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Identification of draft force characteristics for a cultivator tine with variable geometry

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The research described in the literature regarding the effects of geometric parameters on the draft force of cultivator tools are often only applicable to the tested soil types and weather conditions during testing. This research project is an evaluation how real-time adjustment of the tool geometry can be used to influence the draft force. The basis for an optimisation development and the subject of this report is the analysis of the characteristic behaviour of adjustable tines in laboratory and field tests.

The laboratory tests showed a strong dependence of the tine curvature on the draft force. As expected, the results of the field tests are more heterogeneous. The dependence of the rake angle was stronger. With regard to an optimisation strategy, as expected the characteristics is found to be variable and mainly location and soil condition dependent. Accordingly, a force-optimised control can be achieved by a condition related adjustment of the tine geometry.

Keywords
Tillage, cultivator tine, draft force, rake angle, soil bin, field test

In agriculture, the topsoil horizon as plant location represents the most important production means. Therefore, it must be managed for optimal plant growth. Furthermore, soil is roadway for vehicles with wheel loads of more than 10 tons and is exposed to severe soil compaction (Keller et al. 2019). For these reasons, tillage is necessary. Among agricultural processes, tillage operations are the tasks with the highest power consumption (Fröba 2018).

The results shown in this paper were gathered within a project funded by the German Research Foundation, HE 5738/2-2. The overall objective is to evaluate the characteristics of a cultivator tool with variable geometry to optimize and balance power consumption and work result. The fundamental research is building a data base for the selection of strategies for tine geometry adjustment during the working process. Eventually the tool geometry needs to be controlled to optimize between agronomic demands and draft force requirements considering changing soil conditions. The purpose of this report is to summarize the results from laboratory and field tests with regard to force requirements achieved so far.

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Preliminary consideration

Further development of cultivator tool concepts that can cope with the diverse and quite power demanding tasks is part of research today and will be continued in the future. Recent efforts in the area of cultivator tools analyzed, for example, geometry-discrete load of cultivator tines (Bührke et al. 2018). This method offers the possibility to identify zones of different abrasion and to develop tools with higher wear resistance. In context of draft force requirements, models have been found that predict draft force as a function of speed and working depth for discrete tool geometries (Al-Neama 2019). A possibility of reducing draft force is active vibration stimulation of tillage tools (Kattenstroth et al. 2011). Significant reductions in draft force were found. However, power requirements of the necessary additional active elements in some cases exceeded the reduced power.

The most important influence of tool geometry and consequently so in the development of tine geometries is the rake angle (Palme 1976). When considering the rake angle with the lowest draft force, various values are given in the literature. Calculations by Soehne (1956) suggest a minimum force in the range of 11° to 15°, while in his practical tests the value is somewhat higher at about 20°. Others confirm the results or are in a similar range (Vornkahl 1967, Siemens et al. 1965). In some reports, two ranges are given in which the draft force is related to the work result. For example, lower range about 15° to 20° provides a lower drag resistance and in the upper range 20° to 40° supports intense loosening and crumbling of the soil (Soucek et al. 1990, McKyes et al. 1984). The more intense crumbling can be explained by a change in the soil fracture model from tensile failure to shear failure (Elijah et al. 1971, Aluko et al. 2000). With more intensive sliding of shear planes against each other, larger fracture surfaces are produced, however an increasing draft force is to be expected.

The tests were mainly carried out with model tines to reduced complexity. Accordingly, the results are based on the effect of sloped plates while in reality varieties of curved tools are used. Furthermore, the variability of the soil parameters is high, so that the prediction models are sufficiently accurate under the tested conditions, but not precise enough to remain valid in practical use on other soils and in other conditions (Godwin et al. 1977, Soucek et al. 1990).

Design of a cultivator tool with variable geometry

A narrow cultivator tine from Lemken GmbH & Co. KG was used as the initial tool for the prototype. It consists of the elements share tip point and guide plate (Figure 1). Both tool elements are mounted on a tool carrier, which is attached to the tine beam in a pivot point. The tool carrier can be rotated 20° horizontally by means of a hydraulic cylinder with integrated position measuring system. The rotation allows a continuously adjustable rake angle range of α = 14°–34°. The guide plate and therefore the tine curvature can be varied in three positions using a pin plug-in system. In the following, the complete assembly is referred to as the adjustable tine.

A force transducer is used to measure the force components. In the vertical direction, the force is measured by an HBM U9 (20 kN measuring range) and in the horizontal direction by two HBM S9 force sensors (50 kN measuring range). The force sensors signals are captured using QuantumX amplifiers.

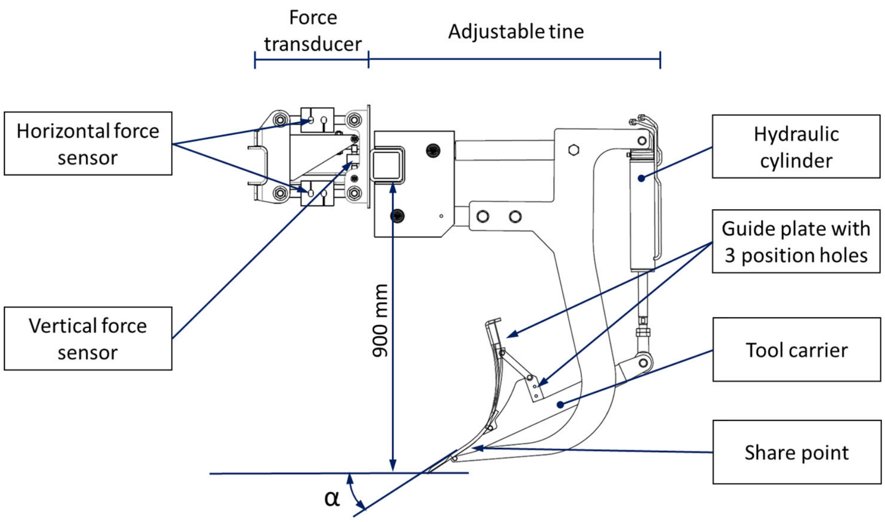

Figure 1: Cultivator tine with variable geometry and force transducer; rake angle α = 34°; guide plate in position 1

Material and method of laboratory tests

The laboratory tests were carried out in the soil bin of the Chair of Agricultural Systems and Technology at the Technische Universität Dresden (technical details: Kalk 1971). The soil bin is 28 m long and filled with loamy sand (9 % clay, 30 % silt, 61 % sand). The soil moisture can be adjusted by an irrigation system. Once the target soil moisture has been set, the natural drying process must be monitored and compensated over the test period. The electro-hydraulically driven carrier vehicle has a three-point linkage that can be moved transversely to the direction of motion. The adjustable tine is hitched to the vehicle with an integrated force transducer. Table 1 shows the parameters set for the laboratory tests.

Table 1: Parameter set for laboratory tests

	Variable	Unit	Values
Working depth	*WD*	cm	10; 20; 30
Gravimetric soil moisture	*SM*	% (dry matter based)	8; 13
Velocity	*V*	km/h	4; 8; 12
Rake angle	*α, RA*	°	14; 24; 34
Guide plate position	*GP*	-	1 (strong curvature, top hole) 2 (medium curvature; center hole) 3 (flat curvature; bottom hole)

Due to the high preparation effort, a statistical test plan was developed for the laboratory tests, which allows to reduce the test scope to a specified number of tests, deviating from the full-factorial test plan, and still reproduce valid results about the dependencies of the parameters as best as possible (Siebertz et al. 2017). The resulting D-optimal test plan comprises a predefined scope of 58 setting combinations compared to 162 possible combinations, which were carried out with three repetitions.

Material and method of field tests

For the field tests, the adjustable tine was duplicated twice and equipped with force transducers. The support frame is designed as a three-point tractor implement (Figure 2). The support frame can be folded to the side so three tines can be measured in parallel, each outside the tractor track. Additional support wheels allow the exact adjustment of the working depth independent of the deflection of the tractor wheels. A field in Woelkau near Dresden was available as test area. The series of tests were carried out in mid-August 2020 after grain harvest on medium-heavy sandy loam at a soil moisture of SM = 11 %.

Figure 2: Field test set up with three adjustable tines

A full factorial experimental design was developed for the field tests. The soil moisture is predetermined by the weather conditions and cannot be changed. Accordingly, the variable parameters are reduced to rake angle, guide plate position, depth and velocity. Using the gradations from Table 1, the field test comprised 81 test combinations. In contrast to the laboratory test, disturbance effects such as soil and vegetation differences have to be expected in the field (Wilbois et al. 2010). To minimize the influence on the tests, a randomized experimental design with three blocks was applied. In each block, the setting combinations have to be repeated once. Accordingly, each setting is tested a total of three times in the test series. During a test run, the guide plate positions are randomized among the three tines and the speed is gradually increased. The parameters working depth and rake angle are randomly assigned to the measurement runs of the blocks and kept constant during a measurement run. The measuring length of a setting combination was set to 50 m depending on the field size.

Draft force evaluation of the laboratory tests

In order to represent the geometry-dependent force characteristic with a reduced test plan, the laboratory results were transformed into a regression function, which can also be used to interpolate any value between the given tests points. For the analysis of the force characteristic, different models were compared in approximation to Bögel (2016), consisting of combinations of linear, interactive and quadratic terms. For the laboratory tests, the combination of linear and interaction terms was chosen because this model achieves a high coefficient of determination with a minimum number of coefficients. The complete regression equation with the parameters presented in Table 1 is shown below.

$$\begin{aligned} F_{Horizontal} = {} & c0 + c1 \cdot RA + c2 \cdot WD + c3 \cdot SM + c4 \cdot V + c5 \cdot GP \\ & + c6 \cdot RA \cdot WD + c7 \cdot RA \cdot SM + c8 \cdot RA \cdot V + c9 \cdot RA \cdot GP \\ & + c10 \cdot WD \cdot SM + c11 \cdot WD \cdot V + c12 \cdot WD \cdot GP + c13 \cdot SM \cdot V \\ & + c14 \cdot SM \cdot GP + c15 \cdot V \cdot GP \end{aligned}$$

Figure 3 shows the mean values of the repetitions of the horizontal force values measured in the laboratory and the force values predicted by the regression model. The regression model has a coefficient of determination of approximately 99 %. A value of 97 % is calculated for the corrected coefficient of determination and is about 2 percentage points lower but is still in a satisfactory range. At this point, a deeper statistical evaluation is omitted, since the model can describe the test data of the soil bin tests sufficiently well. The regression coefficients of the equation described above are given in Table 2. As expected, the coefficients of the linear model correlate positively with the horizontal force, and negatively for the guide plate position. The model is computed partly with negative signs, which cannot be explained by the tool-soil interaction. However, it can be explained by the fact that the effects of the other variables have to be overestimated and compensated.

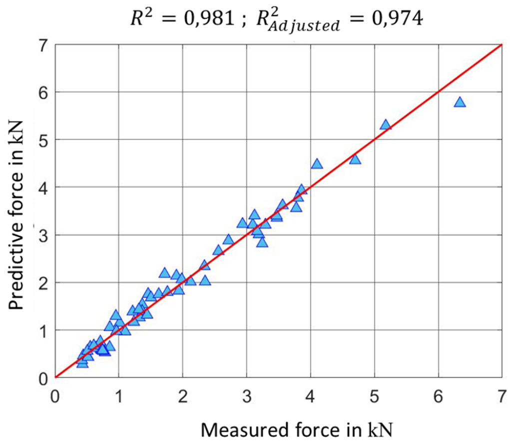

Figure 3: Scatter plot of the regression model based on laboratory tests

Table 2: Coefficients of the regression model of the laboratory tests

Coefficient	***c0***	***c1***	***c2***	***c3***	***c4***	***c5***	***c6***	***c7***
Value	-0.8674	0.0019	0.0040	-0.0192	-0.1046	0.7268	0.0006	-0.0003
Coefficient	***c8***	***c9***	***c10***	***c11***	***c12***	***c13***	***c14***	***c15***
Value	0.0003	-0.0050	0.0079	0.0081	-0.0155	0.0114	-0.0236	-0.0255

Figure 4 shows examples of curved shares for *SM* = 13 % for force curves against speed for two different working depths. While the depth is constant in the diagram, the speed, rake angle in the working process and the guide plate position are variable. In Figure 4 on the left, the curves can be classified into two clusters. The cluster is characterized by a strong influence of the guide plate position or the curvature of the tine. The change of the rake angle within a guide plate position is of minor importance at this working depth. However, it can be seen that the force requirement is slightly increasing from α = 14° to α = 34°. The behavior is also observable at a working depth of *WD* = 20 cm. At *WD* = 10 cm, see Figure 4 on the right-hand side, a greater increase in force level over speed is seen for *GP* = 1. At shallow working depths and slow speeds, the soil material only rises up closely to the guide plate. Therefore, hardly any force effect is to be expected. At higher speeds, however, the soil material is transported over the guide plate and increases the force required for the guide plate position *GP* = 1.

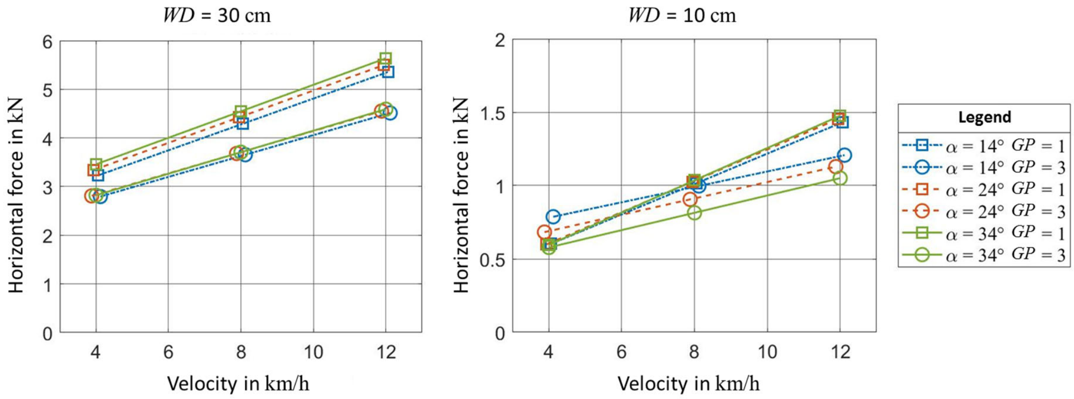

Figure 4: Regression curves of laboratory tests for *SM* = 13 %

By adjusting the geometry of the cultivator tine, it becomes clear that a force band is created when the rake angle and the position of the guide plate are varied. Table 3 compares the maximum, minimum and differential values of the force band for three working depths and a speed of 12 km/h from the regression data.

Table 3: Force band width for *V* = 12 km/h and three working depths

Working depth	Maximum force	Minimum force	Difference
10 cm	1,48 kN	1,05 kN	0,43 kN
20 cm	3,56 kN	2,82 kN	0,74 kN
30 cm	5,63 kN	4,51 kN	1,12 kN

Draft force evaluation of the field tests

During the field tests, 72 combinations were tested. For technical reasons, the measurement run at *WD* = 30 cm and α = 14° or the measurement for *WD* = 20 cm, α = 14° and *GP* = 2 could not be performed and subsequently reproduced. Figure 5 shows the field test results, analogous to the curve arrays of the laboratory tests.

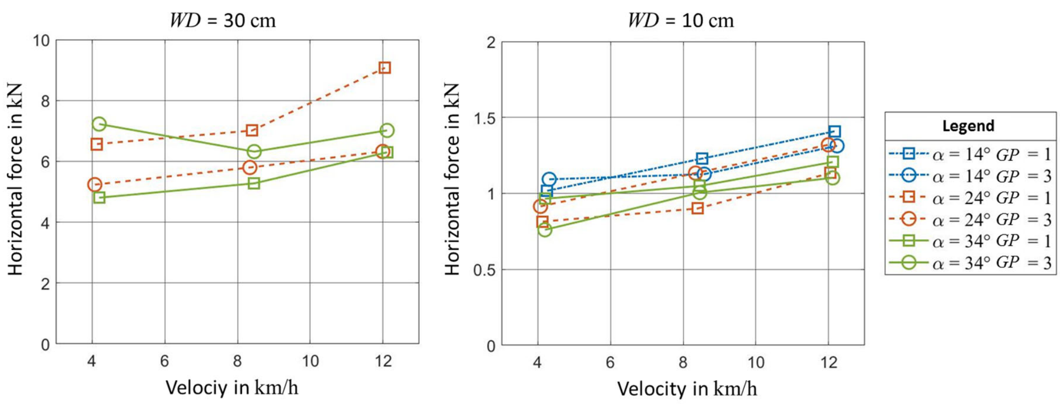

Figure 5: Curve array of horizontal forces of field tests for *WD* = 30 cm and *WD* = 10 cm

As expected, the results from the field test are more heterogeneous than in the laboratory tests. Compared to the laboratory tests, the evaluation of curves does not show any clustering according to the guide plate position. Figure 6.1 and Figure 6.2 show the force as a function of the rake angle for selected working speeds and depths. The mean draft force is plotted with the corresponding standard deviation as the deviation between the repetitions. The effect of rake angle and tine curvature can be considered individually under otherwise constant parameters.

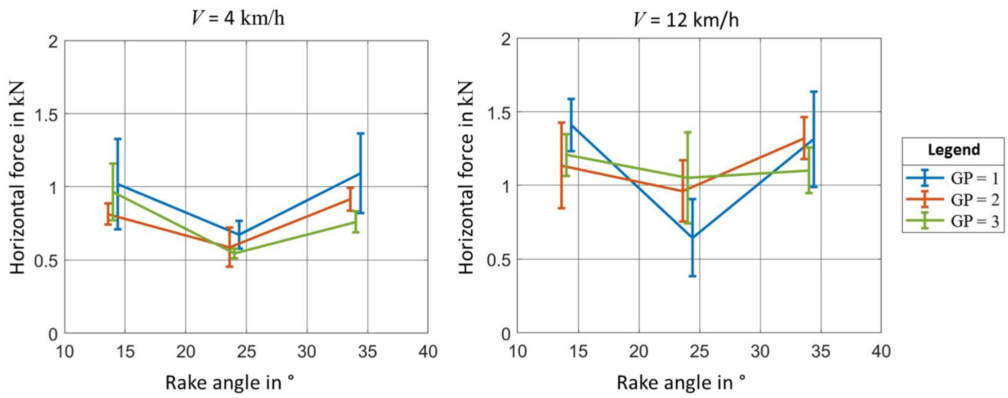

Figure 6.1: Draft force curves of the field tests; separated by speed for *WD* = 10 cm

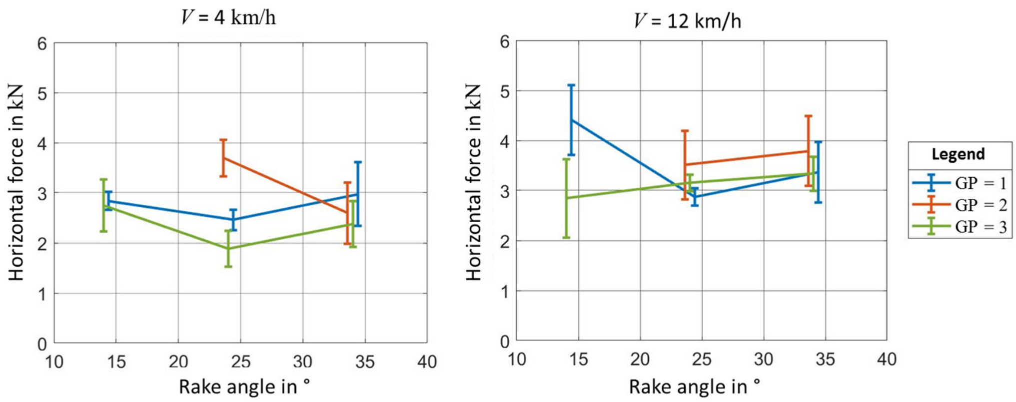

Figure 6.2: Draft force curves of the field tests; separated by speed for *WD* = 20 cm

The effect of the tine curvature is not uniformly manifested compared to the laboratory tests. Qualitatively repeating curves can be seen in the depth setting of *WD* = 10 cm and parts of *WD* = 20 cm. Here, a force minimum is formed around the rake angle $\alpha = 24°$. Elsewhere, force minima were measured at the adjustment limits at $\alpha = 14°$ (Figure 6.2: *V* = 12 km/h; *GP* = 3) and $\alpha = 34°$ (Figure 6.1: *V* = 12 km/h; *GP* = 3).

Based on the variation of the force curves under field conditions, the hypothesis that the force-optimal rake angle changes within a short distance can be expressed. To illustrate this statement, a series of measurements from the field tests was selected as follows: three measurements were taken from one block with three rake angle levels under otherwise identical conditions (*WD* = 10 cm, *GP* = 2, V ascending 4, 8, 12 km/h). Accordingly, pairs of values from three horizontal forces and three rake angles are available for each measurement step. A parabolic function and its extreme point were calculated from the pairs of values. The minimum point is to be considered as the rake angle with the lowest draft force. Figure 7 shows the series of the minimum points plotted versus distance.

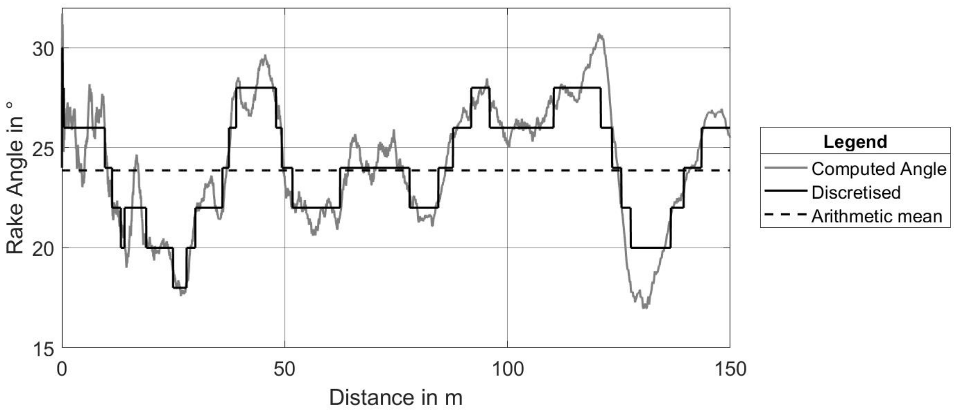

Figure 7: Graph of computed rake angle with minimal draft force

Although the rake angle with the lowest draft force is α = 24° on average, it is evident that the calculated optimum angle is temporary below as well as above the mean value within the run over a period of 25 m. For the field tests, the current state of research suggests that the optimum angle is not a fixed value but variable. This fact still has to be verified in further researches.

Conclusions

A geometry dependency on draft force is recognizable in the laboratory and field test results. At higher force levels, the laboratory tests show that the horizontal force is clearly dependent on the position of the guide plate and less on the rake angle. Here, a flat curved tine results in lower force values. The force curves of the field tests show in about half of the tests the qualitative curve with a force minimum at a rake angle around 24°, which is consistent with the results of the literature described in the preliminary research. However, the other half shows an irregular curve. The different results from field and laboratory tests do not disagree with the already known literature, but underline once again the findings that the results are strongly dependent on the test conditions and that a general prediction model has not been found.

At the current state of research, a locally varying characteristics for the relation between draft force and geometry is assumed. Accordingly, an algorithm has to be designed for force-optimized control which permanently decides about the tine geometry values to achieve the force minimum. Furthermore, a compromise must be found between the fastest possible detection of soil parameter changes and the filtering of individual disturbances such as drive lanes or stones. With changing geometry during the process, it is known that the material flow is influenced to a certain degree. In addition to the consideration of draft force, the working result has also to be considered. The extent to which attributes such as the mixing and crumbling behavior changes has to be investigated.

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