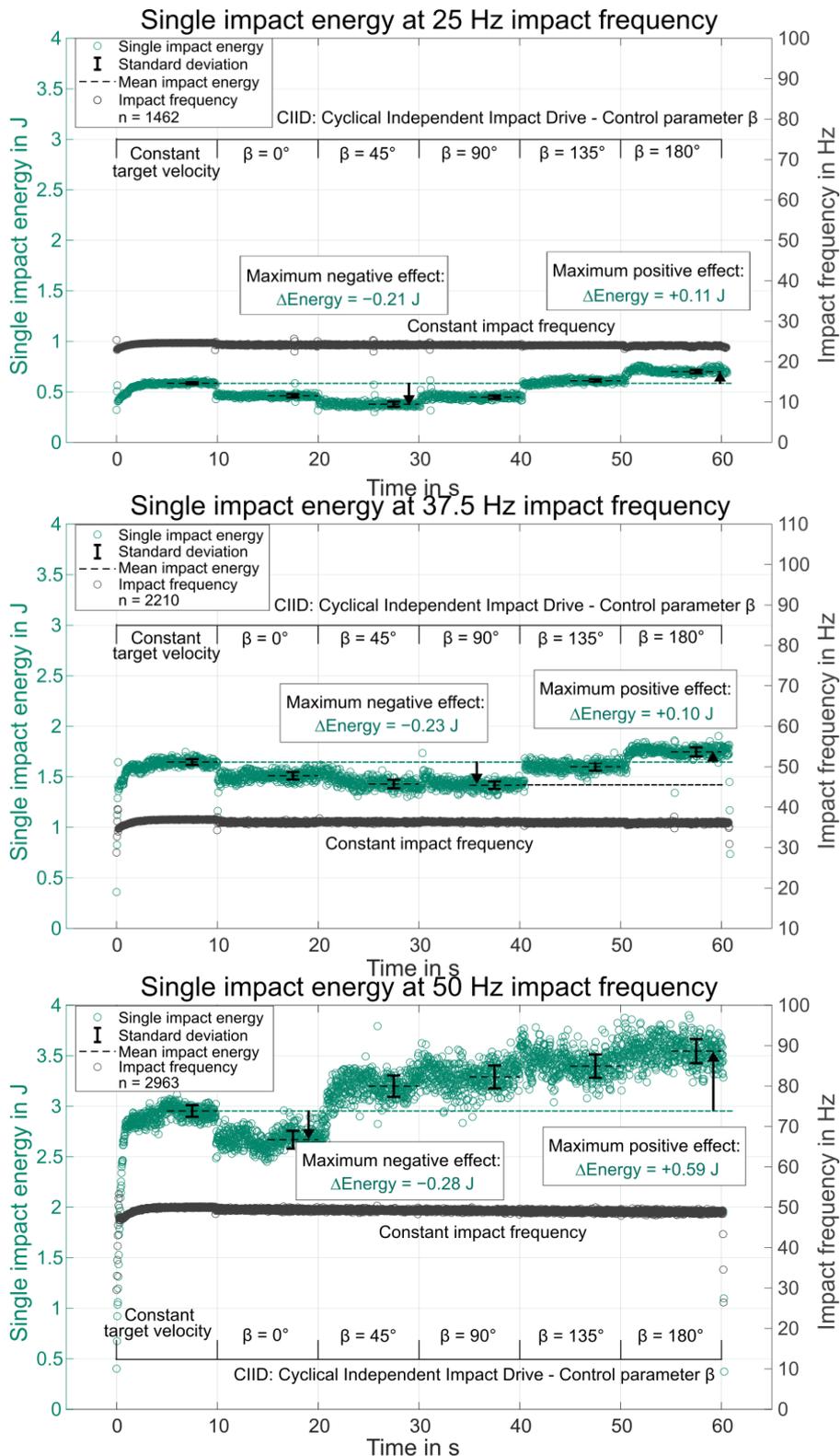
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As the different motor control strategies were investigated in a continuous test run, as explained in **Figure 5**, the measured impact energy values and impact frequencies are plotted over time in **Figure 8**. For the three impact frequencies investigated, each test starts with a constant target velocity. After ten seconds, motor control switches to the CIID motor control concept. The high target velocity angle  $\beta$  was changed every ten seconds to reach different impact energy values at a constant impact frequency.

Independent impact energy and frequency adjustment

**Figure 8**

From zero to ten seconds, a constant target velocity was given. After ten seconds, the new motor control concept was applied. The start angle  $\beta$  was varied by  $45^\circ$  from  $0^\circ$  to  $180^\circ$  every ten seconds. The resulting single impact energies and impact frequencies are given over the test time.



#### Independent impact energy and frequency adjustment

362 It is obvious from **Figure 8** that the impact frequency and impact energy increased during the  
363 first seconds of each test until a constant value was reached. The motor control concepts were switched  
364 every ten seconds. This is reflected by the single impact energy for all three mean target impact  
365 frequencies. The highest mean target frequency of 50 Hz produced the highest mean impact energy and  
366 standard deviation. The lowest target frequency of 25 Hz caused the lowest impact energy and standard  
367 deviation. Compared to a motor control with a constant target velocity, the impact frequency slightly  
368 decreased when the cyclical target velocity was started after ten seconds. The single impact energy  
369 achieved for the cyclical target velocity setting at different start angles  $\beta$  was higher or lower than those  
370 obtained for a constant target velocity depending on the specific control angle  $\beta$ . The maximum single  
371 impact energy was reached at  $\beta = 180^\circ$  for all three mean target impact frequencies. In contrast to this,  
372 the location of the minimum differed for the different impact frequencies. The minimum impact energy  
373 at 25 Hz was with  $\beta = 45^\circ$ , whereas the minimum at 50 Hz was with  $\beta = 0^\circ$ .

374 The variance of motor current increased very strongly from a constant target velocity to the  
375 CIID control strategy. During acceleration, a high motor current was measured. During deceleration,  
376 the measured current was lower. This led to a higher variance compared to the constant target velocity.

377 The statistical results obtained for the different impact frequencies are presented below.

#### 378 Impact Frequency 25 Hz:

379 The effect of the CIID motor control concept was evaluated statistically . At 25 Hz, Levene's  
380 test indicated a variance inhomogeneity for the single impact energies ( $F(5, 720) = 4.859, p < .001$ ) of  
381 the six investigated control concept settings. The Welch ANOVA test indicated a significant difference  
382 ( $F(5, 330.572) = 4938.935, p < .001$ ). Both Bonferroni and Games-Howell post hoc tests showed  
383 significant differences of all six concepts ( $p < .001$ ). The highest effect of 0.32 J was achieved between  
384 the control concept with  $\beta = 45^\circ$  and the control concept with  $\beta = 180^\circ$ . The maximum positive effect  
385 compared to the reference of a constant target velocity was 0.11 J, while the maximum negative effect  
386 was -0.21 J.

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Independent impact energy and frequency adjustment

388 Impact Frequency 37.5 Hz:

389 Levene's test also indicated a variance inhomogeneity for the single impact energy ( $F(5, 1084)$   
 390  $= 3.219, p = .007$ ) at the target frequency of 37.5 Hz. The Welch-ANOVA test indicated a significant  
 391 difference ( $F(5, 503.239) = 1938.208, p < .001$ ) for the impact energy. Bonferroni and Games-Howell's  
 392 post hoc tests showed significant differences of nearly all settings ( $p < .001$ ). Only for the setting with  
 393  $\beta = 45^\circ$  and  $\beta = 90^\circ$  was no significant effect obtained (Bonferroni:  $p = 0.058$ , Games-Howell:  $p =$   
 394  $0.054$ ). The highest effect of 0.33 J was found between the control concept with  $\beta = 90^\circ$  and the control  
 395 concept with  $\beta = 180^\circ$ . The maximum positive effect compared to the reference of a constant target  
 396 velocity was 0.10 J, the maximum negative effect was -0.23 J.

397 Impact Frequency 50 Hz:

398 For the mean target impact frequency of 50 Hz, Levene's test again indicated a variance  
 399 inhomogeneity ( $F(5, 1472) = 21.560, p < .001$ ). The Welch-ANOVA test again indicated a significant  
 400 difference ( $F(5, 673.629) = 2638.764, p < .001$ ) for the impact energy. Both Bonferroni and Games-  
 401 Howell post hoc tests showed significant differences of all six concepts ( $p < .001$ ). The highest effect  
 402 of 0.88 J was achieved between the control concept with  $\beta = 0^\circ$  and the control concept with  $\beta = 180^\circ$ .  
 403 The maximum positive effect compared to the reference of a constant target velocity was 0.59 J, the  
 404 maximum negative effect was -0.28 J. This represents an increase of 20.0 % compared to the reference  
 405 motor control with a constant target velocity.

### 406 **3.2. Cyclical Independent Impact Drive Effect on Drilling Productivity and Vibration**

407 The ROP (green) and  $a_{hv}$  (black) values for the three motor concept settings are plotted in  
 408 **Figure 9**. The first setting covered a constant target velocity. The second and third concepts were those  
 409 with the highest and lowest single impact energies. To find the highest and lowest possible single impact  
 410 energies at the specific frequency of 25 Hz, the resolution of the angle  $\beta$  of  $45^\circ$  from the previous  
 411 subsection was too low. Based on the results of the previous subsection, the angles  $\beta$  were determined  
 412 for the highest and lowest possible single impact energies. The cyclic motor concept with an angle  $\beta =$   
 413  $220^\circ$  reached the highest possible single impact energy of 0.85 J. The cyclic motor concept with an

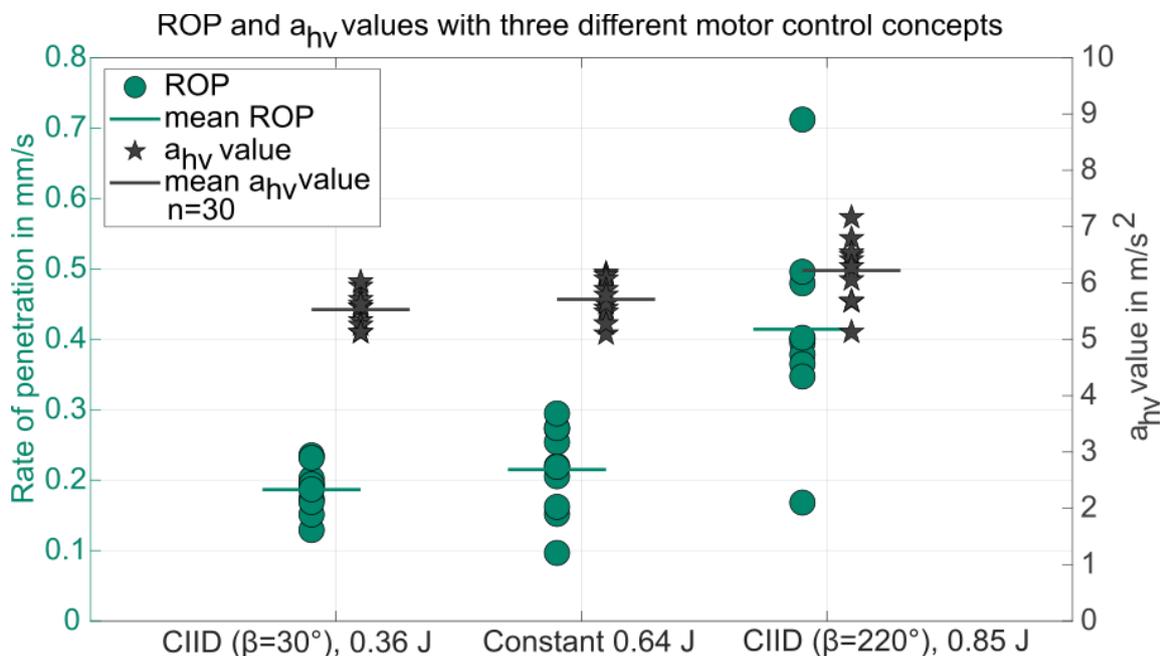
Independent impact energy and frequency adjustment

414 angle  $\beta = 30^\circ$  produced the lowest possible single impact energy of 0.36 J. A single impact energy of  
 415 0.64 J was reached by the motor concept with a constant target velocity. The single impact energies of  
 416 the three investigated motor control concept settings were measured again with the EPTA 05/2009  
 417 procedure.

418 The three motor control concepts in **Figure 9** are sorted from low (left) to high (right) single  
 419 impact energy for an impact frequency of 25 Hz. The ROP and  $a_{hv}$  values increased with the single  
 420 impact energy. ROP (mean = 0.41 mm/s,  $\sigma = 0.14$  mm/s) and  $a_{hv}$  values (mean = 6.22 m/s<sup>2</sup>,  $\sigma =$   
 421 0.60 m/s<sup>2</sup>) were highest for the cyclic motor concept with  $\beta = 220^\circ$ . The lowest ROP (mean = 0.19 mm/s,  
 422  $\sigma = 0.03$  mm/s) and  $a_{hv}$  values (mean = 5.53 m/s<sup>2</sup>,  $\sigma = 0.32$  m/s<sup>2</sup>) were obtained for the cyclic motor  
 423 concept with  $\beta = 30^\circ$ . The motor concept based on a constant target velocity produced ROP (mean =  
 424 0.21 mm/s,  $\sigma = 0.06$  mm/s) and  $a_{hv}$  values (mean = 5.71 m/s<sup>2</sup>,  $\sigma = 0.37$  m/s<sup>2</sup>) that ranged between those  
 425 of the two cyclical motor concepts.

**Figure 9**

ROP (green) and  $a_{hv}$  values (black) measured in the automated drilling study with three different motor control concept settings at an impact frequency of 25 Hz. The motor control concept on the right with the highest single impact energy reached the highest ROP and  $a_{hv}$  values. The motor control setting in the middle is based on a constant motor target velocity and, hence, represents the current state of research.



#### Independent impact energy and frequency adjustment

426 To obtain reliable statements, the measured values were examined statistically. As each  
427 investigated motor concept was subjected to ten test runs, all normal distributions were examined using  
428 the Shapiro-Wilk test. As the Shapiro-Wilk test was not significant for the ROP of any of the three  
429 groups, normally distributed factors can be assumed. Levene's test showed no significant violation of  
430 variance homogeneity ( $F(2, 27) = 2.884, p = .076$ ). The ANOVA test revealed a significant difference  
431 in ROP between the three investigated motor control concepts ( $F(2, 27) = 19.736, p < .001$ ). According  
432 to the Bonferroni post hoc test, the cyclical motor control concept with  $\beta = 220^\circ$  (on the right in **Figure**  
433 **9**) significantly differed from the other two motor control concepts ( $p < .001$ ). No significant difference  
434 was found between the other concepts.

435 The measured  $a_{hv}$  values were lower than the  $a_{hv}$  value given by the manufacturer for the  
436 unmodified hammer drill of  $12.0 \text{ m/s}^2$  with an uncertainty  $K$  of  $1.5 \text{ m/s}^2$ . , The Shapiro-Wilk test did  
437 not indicate any non-normal distributions of the  $a_{hv}$  values measured for the three factor combinations.  
438 Levene's test again showed no significant violation of variance homogeneity ( $F(2, 27) = 2.138, p =$   
439  $.137$ ). The ANOVA analysis revealed a significant difference in the  $a_{hv}$  values for the three motor  
440 control concepts ( $F(2, 27) = 6.548, p = .005$ ). The Bonferroni post hoc test again showed that the motor  
441 control concept with  $\beta = 220^\circ$  only had significantly higher  $a_{hv}$  values compared to the other concepts  
442 (cyclical  $\beta = 220^\circ$  to constant:  $p = .048$  and cyclical  $\beta = 220^\circ$  to cyclical  $\beta = 40^\circ$ :  $p = .005$ ). No significant  
443 difference was found between the concept with the constant target velocity and the cyclical concept  
444 with  $\beta = 40^\circ$ .

#### 445 **4. Discussion**

446 The first subsection discusses the motor control concept's effect on the single impact energy  
447 to answer the first research question "Can a cyclical motor control concept adjust the single impact  
448 energy independently of the impact frequency?". The second subsection evaluates the drilling tests to  
449 answer the second research question: "Does a cyclic motor control have an effect on drilling  
450 productivity and vibration in hammer drilling?".

Independent impact energy and frequency adjustment

#### 451 **4.1. Cyclical Independent Impact Drive Effect on Single Impact Energy**

452           Using the new “Cyclical Independent Impact Drive” motor control concept, it is possible to  
453 vary the single impact energy independently of the impact frequency. This represents a novelty  
454 compared to the current state of research and has not yet been achieved so far[15]. In contrast to a  
455 constantly driven impact mechanism, it is possible to influence the impacts in a certain range for more  
456 or less energy while maintaining a constant impact frequency. Hence, the first research question “Can  
457 a cyclical motor control concept adjust the single impact energy independently of the impact  
458 frequency?” can be answered in the affirmative.

459           Todorov et al. modified the design parameters (e.g. striker mass, impact bolt weight, and air  
460 spring diameter) of the impact mechanism to optimize the impact energy. The resulting improvements  
461 of single impact energy were less than 10 % [12]. In the study reported here, we managed to reach  
462 comparable or even higher increases in single impact energy. With the CIID control concept, the single  
463 impact energy was increased by 16.5 % to 20.0% at various impact frequencies. The cyclical motor  
464 control concept can cause a relevant increase in the single impact energy while maintaining a constant  
465 impact frequency.

466           As different drilling applications are associated with different optimal drilling parameters for  
467 productivity, the motor control concept can be used for further optimization, because impact energy can  
468 now be varied in a certain range independently of the impact frequency [17]. This may increase the  
469 single impact energy in newer hammer drill generations. Moreover, softer materials can be drilled with  
470 the desired lower impact energy without having to lower the impact frequency.

471           CIID time ranges exhibited slightly decreased mean motor velocities compared to time ranges  
472 with a constant target velocity. In contrast to this, impact energies in CIID time ranges were larger or  
473 smaller. The slightly decreased motor velocity can be explained by the use of a different control  
474 parameter set. In later tests, this offset was reduced by optimized parameters although it is not relevant  
475 to the findings of this study, as CIID caused larger or smaller impact energies despite a slightly  
476 decreased motor velocity. Hence, timing of the impact mechanism is relevant to the impact energy.

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477 CIID changes the timing of the impact mechanism, which can be seen in **Figure 7**, as the motor velocity  
478 curves have their maximum or minimum at different motor angles.

479 The minimum impact energy was observed for the different impact frequencies at different  
480 control angles  $\beta$ . For the single impact energy, the timing of piston, striker, and impact bolt is important  
481 [16]. This timing is influenced by the impact frequency as well as by the control angle  $\beta$ . The kinetic  
482 energy of the moving parts in the impact mechanism increases with increasing impact frequency. The  
483 CIID control concept therefore has less influence on the motor velocity over the motor angle  $\alpha$  at higher  
484 frequencies, which is shown in **Figure 7**.

485 The timing in the impact mechanism depends on the force curve  $F(\alpha)$  acting on the striker. The  
486 air spring relevant to the force  $F(\alpha)$  is a progressive spring. A high force acts on the striker when the air  
487 spring is highly compressed [13]. Small variances in motor velocity may have a large effect on force  
488  $F(\alpha)$  during compression. At high impact frequencies, this results in a large effect on the impact energy,  
489 although motor velocity is changed only slightly by the motor control concept. The control angle  $\beta$   
490 interacts with the impact frequency's effect on the single impact energy. To influence the single impact  
491 energy in a targeted manner, the control angle effect must be determined for all relevant frequencies.  
492 The motor control effect on the impact energy is always dependent on the impact frequency.

493 A boundary condition for the motor control concept is that the impact frequency must remain  
494 stable. This must be taken into account when choosing the control parameters. Standard deviation of  
495 the single impact energies measured for the CIID control concept exceeded that obtained for a constant  
496 target velocity. Understanding the motion of the striker would result in further improvements, as this  
497 would also lead to a better understanding of the non-linear system. The acceleration and deceleration  
498 phases of  $180^\circ$  each could be changed to achieve further improvements.

499 When setting the motor control parameters, a conflict of objectives must be resolved. Control  
500 values for a quick change in motor velocity may have stronger effects on the single impact energy, but  
501 may also lead to unstable motor control and operation. This will result in variances in single impact  
502 energy and an unstable impact mechanism. The motor was not actively braked during the low target

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503 velocity phase in this study. The load of the impact mechanism only led to deceleration. A concept with  
504 an actively braked motor would be a promising subject of further research. This could result in higher  
505 crank accelerations while maintaining a constant impact frequency. It would also enable further  
506 adjustment of the timing in the impact mechanism, especially at higher impact frequencies when the  
507 inertial torque is more dominant. This could further increase the motor control effect on the single  
508 impact energy. Such a concept would require a larger electrical intermediate circuit to be able to store  
509 the energy gained during the deceleration phase.

510 The variance in the motor current increased very strongly from a constant target velocity to the  
511 new CIID control strategy. This had been expected, because the motor was no longer controlled  
512 continuously. A motor with a high nominal current was used for the impact mechanism in this study.  
513 Accelerating and decelerating the motor affected the single impact energy. There was a big uncertainty  
514 as to whether the timing of the impact mechanism can be influenced by the motor control affecting the  
515 single impact energy. Cyclic application with an acceleration and deceleration of a drone rotor is not  
516 comparable due to the low inertia and absence of impacts [30]. Investigating the motor control concept's  
517 effect on the single impact energy with a much smaller motor would be the first step towards integration  
518 in a commercially available hammer drill. The mean motor current is relevant to selecting the right  
519 motor for an application, as the permissible motor current limits the motor torque and, hence, possible  
520 acceleration.

#### 521 **4.2. Cyclical Independent Impact Drive Effect on Drilling Productivity and Vibration**

522 An impact frequency of 25 Hz was chosen as the most stable operating point for the drilling  
523 study. As inhomogeneities of the drilling process lead to an additional test variance, the variance  
524 resulting from the single impact energy was kept as small as possible. This resulted in a lower ROP  
525 compared to other studies of hammer drilling [19,34]. 25 Hz is in the lower range of the impact  
526 mechanism to work properly. The drill bit with a radius of 16 mm, in combination with the hard concrete  
527 C50/60, resulted in low drilling productivity at this operating point. A smaller drilling radius and a  
528 softer concrete, such as C20/25, would lead to a higher drilling productivity and would be a more

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529 realistic application for the setup [20]. Nevertheless, an influence on productivity and vibration was  
530 confirmed.

531 Statistical analysis showed that the cyclical motor control concept with  $\beta = 220^\circ$  and the highest  
532 single impact energy led to higher drilling productivity and vibration emission. The cyclical motor  
533 control concept with  $\beta = 30^\circ$  did not result in lower drilling productivity and vibration emission. This  
534 can be explained by the non-linear and elastic/plastic relationship between the single impact energy and  
535 drilling productivity [14]. A certain amount of impact energy is required to reach the plastic part in  
536 penetration and, hence, drilling progress.

537 Cyclic excitation with a higher single impact energy ( $\beta = 220^\circ$ ) resulted in higher  $a_{hv}$  values.  
538 Cyclic excitation with a lower single impact energy ( $\beta = 30^\circ$ ) did not lead to higher  $a_{hv}$  values. This  
539 indicates that a cyclic excitation by the motor alone does not necessarily have to result in a higher  
540 vibration emission. The  $a_{hv}$  values did not increase for the cyclical motor control at low single impact  
541 energy. In this study, the increasing  $a_{hv}$  values correlated more with the single impact energy. This fits  
542 with the results of the study by [13]. Vibration emission also increased with increasing productivity.  
543 Due to the interaction with the cyclic load of the impact mechanism, the two mechanical excitations  
544 could cancel out each other and lead to a lower vibration emission. Optimizing the motor control  
545 concept for lower vibration emission would require additional research. The second research question  
546 "Does a cyclical motor control have an effect on drilling productivity and vibration in hammer drilling"  
547 can therefore be answered in the affirmative. Cyclical motor controls can have an effect on drilling  
548 productivity and vibration. The results of this study suggest that this is an indirect effect due to the  
549 motor control concept's effect on the single impact energy.

550

## 5. Limitations

551 This study examined a specific system configuration with a hammer drill, an impact  
552 mechanism, drill bit, and a certain type of concrete. To ensure its validity, further investigations should  
553 be conducted using different configurations. These additional studies would help validate the findings

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554 in terms of productivity and vibration for other drill bit options. The present study is based on a 16 mm  
555 diameter drill bit. Investigations with other drill bits are recommended, as the drill bit has an influence  
556 on the impact mechanism. In this study, an automated test rig was used to drill the holes at a constant  
557 feed force level. This ensures a stable drilling process [20]. The findings obtained for productivity and  
558 vibration are therefore limited to a constant feed force. Construction workers use hammer drills with a  
559 more fluctuating feed force [36]. The effect of a fluctuating feed force on the cyclical motor control  
560 concept was not investigated in this study. It is therefore unknown whether a stable drilling process can  
561 be ensured by a cyclical motor control concept at a high feed force variance.

## 562 **6. Conclusion and Outlook**

563 This paper presents the new “Cyclical Independent Impact Drive” (CIID) motor control concept  
564 with a cyclically set target velocity for impact mechanisms. By means of this concept, it was possible  
565 to adjust the single impact energy independently by the impact frequency in hammer drilling. Impact  
566 timing was influenced by a cyclic, high-frequency motor excitation. The single impact energy can be  
567 adjusted within a certain range independently of the impact frequency. This was demonstrated over a  
568 range of impact frequencies and is a novelty compared to the state of the art.

569 The single impact energy has a big influence on drilling productivity. The new control concept  
570 was therefore tested in two studies. The measurement procedure EPTA 05/2009 was used to measure  
571 single impact energy. An automated drilling study was performed to measure drilling productivity. A  
572 higher impact energy and drilling productivity were reached while maintaining an unchanged impact  
573 frequency. The concept is a promising approach to increasing productivity in the construction industry.  
574 The effect on the single impact energy could be further increased by actively braking the motor. This  
575 would allow for an even higher acceleration of the motor while leaving the impact frequency  
576 unchanged. Investigating how to change the new motor control concept during drilling to optimize the  
577 process would be the most promising further research. Concrete and other hard materials may have  
578 heterogeneous and locally changing properties. Therefore, live adjustment of drilling parameters by the

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579 motor control could ensure an optimal drilling process, even in case of changing material properties.  
580 This would require measurement of the changing properties of materials during drilling. Another  
581 approach would be to transfer the control to other devices. As chisel hammers only have an impact  
582 mechanism without a rotational drive train, direct implementation would be possible. Integration in an  
583 impact wrench to achieve higher impact torques would be another option. This possibility was  
584 investigated by Lee et al. (2013). Their simulations, however, still remain to be confirmed  
585 experimentally. They proposed to control the motor torque to influence the impact torque. Testing this  
586 approach with a cyclically set target velocity would be a promising method for this purpose.

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#### 592 **Credit author statement**

593 **Sebastian Zimprich:** Conceptualization, Methodology, Data acquisition, Data processing,  
594 Writing – Original draft preparation, Visualization, Investigation, Project administration, Formal  
595 analysis, Validation, **Johannes Reiser:** Data acquisition, Data processing, Visualization, Writing -  
596 Reviewing, **Frieder Matter:** Data acquisition, Data processing, Writing - Reviewing, **Jan Heinrich**  
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600 The authors declare that they have no known competing financial interests or personal  
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602 **Data availability**

603 Data will be made available on request.

604 **Declaration of Generative AI and AI assisted technologies in the writing process**

605 During the preparation of this work the authors used deepl.com and grammarly.com in order to  
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608

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