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Tree Felling with a Drill Cone

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Abstract

Motor-manual timber felling is one of the most dangerous operations in the forest and cannot be completely replaced by fully mechanized timber harvesting by a harvester when dealing with large and deciduous trees. Shifting the center of gravity of tree ready to be felled beyond its tipping line using conventional felling wedges is dangerous because the forest worker is directly behind the stem and under the tree crown until just before the tree falls. The worker can be hit by the trunk itself, but also by falling parts of the crown. In a preliminary study for the development of a new type of felling head, felling with a drill cone that can open the felling cut with the help of an applied torque was investigated. A drill cone does not require any special cutting technique, no counter forces to the tree, works without impulses, it is self-retaining and can be unscrewed again.

In order to determine the torque required for felling the tree as a function of the tree parameters, the mathematical equation framework was established and practical experiments were used to determine the friction parameters and verify the calculations. The torque of the drill cone is used to bend the intact fibers of the hinge, shift the center of gravity of the tree in the direction of fall, and to overcome the friction of the drill cone on the felling cut. The effects of forward or backward leaning trees on the required torque can also be quantified. It has been shown that the efficiency of a drill cone is low, but this is compensated for by the high internal torque to lift ratio. The maximum measured input torque for felling trees with a felling diameter up to 55 centimeter was 100 Nm.

Keywords: drill cone, tree felling equipment, work safety when felling trees, physics of tree felling, torque balance

1. Background

The proportion of motor-manual timber felling has fallen significantly during mechanization towards fully mechanized timber harvesting. However, estimates state that a third of the annual logging in the German state forests is done motor-manually (BMEL 2020). The lower the degree of mechanization or the higher the proportion of impassable forest areas in a country, the higher the proportion of chainsaw work, as Moscalic et al. (2017), Judd and Serap (2021) or Hall and Han (2006) show using the example of ten Eastern European countries, the United States and Canada.

Due to forest conversion towards climate-adapted forests, it can be assumed that the proportion of motor-manual felling will increase again. This can be explained in part by significantly higher demand for deciduous trees. In particular, the pure stands dominated by conifers are to be converted into multi-layered mixed forests (Federal Ministry of Food, Agriculture and Consumer Protection 2011). However, deciduous trees are only suitable to a limited extent for felling and processing by the harvester. In particular, trees that have reached their target size pose a problem for harvester felling due to their large diameter, high weight of the trunk and crown, stronger branches and a higher proportion of steep branches, since the harvester heads that are commonly available on the market are designed for softwood and reach their application limits when used on hardwood (Sanktjohanser 2019).

Furthermore, in certified forests, the distance between strip roads of more than 20 m should be provided. For PEFC-certified forests, a distance of more than 20 m is recommended on sensitive sites (PEFC 2014). In the case of FSC-certified forests in Germany, the aim is to provide a distance of 40 m from the middle of a lane to the middle of the next in the future (FSC 2018). With a few exceptions, harvesters cannot process the gaps in larger aisle distances because the crane range is limited to 10 m. Longer ranges would need a higher counterweight of the machine and this would significantly increase the dead weight to ensure a sufficiently large standing moment. For this reason, the trees in the area between the strip roads must be felled motor-manually. When these trees are felled in the direction of the strip road, the subsequent processing can be done by the harvester, meaning that processing with chainsaws will not be required.

However, the dangerous work of felling still has to be done by the forest worker. In 2019, 36 people died working in the forest in Germany, with 75% of these fatal accidents occurring during motor-manual felling. There are another 900 non-fatal accidents related to motor-manual felling (SVLFG 2017). Robb and Cocking (2014) collected comparable statistical data from other European countries. The danger does not only come from the falling trunk, but also from falling parts of the crown loosed by the wedging.

The question arises how the safety for the worker in motor-manual felling can be further increased. There is a multitude of technical aids that support the felling process or even make it possible at all. Lindroos et al. (2007) examined standard hand tools such as a hydraulic log pusher (a large hydraulic cylinder which stands on the ground side the tree and tries to push it far above the felling cut), a felling lever and a conventional felling wedge to determine the lifting torque of these tools during felling raise. It has been shown that the log pusher has the greatest potential. In the last decade, however, some new felling aids have also been added that technically support the »wedging« of the tree.

Mechanical or hydraulic felling wedges consist of a wedge that is driven into the felling cut by means of a hydraulic cylinder or a trapezoidal spindle drive between two spring plates that get caught in the wood and thus prevent it from slipping out of the felling cut (Hoffmann and Jaeger 2021). Lyons and Ewart (2012) showed a similar felling aid with a vertically arranged trapezoidal spindle drive. The lifting moments that these felling aids generate are similar to those of conventional wedges driven in with an axe. However, the wedging process takes place with less vibration because it takes place continuously and ergonomically relieves the forest worker (Brosche 2018). As felling technique, an extended variant of the safety felling technique with a retaining strap is recommended. After completing the felling cut up to the holding strap, a conventional wedge is set to secure it. Then, at the point where the felling aid is to be placed, the felling cut is widened in a V-shape at the top and bottom with the tip of the chainsaw. This gives the felling aid a better hold (Brosche 2018). Others also recommend that the base of the felling aid should be straightened out in a similar way as for trimming the roots. This prevents the mechanical wedge from only splitting up individual wood fibers and thus not creating a wedge effect, in the worst case even falling out of the felling cut (AID 2015).

What has not yet been studied in depth in terms of tree wedging is the use of a drill cone. Drill cones are cone-shaped rotating bodies with a uniform coarse thread, which ensures a tight fit in the felling cut. In contrast to a standard, smooth felling wedge, a drill cone does not require any counterforce to be driven in. By turning, the drill cone screws itself into the felling cut and opens it in the process. It does not have to be reset. Drill cones, available on the market for felling weak wood, are operated with a cordless screwdriver (with and without an impulse function) or with a ratchet. The previously common use of drill cones was limited to splitting firewood along the grain.

A drill cone is compact and does not require any internal mechanics. Therefore, it can be conceivable as a component of a hydraulic powered fully mechanized felling unit. This would make it possible to improve the working safety or even completely replace dangerous work with a safe work equipment. Two of the technical felling aids already mentioned, the Strixner AP3 and the Forstreich TR300, have been tested by the KWF and enable the wedge process to be controlled from a safe distance using a radio remote control (Lippert 2019a, 2019b). However, the notch and the felling cut still have to be made by the forest worker with a chainsaw. In addition, the V-shaped trimming of the felling cut can hardly be done by machine. The use of these felling aids therefore only represents a first step towards improving motor-manual felling.

For the possible mechanization of a felling unit using a drill cone, the choice of a corresponding width of the hinge is also of great relevance. The accident prevention regulations for forest work in Germany specify a width of the hinge of at least one tenth of the diameter (SVLFG 2017). This increases the risk of crown breakage and makes the work very unergonomic and unproductive, the larger the trees to be felled. Höllerl (2017) reports that, in the case of larger tree diameters, workers often leave in place an oversized »anxiety bar« out of caution, which makes tree felling even more difficult and time demanding (Höllerl 2017).

2. Aim of Study

The aim of this study is to find new mechanized solution for tree felling. It should be checked whether a hydraulically operated drill cone offers a good and safe way to mechanize the wedging of a tree.

In particular, it should be investigated which lifting moments can be generated depending on the input torque of a drill cone. The aim is to clarify the influence of different widths of the hinge on the power requirement.

3. Materials and Methods

3.1 Mathematical-Physical Relationships in Tree Felling

When using the classic, motor-manual methods for the controlled felling of a tree, a felling notch pointing in the direction of fall and a felling cut on the back side are made so that a hinge of a defined width remains (SVLFG 2017). A felling wedge is inserted into the felling cut so that the weight of the tree, depending on the position of its center of gravity, rests partly on the hinge and partly on the felling wedge.

This hinge can be viewed as a plank whose wood fibers have remained intact. As Guimier (1980) showed, the compressive force of the bar on the fibers is evenly distributed over its cross-section. When the hinge bends, the previously uniform stress distribution is overlaid with an additional action. If only the bending stress is considered, the edge fibers in the direction of the notch are compressed, while those in the opposite direction are stretched. The course of the differences in tensions is linear. In the intervening neutral fiber (velocity pole of the sloping tree), the stress is zero. In the case of a combined effect, both courses are superimposed. This results in a compressive stress profile with greater compressive stresses on the side of the notch with reduced compressive stresses on the opposite side. When the tensile stresses resulting from the bending stress are greater than the compressive stresses on the side of the notch, the fibers on the tensile side experience low tensile stresses, while the fibers in the felling direction have to absorb more than twice as much compressive stress. However, as the tree leans progressively, as the bending stress increases, the compressive stress decreases. Since e.g. the tensile strength (95 N/mm^2) of spruce is twice as high as the compressive strength (45 N/mm^2) (DIN 68364; 2003-05), when a tree is tipped over, the fibers first compress in the felling direction due to the compressive stress, but still carry the load. In contrast, if wood fibers on the opposite side tear off completely due to the tensile stress, they are no longer supporting. Due to this anisotropy, the neutral fiber does not remain in the middle of the hinge, but shifts in the 1/3 to 2/3 division towards the notch side.

As soon as the top cut hits the bottom cut of the notch, extremely high tensile forces suddenly arise on the entire hinge, causing the entire bundle of fibers to tear and losing its function as a tilting hinge with guidance and support (Guimier 1980).

When describing the process of tree felling mathematically, it can be quickly concluded that there are great uncertainties in estimating the weight of the tree and the position of its center of gravity. Lindroos et al. (2007) tried to simplify this problem by presenting the tree that is not hanging forwards or backwards as a rotational solid with its center of gravity in the middle and with the pivot point in the middle of the hinge. The falling movement takes place on a vertical plane assuming that the tree takes no lateral forces or positional deviations during the movement. In the study of lifting forces during felling, Franz (2020) describes the trunk as a truncated cone and the crown as a bowl with homogeneous mass distribution. The center of gravity of the entire tree is calculated by offsetting the two centroids. However, a crown rarely has a homogeneous mass distribution, individual strong branches can have a strong influence on the position of the center of gravity, and the density of the crown differs from that of the trunk. Furthermore, conifers are difficult to depict with this description. It is important to identify the total mass of the tree. Pretzsch (2019) describes one way of refining the coarse fuzziness of this input variable. With the help of an expansion factor, conclusions can be drawn about the tree weight from the solid wood mass. The weight (F_{wt}) is then calculated from the mass (m) of the tree and the gravitational acceleration (g).

Jacobsen et. al (2003) set up age-dependent functions for the proportions of individual tree compartments in the total biomass of the tree. From this, the following relationship (Eq. 1) can be derived for the age-dependent expansion factor for spruce in relation to the solid wood mass:

$$ef_{\text{spruce}}(x = \text{age of tree}) = 0.0001x^2 - 0.0216x + 2.214 \quad (1)$$

$$F_{\text{wt}} = \pi \times \frac{d^2}{4} \times h \times f_{\text{spruce}} \times ef_{\text{spruce}} \times \rho_{\text{spruce}} \times g \quad (2)$$

Where:

ef_{spruce} expansions factor, spruce; according to [1] at age of 55 ≈ 1.33

d breast height diameter, cm

h tree height, m

f_{spruce} timber form factor, 0.513 (Site class I, age = 55 (Schober 1995))

ρ spruce wood density of spruce

g gravitational constant.

The standing moment of the tree, calculated from the weight and distance of the center of gravity from the tipping point, counteracts the falling of vertical trees and rear hangers. The greater the horizontal distance of the tree gravity center from the tipping edge, in our case from the middle of the hinge, the greater the standing moment.

By wedging the tree with the changing inclination of the tree, the distance between the center of gravity and the tipping line (l) is reduced. When the center of gravity is vertically above the tipping line, the standing moment (M_{stand}) is 0 Nm and the tree has reached the unstable position. In the event of a subsequent inclination in the felling direction, it would fall of its own accord (see Eq. 3,4 and 5 and Fig. 1).

$$M_{\text{stand}} = F_{\text{wt}} \times l \tag{3}$$

Where:

l horizontal distance between center of gravity and tipping line.

$$l = l_{\text{lever}} + \frac{2}{3} b_{\text{hinge}} - \frac{d}{2} \pm x_{\text{shift}} \tag{4}$$

$$x_{\text{shift}} = \sin(a) \times h_{\text{cg}} \tag{5}$$

Where:

l_{lever} lever between end of felling cut and effect point of drill cone/ hydraulic cylinder

b_{hinge} width of the hinge

x_{shift} shift of center of gravity to tipping line (+ backward leaning trees; - forward leaning trees)

h_{cg} height of center of gravity

α slope of tree axis from the vertical.

It must be emphasized here that the measurement of the inclination, the height of the center of gravity, the tree mass and the lateral distance of the center of gravity of the tree from the vertical above the tipping point is not trivial and can usually only be estimated. This makes it difficult, if not impossible, to draw conclusions about measured torques from field tests. Nevertheless, the initially purely theoretical analysis of the problem space helps to understand the mode of action of the wedge process and the influencing factors of the parameters.

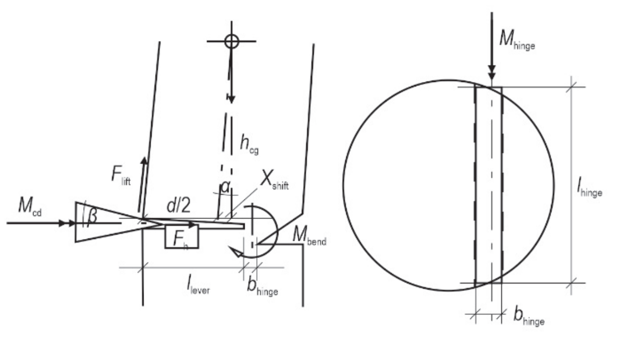

Fig. 1 Representation of Eq. 3 to 10

In addition to the standing moment of the tree, the bending resistance (M_{hinge}) of the hinge must also be overcome. It is not only the size of the cross-sectional area that counteracts the bending moment that is decisive, but also its geometric shape. This geometric influence is represented by the bending section modulus, which reflects the quotient of the area moment and the distance to the edge fiber (Böge and Böge 2009). Since the hinge can be approximately described as a rectangle, this section modulus is calculated using the following Eq. 6 and 7, see also Fig. 1.

$$M_{\text{hinge}} = \sigma_{\text{flexural strength}} \times W_{\text{hinge}} \tag{6}$$

$$W_{\text{hinge}} = \frac{l_{\text{hinge}} \times w_{\text{hinge}}^{2}}{12} \tag{7}$$

Where:

$\sigma_{flexural\ strength}$ flexural strength of spruce

W_{hinge} bending section modulus

l_{hinge} length of hinge

w_{hinge} width of hinge.

The equation shows that the width of the hinge, which is perpendicular to the axis of rotation, has a greater influence then its length. The bending strength of the wood fibers must also be taken into account when calculating the necessary bending moment.

In order to calculate the effect of the drill cone, two physical relationships from mechanics are relevant. On the one hand, the drill cone has a thread that causes the feed into the felling cut when rotated. The horizontal feed force can be calculated from the pitch of the thread (8).

On the other hand, due to its wedge-shaped cross-section, the drill cone causes a lifting force that lifts the tree. This lifting force depends on the opening angle of the wedge and can be calculated using Eq. 9.

$$F_{\text{h}} = \frac{M_{\text{cd}} * 2 * \pi * c_{\text{cd}}}{s_{\text{tp}}} \tag{8}$$

$$F_{\text{lift}} = \frac{F_{\text{h}}}{\tan(\beta)} \tag{9}$$

Where:

F_h horizontal feed force of drill cone
M_{cd} torque of drill cone
c_{cd} efficiency of drill cone
s_{tp} thread pitch of drill cone
F_{lift} lifting force of drill cone
β spread angle of drill cone in °.

The bending moment acting in the fracture strip (M_{bend}) can be calculated by multiplying the lever length, which is the distance between the point of action of the drill cone and the tipping point of the tree, by multiplying it by the lifting force (see Fig. 1).

$$M_{bend} = F_{lift} \times (l_{lever} + \frac{2}{3} b_{hinge}) \tag{10}$$

3.2 Field Tests

The trials were divided into two phases and run from autumn 2019 to summer 2020.

3.2.1 First Test Phase

In order to avoid the negative influence of the fuzzy input variables described above for standing trees, felling tests were initially carried out on short, upright standing trunk sections. These were approximately 1.5 meter tall spruce logs that were used within two weeks after felling. The first step was to create a notch of about 1/5 of the diameter. In order to achieve the most exact possible and repeatable formation of the hinge, a saw frame was designed for a hand-held power-saw, and it was positioned with the help of the felling notch that had already been created. With the help of this frame, the width of the hinge could be adjusted with millimeter precision and the hinge sides could be shaped in parallel.

After that, instead of the saw frame, a rack for a short-stroke hydraulic cylinder was attached (see Fig. 2, left).

This mounting rack had the advantage that no box-shaped cut-out had to be made on the log, as is the case with conventional hydraulic rams used as a felling aid.

The built-in joint bearings ensured a permanent vertical transmission of force, even if the upper trunk section has tilted around the pivot point in the hinge when the lifting height increased. A 200 kN measuring ring (HBM 6) was located under the hydraulic cylinder. A laser distance meter mounted on the side recorded the lifting height. The hydraulic cylinder had a maximum lifting height of 50 mm and a piston diameter of 65 mm. In combination with the hydraulic unit used, a maximum lifting force of 82 kN could be generated with a hydraulic pressure of 250 bar. During the felling process, the necessary lifting force was recorded by the sensors with increasing lifting height until the wood fibers of the hinge failed. For the evaluation of the test, the wood moisture content was measured in the notch using a commercially available wood moisture meter (Brennenstuhl MD).

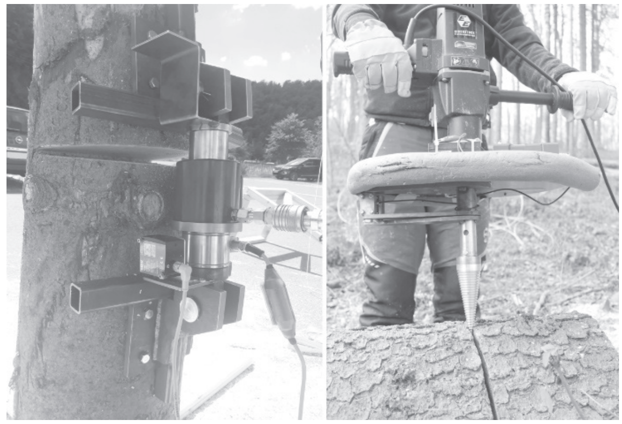

Fig. 2 Test design to measure bending resistance of hinges with varying width (left) and torques that occur during the wedging process with drill cone (right)

The width and length of the hinge as well as the lever length between the hinge and the center of the hydraulic piston were measured with a ruler. The diameter of the trunk section at the height of the felling cut was measured with a caliper. 13 segment tests were carried out.

3.2.2 Second Test Phase

Then, 14 real trees were felled using a drill cone. These tests took place on two land areas in the Eastern Erz-Mountains, situated at about 450 m above sea level. The first area was a mixed stand of spruce and larch on level terrain, with only the spruce being used for the experiments. These had an age of about 55 years and were assigned to yield class I. On average they have a felling diameter of 31.1 cm and a height of 22.4 m. The second area was a pure spruce stand around 80 years old with a slight incline. The spruces had a felling diameter of 44.5 cm and a height of 27.9 m. All selected trees had a centric center of gravity and there was no wind blowing at the time of felling.

In order to measure the torques that occur during the wedging process with the drill cone, a specially designed measuring aid was used (see Fig. 2, right).

An electrical core drill with a drive power of 1800 watts, which generates a torque of 290 N*m at a speed of 1/s, was used for the drive and supplied by a 2 kW emergency power generator. The measuring aid is designed in such a way that the force is transferred to the drill cone via two levers. A 5 kN force sensor

(HBM 9c-5kN) is arranged between the two levers. The data is transferred from the measuring amplifier (HBM Quantum MX840) to a laptop via a WLAN router. The torque with which the drill cone is screwed into the felling cut can be calculated using the lever length of 20 cm and the force measured on the sensor. The drill cone used is made of aluminum and has a length of 180 mm. The maximum diameter is 50 mm and it has a pitch of 0.006 m. This value also corresponds to the pitch of the thread. Since the point of action of the drill cone always remains on the felling edge when screwing in, the effective lever length is constant.

The trees were felled using a felling technique focused on work safety. First, a notch of about 1/5 of the diameter was made. Then the hinge was marked. A wide range of thinner and thicker trees were felled with hinge widthes between 1 cm and 5.5 cm. The width of the hinges varied between half and twice the recommended width of one tenth of the felling diameter. Depending on the size of the tree, the convenient felling cut was then carried out until only the retaining strap remained. A check was carried out to ensure that the hinge had been formed evenly and parallel. If necessary, it was carefully trimmed. A conventional felling wedge was set to secure it, then the retaining strap was severed. The drill cone was then used to fell the tree. The rootstock was measured in the same way as in the first test phase, and the tree length was also recorded with a tape measure.

On some trees, the tree was felled at a tree height of approx. 1 m. The notch and felling cut were then made again on the tree stump with the same measurements as for the previous tree felling. The aim was to eliminate the effect of the tree weight force and only to record the influence of the hinge in order to determine the composition of the required moment and the influencing strengths of the different active components.

4. Results

4.1 Results of Test Phase 1

Table 1 summarizes the test data obtained during the first test phase – felling of short wood segments with the help of an external hydraulic cylinder.

Table 1 Summary of first test phase results

Moisture %	Width of hinge, cm	Length of hinge, cm	Bending modulus of resistance, mm^3	Felling diameter, cm	Lever m	Measured maximum lifting force, N	Resulting bending moment, N*m	Bending stress, N/mm^2
27.0	1.5	31.5	11,813	35.0	0.315	3812	1201	101.65
20.4	2.0	30.5	20,333	36.0	0.340	4854	1650	81.17
27.2	2.0	29.5	19,667	34.0	0.317	4358	1381	70.25
24.4	2.7	29.0	35,235	34.5	0.327	2614	855	24.26
29.1	2.8	34.5	45,080	36.0	0.325	5308	1725	38.27
26.8	3.0	32.0	48,000	34.0	0.310	8054	2497	52.02
25.0	3.5	33.5	68,395	36.0	0.330	4288	1415	20.67
33.0	3.5	31.5	64,313	34.5	0.310	9100	2821	43.86
20.0	4.0	35.5	94,666	37.0	0.300	8800	2640	27.89
24.5	4.0	32.0	85,333	34.0	0.293	9786	2867	33.60
27.2	4.0	35.5	94,666	37.0	0.315	13,128	4135	43.68
25.1	5.5	34.0	171,417	35.5	0.320	15,924	5096	29.73
27.7	5.5	34.0	171,417	35.5	0.300	17,442	5233	30.53
Mean								
26.0	3.2	32.6	68,071	35.2	0.313	7910	2458	45.52
Sd								
3.18	1.2	2.0	56,156	1.0	0.161	4600	2111	22.62

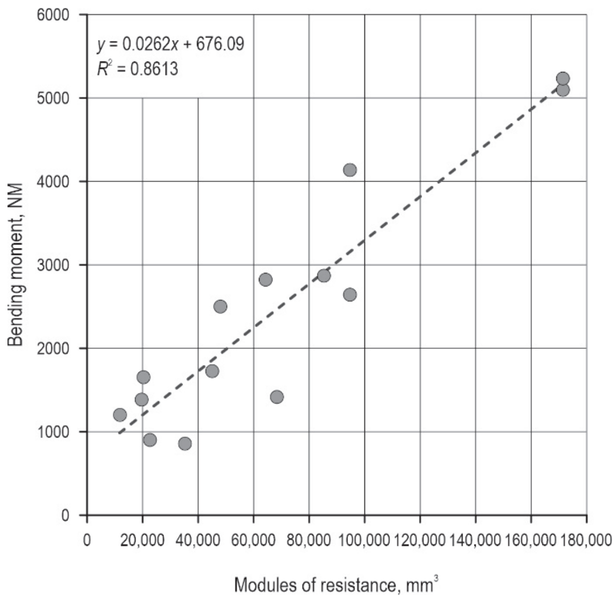

Fig. 3 Relationship between maximum bending moment and modulus of resistance

The respective lifting height-bending moment-curves showed a degressive progression up to the maximum. It is relevant to increase the bending moments up to the maximum, from which the bending moments exceed the strength of the wood fibers, the fibers suddenly break and the curve jumps back to the initial value. The course of the curve can be explained by the fact that a frictional connection must first be established and the lifting height at the felling cut does not change significantly. Looking at the measured maxima of the individual tests as a function of the section modulus, Fig. 3 shows a linear correlation. As the modulus of resistance increases, so does the required bending moment. The coefficient of determination is 0.86.

Based on the linear regression, the necessary maximum bending moment can be shown for different dimensions of hinges with selected tree dimensions.

It can be seen in Fig. 4 that there is a quadratic increase in the curves as the width of the hinge increases. The functions shown represent a diameter class from 15 to 55 cm. The bending moment increases with the increase of the tree diameter. However, if the necessary maximum bending moment is set in relation to the lever length, which is based on the distance between the hinge and the effective point of the hydraulic cylinder, or in the previous practical use of the felling wedge, the situation changes.

Due to the lever principle, the necessary lifting force at the wedge base is significantly lower for large diameter classes than for small diameter classes. This means that larger trees (whose tree weight is initially neglected) are much easier to fell than smaller trees, which have an unfavorable lever geometry. This relationship is illustrated in Fig. 5 (light and dark gray area). The dashed line shows the recommended width of the hinge of one tenth of the diameter across all diameter classes.

Under the assumption that only the bending of the remaining »plank« is considered, it can be seen that the recommendation with regard to the necessary force is optimal for medium-sized trees and is overestimated for smaller tree diameters. The wedge force for a tree with a DBH of 50 cm and a hinge width of 50 mm is about 15 kN, while it is only half of that for a tree with a DBH of just 15 cm.

When adding the proportionate weight of a vertically standing tree, whose life mass was calculated according to Eq. 1, the resulting relationship is shown in Fig. 5 (light gray and dark gray area). It turns out that the proportion of the tree weight force causes a shift along the *Y*-axis, and the stronger it is, the greater the DBH of the tree. It can also be seen that an excessively strong hinge results in a disproportionately high wedge force with the higher DBH, but the 1/10 recommendation fits well for sizes below 50 cm. The wedge force for a tree with a DBH of 50 cm and a hinge with a width of 50 mm is around 25 kN, taking into account the proportionate tree mass.

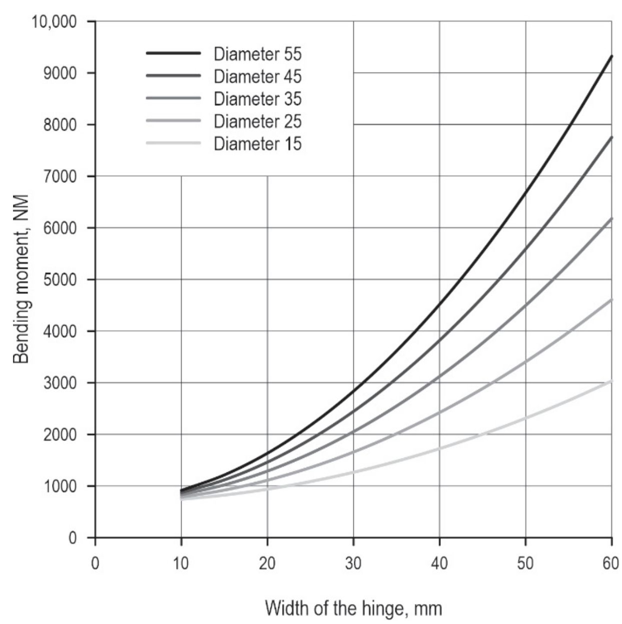

Fig. 4 Maximum bending moments at different tree diameters and varying width of hinges

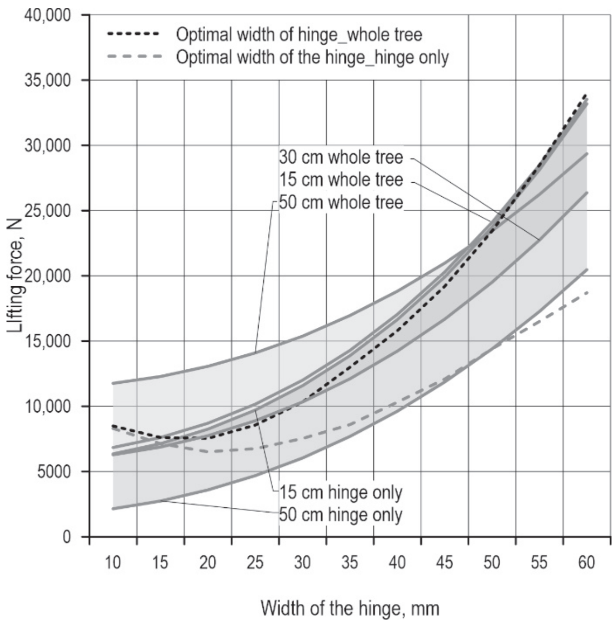

Fig. 5 Lifting force required depending on hinge width (middle grey area), and additionally depending on proportionate tree weight (light grey area)

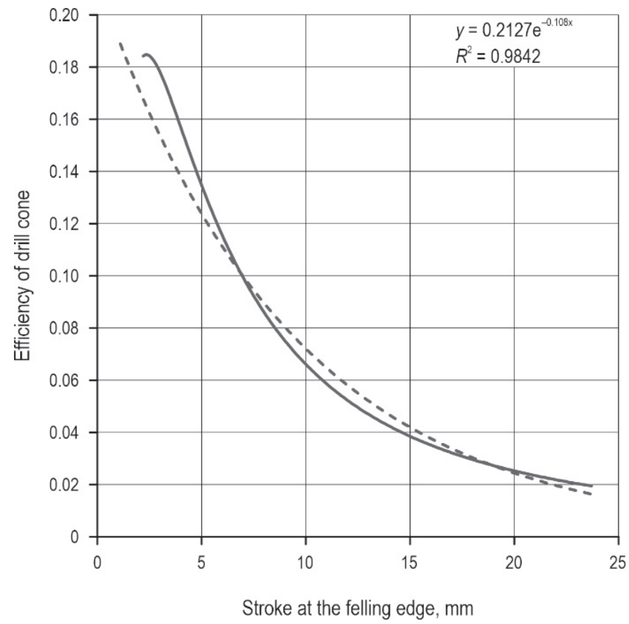

Fig. 6 Efficiency of drill cone as a ratio of resulting bending moments from load with drill cone itself to load with non-contact hydraulic cylinder

4.2 Results of Test Phase 2

In contrast to felling with an axially acting hydraulic lifting cylinder, felling with a drill cone was investigated in the second test phase. In the first step, analogous to the first series of tests, »stumps were felled«, whereby the hinge was bent open for 1.5 m high trunk parts, whose dead weight and center of gravity were negligible. These investigations offer a comparability to the test series of the first phase, they also offer statements about the felling of trees with a drill cone, in which the difficulty to measure parameters »tree mass« and »center of gravity« remain deliberately hidden.

4.2.1 Investigation of Drill Cone Felling at »Stumps«

With the field tests of the second test series, in which stumps were felled with a drill cone, the required torque curve was recorded. These results show polynomial torque curves. With the help of Eq. 6 to 10, the resulting bending moments were calculated, but resulted in quite huge moments, since initially the efficiency of the drill cone, which is included in Eq. 8, was neglected.

Fig. 6 shows the direct comparison of a test from the first test series (hydraulic lift) with a drill cone test on a geometrically uniform piece of wood ready to be felled. The illustration shows the reciprocal of both lifting moments, it describes the efficiency of the drill cone. At the beginning of the wedging process with the drill cone, the efficiency is approximately 20%. As it is screwed in, its efficiency drops to around 2% in the form of a negative exponential function.

The reason for the decreasing efficiency is the steadily increasing friction, because the drill cone lifts the wood body, in addition the bending stress in the hinge increases and the nominal force itself acts on it. This leads to a concavity in the contact zone, which further increases the friction surface. Despite this low level of efficiency, the drill cone is able to generate high lifting forces with a relatively small input torque due to its high transmission ratio. The polynomial curves corrected with the negative exponential function (effective curve of the efficiency) now show a logarithmic progression that runs the same as the hydraulic cylinder tests (see Fig. 7, dark grey lines). The frictionless lifting torque of the drill cone (straight line) was reduced by a factor of 5 for better representation. The area between the straight and the dotted dark grey line represents the frictional heat, the area between the X-axis and the dark grey dotted line represents the mechanical work. These investigations were carried out on a tree stump only. The combined effect is described below.

Based on the field test described in Table 2 (last line, felling diameter 42), calculation of the acting lifting

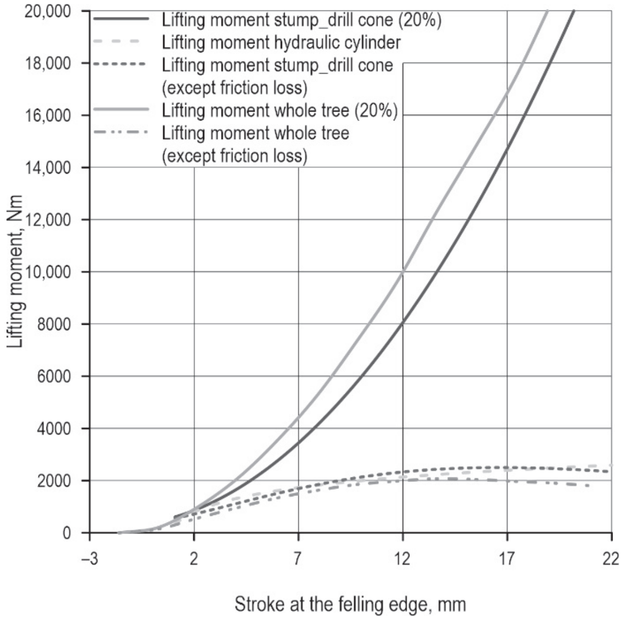

Fig. 7 Separation of frictional work from mechanical work of drill cone on a tree stump (dark grey lines)

moment with the experience of the friction coefficient curve efficiency from the stump analysis were made. In contrast to the dark grey curves, it can be seen that the weight of the tree results in a steeper rise of the curve at the beginning. On the other hand, the leaning tree is reflected in the reduced power requirement beyond the stroke of 14 mm

4.2.2 Investigation of Drill Cone Felling on Standing Trees

Table 2 shows the data of the 14 trees that were felled with the measuring aid described above.

The measured lifting moments show a polynomial pattern. One second corresponds to one rotation of the drill cone and thus 6 mm feed in the felling cut. As soon as the tree begins to tip over, there is no frictional connection between the drill cone and the tree, and the measured torques on the drill cone drop abruptly.

The torque curves of the drill cone were corrected with the help of the knowledge already gained about the efficiency of the drill cone (see Fig. 7, bright grey curves). This shows that the necessary lifting moment

Table 2 Summary of tree dimension for test phase 2 – standing trees

Width of hinge, cm	Length of hinge, cm	Felling diameter, cm	Lever, m	Tree length, m	Measured torque, Nm
1.65	34.5	35.0	0.192	23.0	94.99
2.20	24.6	25.7	0.150	21.9	35.30
3.00	23.0	25.0	0.171	22.0	90.14
3.15	30.0	35.1	0.215	19.5	70.22
3.25	34.0	39.0	0.215	24.8	70.28
3.35	29.0	35.0	0.230	24.9	72.04
3.50	29.0	30.0	0.155	23.1	48.79
3.60	29.0	29.5	0.155	20.7	43.73
4.00	24.5	25.5	0.170	17.9	12.82
4.00	44.5	48.0	0.275	21.1	76.85
4.00	34.5	34.5	0.220	25.8	27.93
4.25	32.0	32.0	0.210	23.7	59.03
4.70	27.0	27.0	0.160	22.9	75.09
4.70	40.0	42.0	0.225	22.1	91.55
Mean					
3.53	31.1	33.1	0.156	22.4	62.05
Sd					
0.87	6.0	6.7	0.037	2.2	24.19

is initially higher than before due to the additional dead weight of the tree. However, it also shows that the leaning tree nominally ensures a maximum of the effective lifting moment at a stroke of 14 mm. If the tree tilts further or the center of gravity shifts in the felling direction, the proportion of the force of the tree weight acting on the drill cone decreases, while the proportion on the hinge increases,

The superimposition of the increasing lifting moments due to the bending of the hinge on the one hand, and the decreasing lifting moments on the other hand due to the shift in the center of gravity, will be considered in the following section.

First, however, the maximum occurring lifting moments of the lifting moment curves adjusted by the efficiency of the drill cone were set in relation to the geometric shape of the hinge and the lever arm. The results of this analysis are shown in Fig. 8. In contrast to Fig. 3, a clear statistical relationship is no longer recognizable; the cause is the already mentioned inaccuracy of the boundary conditions of the center of gravity of the tree and the tree weight, whereby the tree weight can be estimated using Eq. 1. Methods for the optical determination of the center of gravity were carried out, but their usability was challenged. On the one hand, a high degree of accuracy must be achieved (the center of gravity of a vertical tree with BHD 50 only has to shift by about 15 cm before it falls); on the other hand, determining the center of gravity on a standing tree offers too many errors (crown alignment, trunk curvature, relation of the crown mass to the stem mass). These error influences are likely the reason for the wide scattering of the results in Fig. 8 and will be taken up again in the discussion.

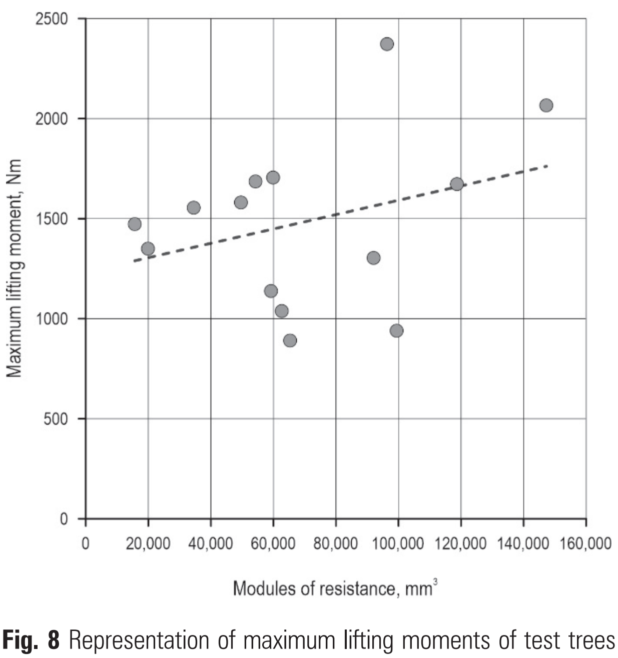

Fig. 8 Representation of maximum lifting moments of test trees depending on modulus of resistance. Compare Fig. 3

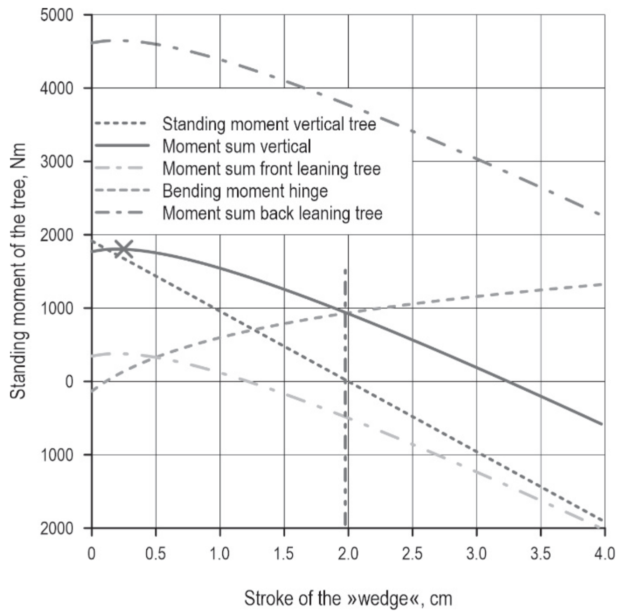

Fig. 9 Sum of moments at tree felling

Fig. 9 now shows the shape of the standing moment of a virtual vertical tree with dimensions that are consistent with the tests presented in Fig. 7 during the felling process (DBH 40 cm, height 30 m). It can be seen that the standing moment of the tree (dotted line) is highest in the starting position. As the lifting height of the drill cone increases, the standing moment decreases until the unstable position is reached above the tipping point (vertical dash colon line). At the same time, the bending moment in the hinge (dash line) increases with the knowledge gained from the first test phase. The standing moment is significantly greater than the necessary bending moment for the hinge. Furthermore, it can be seen that the maximum of the sum of both moments (straight line) is at approx. 0.5 mm lifting height (grey cross).

The tree already reaches its unstable position at a lifting height of 3.5 mm, since the center of gravity has reached the tipping point there. If the tree is wedged past this point, it will fall (when felling cut has been completed). It is therefore not necessary to exceed the maximum bending stress in the hinge during wedging. The fibers of the hinge fail during falling as the falling tree acts as a lever and also creates a torque in the hinge. The cumulative curve of a backward leaning tree (long dashed dot line) would appear as a vertically upshifted curve, that of a forward leaning tree (short dashed dot line) as vertically downshifted; the tipping line is accordingly shifted to the right and left, respectively. The incline is 1% each.

This means that approx. 1900 Nm lifting moment must be applied on the example tree in order to overcome both the standing moment and the bending strength of the hinge. A lever (distance between the starting point of the drill cone and the hinge) of 0.3 m corresponds to a necessary lifting force of 6.400 N (12 Nm drill cone torque). The lifting force of the backward leaning tree is about 15,900 N (30 Nm drill cone torque). A backward leaning tree (with an incline of 5% that corresponds to 1.5 m offset of the tip of the crown) requires a lifting force of 53,900 N (102 Nm drill cone torque).

Due to the low level of efficiency, the application of these large forces is compensated for by the high transmission ratio inherent in the drill cone. In the example, torques of about 55 Nm are required; the field tests showed that the required torques varied between 30 and 100 Nm (Table 2, last column).

5. Discussion

The measuring aids and the measuring methodology were described, the force components of tree felling with a drill cone were separated and the influencing factors determined. The torque of the drill cone is used to bend the intact fibers of the hinge, to move the center of gravity of the tree in the direction of fall and to overcome the friction of the drill cone on the felling cut. With the help of the mathematical relationships and the determined coefficients, it is possible to convert the torque used by the drill cone, depending on the tree and felling geometries, into the necessary lifting forces and bending moments, and thus to predict the performance of the drill cone motor. It is also possible to quantify the effects of deviations in the vertical center of gravity of the tree to be felled. It has been shown that the indentation that occurs when using a drill cone reduces the effective lifting height. In the second phase tests, the design of the measuring aid for the torsion cone input torque did not allow a simultaneous height measurement, which is a deficiency and should be supplemented in future tests.

The results of the test series do not in any way represent statistically sufficiently reliable data, but rather an attempt to penetrate the problem area with certain restrictions, using the example of the tree species spruce. It also seems almost impossible to find enough similar standing trees and to fell them in the same way in order to present reliable statements on the behavior of a drill cone during tree felling. For example, the influence of the height of the fracture step was initially deliberately neglected, also because the shape of the height of the fracture step varied in chainsaws. The width of the hinge can be adjusted to the target afterwards, the height of the fracture step is already fixed when the felling cut is made and, moreover, it was not always possible to achieve a constant size on both sides.

A relationship between the bending stresses calculated in Table 1 (last column) and the height of the fracture step cannot initially be identified. Fig. 10 shows that the bending stress decreases as the section modulus of the hinge increases. This can be explained by the fact that the model assumption of a rectangular »plank cross-sectional area« does not correspond to reality, since the chord of the notch and the felling cut are not on the same level, but the felling cut should be about 1/10 of the tree diameter above the chord of the notch. In the case of wide hinges, it could be observed that a crack developed along the fiber under bending stress at the end of the felling cut, so that a rectangular cross-sectional area actually worked. The thin hinges, in which the width of the hinge was less than the nominal height offset, reacted so elastically that tearing at the end of the felling cut did not occur, but the bending of the zone was able to absorb higher bending stress.

The results of test series 1 (determining the bending moment of the plank) have shown that higher bending moments have to be applied with increasing width of the hinge, and that trees are therefore initially more difficult to fell. In view of the fact that

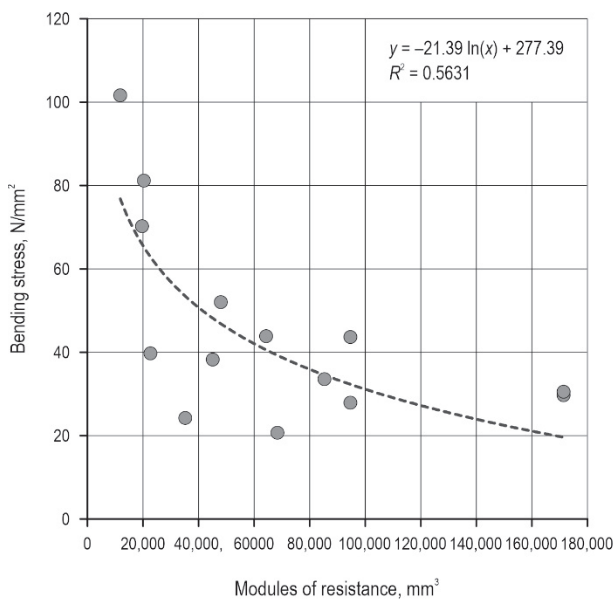

Fig. 10 Bending stress in dependence of modulus of resistance

larger trees also have a longer lever between hinge and wedge base, there is a distortion of the relationships. For example, a tree with a DBH of 15 cm requires more lifting power at the wedge base than a tree with a DBH of 25 cm; the power requirement for trees with a DBH of 20 and 30 cm is about the same. Gullberg and Gullberg (2005) state that a hinge of more than 30 mm is not useful even for larger trees. Our tests have shown that the lifting forces up to a width of the hinge of 30 mm can remain about the same at around 8 kN for all diameters considered. If larger hinge strengths are selects, then the influence of this and the diameter at breast-height increases significantly. However, the tests by Gullberg and Gullberg (2005) were also based on pure bending tests with wooden beams. If, on the other hand, it is considered that the bending moment of the hinge plays a subordinate role compared to the standing moment, which has to be overcome when felling a tree, this limitation as a general recommendation should be challenged.

Lindroos et al. (2007) have described that »Theoretically, a tree tips over when a surplus torque is created, i.e., when the input torque exceeds the sum of the tree's mass torque and the hinge's bending resistance«. However, they only carried out measurements on trunk wood sections. Franz makes the same assumption in his work (Franz 2020). The present investigation has shown that the sum of the standing moment and the maximum bending moment does not have to be applied at the time of the failure of the wood fibers in the fracture strip, but that there is a temporal decoupling of the two moments in the felling process. This is possibly also the reason why Franz overestimates the necessary lifting forces in his calculation compared to practice.

Lindroos et al. (2007) have already pointed out in their study that the deformation of the wood that occurs when using a felling aid must also be taken into account. This is in accordance with the explanation for the low efficiency achieved by the drill cone in the present study. It has been shown that the drill cone pressed strongly into the sapwood. It was also visible through partially light burn marks, also noticeable on the drill cone itself, that a high temperature developed due to the friction. By pressing the drill cone into the sapwood area of the wood, the exact lifting height at the felling cut did not match the geometry of the drill cone, but could not be measured in previous tests. Therefore, as already described, it is recommended to measure the lifting height with the laser distance meter in the same way as with the hydraulic cylinder when repeating the tests with the drill cone. It has been shown that a drill cone is suitable as a felling aid for mechanical felling and that the drive power should be selected so that torques of up to 100 Nm are possible. However, this statement does not apply to pronounced rear hangers or trees with a DBH over 55 cm, because these trees are not within the scope of this study.

The drill cone has some advantageous properties. It is self-retaining, has a firm seat, can be unscrewed again by turning in the opposite direction, the lever length remains constant, smooth wedging is possible and, due to the coarse thread, unlike a classic felling wedge or a hydraulic log pusher, it does not require any counterforce when wedging.

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