COMPARISON OF TWO METHODS FOR TREE UPROOTING FORCE MEASUREMENT

Jakub ČEDÍK[1], Radek PRAŽAN[1], Marian RYBANSKY[2], Ladislav JÍLEK[1], Vladimír ŠLEGER[3], Martin HAVLÍČEK[4]

[1]Research Institute of Agriculture Engineering, Drnovská 507, 161 01, Prague 6, Czech Republic, email: cedikj@tf.czu.cz, radek.prazan@vuzt.cz
[2]University of Defence, Faculty of Military Technology, Kounicova 65, 662 10 Brno, Czech Republic, email: marian.rybansky@unob.cz
[3]Czech University of Life Sciences Prague, Faculty of Engineering, Department of Mechanical Engineering, Kamýcká 129, 165 21, Prague 6, Czech Republic, email: sleger@tf.czu.cz
[4]Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Designing and Machine Components, Technická 4, 166 07 Prague 6, Czech Republic, email: martin.havlicek@fs.cvut.cz

Abstract
The article is focused on the measurement of uprooting force of a spruce trees of different stem diameter using two methods and their comparison. First method uses a single-axis force transducer and the tree is uprooted by pulling a steel cable with a tractor winch. Second method uses a double-frame dynamometer, mounted in the three-point hitch of the tractor and the tree is uprooted by driving a vehicle into it. 7 trees were uprooted using each method and their comparison was made. The results showed a linear dependency between maximum uprooting force and tree stem diameter.

Key words: *tractor; force measurement; three-point hitch; tree uprooting.*

INTRODUCTION

The information about the actual magnitude and layout of the traction forces evoked by a tractor or other non-road vehicle is necessary for the optimal utilization of its traction potential or in terms of strength and fatigue studies (*Roca et al., 2019*). It also carries information about the soil mechanical properties (*Novák et al., 2014*).

Measurement of force, in general, can be based on several different principles. Ştefãnescu and Anghel in their study (*Ştefãnescu & Anghel, 2013*) distinguished 12 main types of electrical force transducers. However, electrical resistance strain gauges are still most used currently due to its simplicity, sufficient accuracy and low cost (*Ştefãnescu, 2020*). Moreover, for most applications in multi-axial force sensors the electrical resistance strain gauges are used (*Alipanahi et al., 2022; Liu & Tzo, 2002; Templeman et al., 2020*).

Measurement of traction forces is possible in one, two or three directions. In the case of one-directional force measurement only one force sensor can be used (*Kroulík et al., 2015*). The sensor can be also build in a suitable measurement frame (*Procházka et al., 2015*). This approach can offer a suitable accuracy in one axis, however, the results does not contain information about the vertical or lateral forces (*Novák et al., 2014; Roeber et al., 2017*).

The measurement of the traction forces in more directions can be done by means of single-frame or double-frame dynamometers (*Roca et al., 2019*). The frame dynamometers are usually universal and can be used on more types of vehicles, on the other hand, its dimensions and mass affect the geometry and mass distribution of the vehicle or vehicle-implement system (*Alimardani et al., 2008; Kheiralla et al., 2003; Roca et al., 2019*). Single-frame dynamometers (*Al-Jalil et al., 2001; Alimardani et al., 2008; C.G.Bowers & Jr., 1989; Kheiralla et al., 2003; Kumar et al., 2016; O'Dogherty, 1996*) are used for two-directional measurement of traction force. According to (*Roca et al., 2019*), longitudinal and vertical forces are measured using the single frame dynamometers. However, when compared to double-frame dynamometers, their mass and dimensions are smaller. The principle of double-frame dynamometers (*Askari et al., 2011; Chaplin et al., 1987; Jeon et al., 2019; Palmer, 1992; Pijuan et al., 2012; Roca et al., 2019*) is based on two frames, connected with force sensors. One frame is connected to the

vehicle and the other to the implement or other source of the measured traction force. These dynamometers offer a three-directional traction force measurement with a good accuracy, however, their dimensions and mass are higher when compared to single-frame dynamometers. Also, some dynamometer designs may suffer with cross sensitivity problems, especially when there is a separate sensor for lateral force measurement (*Palmer, 1992; Roca et al., 2019*).
The evaluation of tree uprooting force or moment (or uprooting resistance) is in literature usually evaluated due to slope stabilization, windfirmness and tree productivity (*Campbell & Hawkins, 2004; Cannon et al., 2015; Peltola et al., 2000; Rahardjo et al., 2009*). Except the tree stem diameter, there are many other factors affecting the tree uprooting force such as tree species and their condition, root system and its condition, soil type and its condition, failure mode, position of the center of mass, tree dimensions and others (*Bartens et al., 2010; Campbell & Hawkins, 2004; Cannon et al., 2015; Rahardjo et al., 2009; Ribeiro et al., 2016; Szoradova et al., 2013*). However, despite these factors, authors found in most cases linear dependency of the uprooting resistance on the tree stem diameter or stem mass (*Campbell & Hawkins, 2004; Cannon et al., 2015; Ribeiro et al., 2016*).
The objective of the paper is to determine the dependency of the tree stem diameter on the uprooting force, in order to estimate a required traction force of a vehicle crossing the forest vegetation, using a single strain gauge sensor and a double-frame dynamometer with six strain gauge sensors and compare these two methods.

MATERIALS AND METHODS

The measurement took place on the land of school forest company Masarykův Les Křtiny near the Brno city at the Czech Republic. The measurement was performed using two methods, a single axis force sensor and a double-frame dynamometer.
As a single axis sensor a HBM U10M (nominal load 125 kN, relative error 0.02%) sensor was used (Fig. 1a). The double-frame dynamometer used for measurement can be seen in Fig. 1b. Its maximal load is 400 kN and uses six half-bridge strain gauge sensors in order to obtain a three-directional results of the traction force and moment.

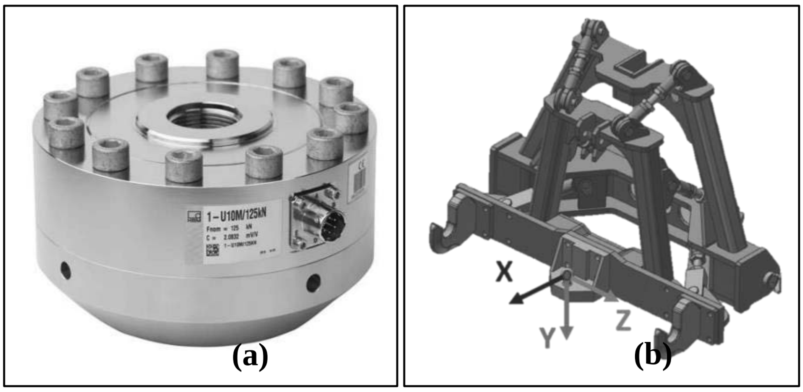

Fig. 1 Force transducers – a) HBM U10M, b) double-frame dynamometer with x, y and z axis labels

The calculation of the resultant force of the double-frame dynamometer, related to the origin of the coordinate system, is based on the coordinates of all 12 connecting points, from which the lengths of the connecting rods are calculated according to equation (1) and measured forces in these rods.

$$L_i = \sqrt{(X_{i.1} - X_{i.2})^2 + (Y_{i.1} - Y_{i.2})^2 + (Z_{i.1} - Z_{i.2})^2} \qquad (1)$$

Where L_i is length of the individual connecting rod (m); $X_{i,1}$ is x–coordinates of connecting points on the implement side frame (m); $Y_{i,1}$ is y–coordinates of connecting points on the implement side frame (m); $Z_{i,1}$ is z–coordinates of connecting points on the implement side frame (m); $X_{i,2}$ is x–coordinates of connecting points on the tractor side frame (m); $Y_{i,2}$ is y–coordinates of connecting points on the tractor side frame (m); $Z_{i,2}$ is z–coordinates of connecting points on the tractor side frame (m), i=1–6.

The values of the X, Y and Z components of the forces, measured in the individual connecting rods are calculated according to equations (2), (3) and (4).

$$F_{iX} = F_i \frac{X_{i.1} - X_{i.2}}{L_i} \tag{2}$$

$$F_{iY} = F_i \frac{Y_{i.1} - Y_{i.2}}{L_i} \tag{3}$$

$$F_{iZ} = F_i \frac{Z_{i.1} - Z_{i.2}}{L_i} \tag{4}$$

Where F_{iX} *is* x–component of the measured forces in the connecting rods (N); F_{iY} *is* y–component of the measured forces in the connecting rods (N); F_{iZ} *is* z–component of the measured forces in the connecting rods (N); F_i *is* measured force in the individual connecting rod (N), i=1–6.

The X, Y and Z components of the resultant force are calculated as a sum of the components of the individual measured forces F_1-F_6 in the respective axis.
Resultant force calculation is based on its X, Y and Z components, according to equation (5).

$$F_R = \sqrt{{F_X}^2 + {F_Y}^2 + {F_Z}^2} \tag{5}$$

Where F_R is resultant force (N); F_X is the X component of the resultant force F_R; F_Y is the Y component of the resultant force F_R; F_Z is the Z component of the resultant force F_R.

Before the measurement the diameter of the tree stem was measured at the height of approx. 110 cm above the ground level. When using a single force sensor the rope was fixed at the same height and using a steel cable and a winch of the tractor the tree was uprooted while measuring the curse of the uprooting force. When using a double-frame dynamometer the device was mounted into the three-point hitch of the tractor and using a reverse gear of the tractor the tree was uprooted using the implement side of the double frame dynamometer while measuring the course of the force between tractor and the tree stem. The maximum uprooting force from the course was taken as a result. In both cases the data were recorded with a frequency of 50 Hz.
During the measurement 7 trees were uprooted using the single axis force sensor and 7 trees using the double-frame dynamometer. All uprooted trees were spruces, basic characterization of each uprooted tree can be seen in Table 1.

Tab. 1 Characterization of the uprooted trees

Sensor	Stem diameter (cm)	Stem circumference (cm)	Dry branch height (cm)	Semi-dry branch height (cm)	Green branch height (cm)	Tree height (cm)	Tree crown height (cm)	Root width (cm)	Root height (cm)	Root depth (cm)
HBM U10M	19.9	625	210	580	780	1640	260	220	155	55
HBM U10M	16.9	531	210	670	980	1650	260	310	125	90
HBM U10M	22.8	716	220	420	850	1710	330	390	120	60
HBM U10M	24.3	763	230	300	510	1620	520	350	315	100
HBM U10M	12.4	389	200	360	720	1540	250	230	160	55
HBM U10M	16.7	524	210	660	630	1630	360	310	110	65
HBM U10M	10.5	329	190	230	380	1530	230	200	130	50
Double-frame dyn.	13.4	421	220	580	750	1480	370	160	75	45
Double-frame dyn.	9.6	301	320	490	590	1110	180	40	30	45
Double-frame dyn.	11.3	355	210	500	530	1250	230	160	100	40
Double-frame dyn.	18.7	587	190	695	880	1620	310	220	215	70
Double-frame dyn.	19.7	619	260	190	620	1640	340	195	125	90
Double-frame dyn.	24.9	782	200	620	710	1670	370	250	90	40
Double-frame dyn.	20.1	631	200	360	660	1950	320	270	45	40

RESULTS AND DISCUSSION

In Figure 2 the courses of the uprooting force using the single axis sensor and the double-frame dynamometer are shown. It is evident that uprooting using a single axis force sensor takes a longer time due to the speed of the tractor winch.

In Figure 2b it can be noticed that the main component of the resultant force F_R is F_X, which was expected due to direction of the traction force, evoked by vehicle. F_Y also showed a not negligible force magnitude which is given by the stem inclination during the uprooting of the tree. However, F_Y reached in all cases its maximum after the maximum of F_X and F_R.

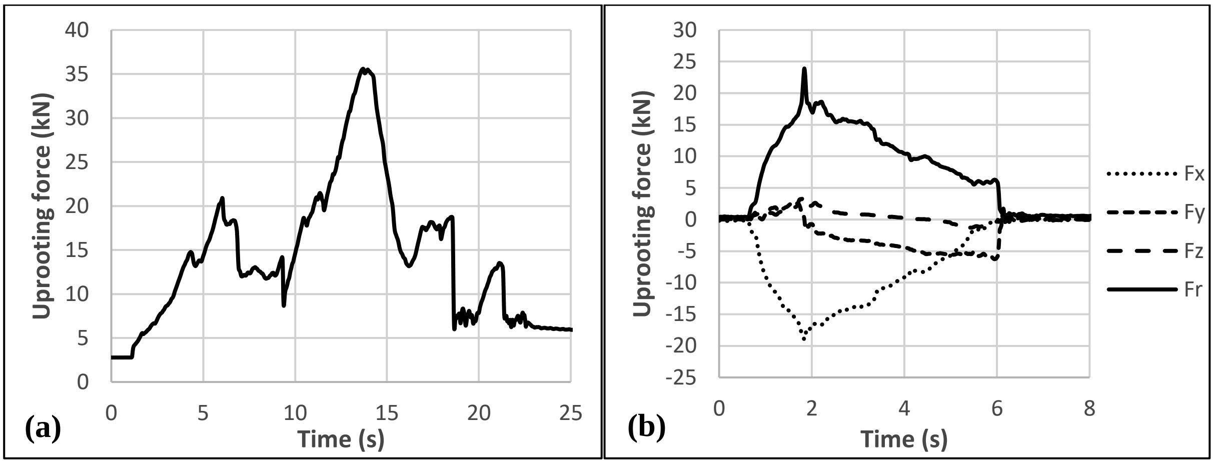

Fig. 2 The course of the forces during uprooting a tree using a single axis sensor (a) and double frame dynamometer (b) for a selected trees

In Figure 3 the overall results of both of the methods are shown. It is evident that the linear dependency between uprooting force and stem diameter was found, this trend was also found by other authors focusing on similar problematics (*Campbell & Hawkins, 2004; Cannon et al., 2015; Ribeiro et al., 2016*). For the double-frame dynamometer the resultant force F_R and its horizontal component F_X are shown, since the F_X causes the main disruption of the roots. It can be seen that only in two uprooted trees there is a noticeable difference between F_X and F_R and a slight difference in slope between the linear trend of F_R and F_X can be observed.

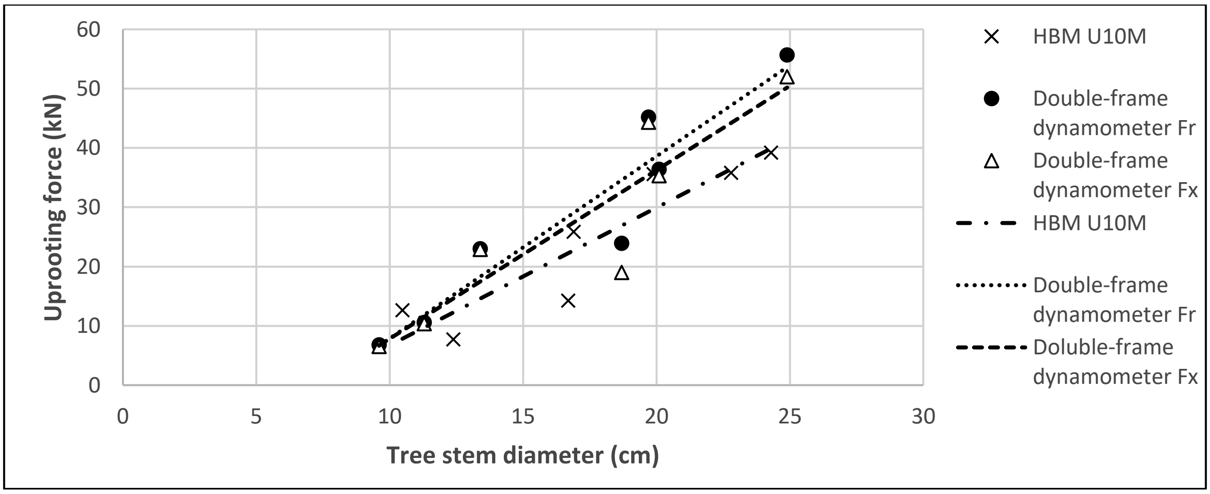

Fig. 3 The comparison of maximal reached values for both methods

From Figure 3 it is also evident that the results of both of the methods are comparable, especially when uprooting trees with the smaller stem diameter, approx. under 20 cm. The trend obtained using HBM

U10M has a lower slope in comparison with both trends obtained using the double-frame dynamometer (F_R and F_X). This is caused mainly by the variability of the actual uprooting force, which depends on many factors, as mentioned in the Introduction section. However, the method of the tree uprooting could have also affected the results into some extent. When uprooting a tree by driving a vehicle into it, higher friction between the measuring frame and the tree stem must be overcome in comparison with uprooting a tree using a steel cable and the single-axis sensor.

CONCLUSIONS

The contribution was focused on determination of dependency of tree stem diameter and uprooting force using two methods and their comparison. The study follows on from the work of Mason et al. who did similar research using a buried fence posts (*Mason et al., 2012*). From the results it can be stated that linear trend between tree stem diameter and its uprooting force was found. However, slightly higher uprooting force was obtained using a driving vehicle with double-frame dynamometer, which is mainly caused by the variability of actual uprooting force and higher friction between the frame and the tree stem. When uprooting trees with a stem diameter above approx. 20 cm using a driving vehicle, the vehicle should be able to reach the traction force of at least 50–60 kN per one uprooted tree.

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Corresponding author:
Ing. Jakub Čedík, Ph.D., Research Institute of Agriculture Engineering, Drnovská 507, 161 01, Prague 6, Czech Republic, phone: +420 233 022 230, e-mail: cedikj@tf.czu.cz