Mechanical properties of cereal stem

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Abstract: The paper deals with the measurement of the resonance frequencies of wheat stems with special respect to different wheat varieties. For the measurement, the dynamical method of the transverse frequency was used. Formulas were derived for the calculation of the bending toughness of stems. The *t*-test was used for the evaluation of the strength coefficient in bending for the samples of stems of different wheat varieties. The results can be used for the evaluation of the wheat resistance to lodging.

Keywords: wheat stems; resonance frequency; strength coefficient in bending; modulus of elasticity; mechanical properties of stem

Plant lodging results in a lower grain yield and its substandard quality, and also the mechanical harvesting conditions are strongly deteriorated. This process leads to considerable losses in agriculture – the losses of grain due to the lodging of the plant reach 25–50% in some years (Pruckovova & Uchanovova 1976).

In agricultural practice, two kinds of plant lodging are distinguished: the stem lodging and the root lodging. The stem lodging begins by flexion and/or breaking of the individual stems. The plant stems start to elongate and the lower internodes are then weaker: plants decline and they are not able to lift the weight of the heavy part of the plant.

The domestic and foreign experience indicates that the resistance to plant lodging depends on the plant stem length. An important task in the attempts to reduce plant lodging is played by the mechanical properties of the stems. Among others, an important role belongs to the elastic and viscoplastic properties. The elastic properties can be given by the stem resonance frequencies as well as by the stem modulus of elasticity (Dunca 2005), the viscoplastic properties are given by internal tensions. The strength properties are given by the strength coefficient in bending. (Dunca 2004).

In this paper are given the measured resonance frequencies as well as the calculated strength coefficients of various wheat varieties.

MATERIALS AND METHODS

We used samples of wheat stems of various varieties. The names of varieties are introduced in Tables 1–5.

The resonant frequencies of the wheat stems were found out using the dynamic resonant method of transversal oscillations. The strength coefficients in bending were calculated according to the formula on the basis of the measurement of resonant frequencies of the stems, the length of the plant stems, the outer stem diameter and the stem wall thickness. We approximated the stem internodium cross section by annulus.

Block scheme of the measuring equipment is given in Figure 1.

As the source of the frequencies, we utilised the RC generator. For the function of the alarm – clock and sensor, we utilised the gramophone pick-up. We counted the frequencies by the frequency counters. The voltage at the resonance frequency was registered by the milivoltmeter.

The tension of the resonance frequency was recorded in the milivoltmeter. During the measurement, the stem samples were fixed into two places. The fluent change of the source frequencies led to the state of the resonance, where the amplitude frequency was maximum and the maximum deviation of the milivoltmeter was observed. The resonance frequency characterises the stem elastic properties. Frequencies f_1 and f_2 preset frequencies when maximum amplitude is equal to one half before and after resonance. Damping factor δ is expressed by the formula

$$\delta = \frac{\pi}{\sqrt{3}} \times \frac{\Delta f}{f}$$

where:

f – resonance frequency

$\Delta f = f_2 - f_1$

Table 1. Resonance frequency f (Hz), damping factor δ (1), frequency f_1 (Hz) and f_2 (Hz) of wheat variety (FRA) Nougat

n	U (mV)	f (Hz)	f_1 (Hz)	f_2 (Hz)	Δf (Hz)	δ (1)	K (Hz)
1	2.3	245.4	241.7	250.6	8.9	0.06564	3 738.57
2	2.7	246.9	242.4	250.1	7.7	0.05645	4 377.66
3	2.4	248.2	244.0	251.9	7.9	0.05761	4 308.28
4	2.3	245.5	237.8	250.8	13.0	0.09585	2 561.29
5	2.9	246.3	241.8	249.7	7.9	0.05806	4 242.16
6	1.6	246.2	242.4	249.6	7.2	0.05293	4 651.43
7	1.6	246.3	243.4	251.1	7.7	0.05659	4 352.36
8	1.8	246.6	242.4	251.2	8.8	0.06459	3 817.93
9	2.4	246.9	239.7	252.1	12.4	0.09090	2 716.17
10	2.4	247.7	241.1	251.6	10.5	0.07673	3 228.20
11	2.4	247.3	243.6	252.0	8.4	0.06148	4 022.45
12	3.4	247.6	242.9	250.8	7.9	0.05775	4 287.45
13	1.8	247.1	241.9	249.9	8.0	0.05860	4 216.72
14	1.9	247.4	244.0	252.3	8.3	0.06072	4 074.44
15	1.75	247.9	243.0	252.5	9.5	0.06936	3 574.11
16	2.5	244.7	240.6	250.3	9.7	0.07175	3 410.45
17	2.3	246.0	242.0	249.9	7.9	0.05813	4 231.89
18	1.5	248.3	244.3	250.4	6.1	0.04447	5 583.54
19	1.7	246.6	240.7	248.4	7.7	0.05652	4 363.06
20	1.8	245.3	241.2	248.8	7.6	0.05608	4 374.11
Σ	43.45	4 934.2	4 840.9	5 014.0	173.1	1.27021	80 132.27
$\bar{x}$	2.2	246.71	242.04	250.7	8.66	0.06351	4 006.614

$K = f/\delta$

The comprehensive view of the measurement instrument at the transverse oscillations of a stem sample is given in Figure 2.

Evaluation of the mechanical data

The sample transversal oscillation is described by differential equation of fourth order (Plander & Tomaš 1968):

$$a^2 \times \frac{\partial^4 u}{\partial x^4} + \frac{\partial^2 u}{\partial t^2} = 0 \qquad (1)$$

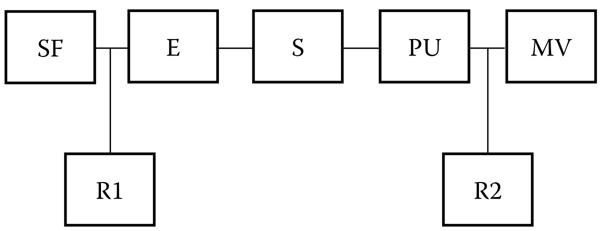

Figure 1. The block diagram of the measuring equipment

where:

$$a^2 = \frac{EJ}{\rho S}$$

E – stem modulus of elasticity
J – second moment of area
ρ – stem density
S – stem cross section area

The solution of Eq. (1) can be expressed as:

$$u = u(t)X(x) \qquad (2)$$

where:
$u(t) = (A \cos \omega t + B \sin \omega t)$
$\omega = 2\pi f$
f – frequency
$X(x)$ – function expressed by the following formula

$$X(x) = C_1 \cos kx + C_2 \sin kx + C_3 \cosh kx + C_4 \sinh kx \qquad (3)$$

where:

$$\cosh kx = \frac{e^{kx} + e^{-kx}}{2}$$

$$\sinh kx = \frac{e^{kx} - e^{-kx}}{2}$$

Figure 2. The comprehensive view of the measurement instrument at the transverse oscillations of a stem sample

After substitution of Eq. (2) into Eq. (1) we get

$$\frac{\partial^4 X}{\partial x^4} - \frac{\omega^2}{a^2} X = 0 \qquad (4)$$

where:

$$\frac{\omega^2}{a^2} = k^4$$

$kl_1 = \lambda$
l_1 – internodium length
λ – parameter

Moment inertia of the annulus is

$$J = \frac{\pi}{64}(d_2^4 - d_1^4) \qquad (5)$$

where:
d_2 –outer diameter
d_1 – inner diameter

$$S = \frac{\pi}{4}(d_2^2 - d_1^2) \qquad (6)$$

where:
S – area

Utilising Eqs (4), (5) and (6), we get for the modulus of elasticity E

$$E = \frac{64\pi^2 l_1^4 f^2 \rho}{\lambda^4 (d_2^2 + d_1^2)} \qquad (7)$$

The utilisation of the equation of the bending line (Smirnov 1956) leads to

$$y'' = \frac{M}{EJ} \qquad (8)$$

where:
M – moment force
J – second moment of area (cross section)
E – modulus of elasticity
y – bending of stems

The solution of (8) gives

$$y = \frac{Fl^3}{3EJ} \qquad (9)$$

where:
l – stem length
F – force

The solution of (9) gives

$$k = \frac{F}{y} = \frac{3EJ}{l^3} \qquad (10)$$

where:
$k = k_1 \times k_2$
k – stronghold (firmness)
k_1 – constant
k_2 – strength coefficient in bending

Using Eqs. (5), (6), (7) and (10), we obtain

$$k = \frac{3 \times \frac{64\pi^2 l_1^4 f^2 \rho}{\lambda^4 (d_2^2 + d_1^2)} \times \frac{\pi}{64} \times (d_2^4 - d_1^4) \times \frac{4}{4}}{l^3} \qquad (11)$$

Using (11) leads to

$$k = \frac{12\pi^2 l_1^4 \rho}{\lambda^4} \times \frac{\pi}{4} \times \frac{(d_2^4 - d_1^4) f^2}{(d_2^4 - d_1^4) l^3} \qquad (12)$$

Table 2. Mechanical properties of wheat stems of variety (DEU) Rimpaus Braun

n	f (Hz)	d_2 (mm)	Δr (mm)	l_r (mm)	k_2 (mm^{-1}/s^2)
1	234.2	3.81	0.30	1 120	1.29-04
2	242.8	3.45	0.32	1 160	1.18-04
3	236.8	4.78	0.40	1 070	2.51-04
4	240.1	3.33	0.28	1 080	1.22-04
5	242.7	4.25	0.33	1 160	1.53-04
6	240.7	3.83	0.25	990	1.67-04
7	237.1	3.97	0.38	1 160	1.54-04
8	237.5	4.10	0.38	960	2.82-04
9	238.0	4.45	0.38	1 070	2.24-04
10	235.7	4.51	0.35	1 075	2.04-04
11	243.4	4.70	0.37	1 190	1.76-04
12	241.3	4.40	0.40	1 040	2.60-04
13	241.5	3.65	0.43	1 100	1.90-04
14	237.7	4.34	0.46	1 100	2.37-04
15	241.6	3.94	0.38	1 210	1.39-04
16	242.3	2.72	0.23	1 040	0.93-04
17	244.5	3.32	0.25	1 180	0.87-04
18	242.0	4.49	0.42	1 055	2.67-04
19	264.1	2.83	0.25	1 120	1.00-04
20	271.3	3.45	0.29	1 100	1.59-04
Σ	4 855.3	78.32	6.85	21 980	35.23-04
$\bar{x}$	242.77	3.92	0.34	1 099	1.76-04

Table 3. Properties of individual wheat varieties

n	Variety	f (Hz)	S (mm^2)	l (mm)	k_2 (mm^{-1}/s^2)
1	Peragis	250.5	3.73	1 105.5	1.72-04
2	Rimpaus Braun	248.8	3.92	1 099.0	1.76-04
3	Pero	248.9	3.39	1 043.5	1.89-04
4	Roetelstein	251.3	4.32	961.5	3.09-04
5	Panaceja	246.2	3.23	840.0	3.43-04
6	Vicking	269.1	3.67	859.3	3.53-04
7	Nougat	246.7	3.69	782.8	4.84-04
8	Hana	242.4	3.56	744.5	5.19-04
9	Pepital	251.7	3.42	725.3	5.85-04
10	Riale	240.4	2.77	572.3	8.40-04

Using (12) gives

$$k = k_1 \times \frac{\pi}{4} \times \frac{(d_2^2 - d_1^2)\, f^2}{l^3} \qquad (13)$$

Using (13), we obtain

$$k = k_1 \times \frac{S f^2}{l^3} \qquad (14)$$

$$k_2 = \frac{f^2 S}{l^3} \qquad (15)$$

where:
f – resonance frequency (Hz)
S – cross section area of stems (mm^2)
l – length of stems of plant (mm)

Table 4. Results of t-test between average strength coefficients in bending k_2

Variety	Nougat	Vicking	Riale	Pero	Panaceja
Hana	0.7741^{-}	4.5194^{+++}	1.6979^{+}	10.5523^{+++}	4.4823^{+++}
Nougat	–	3.1528^{+++}	5.1621^{+++}	8.0317^{+++}	2.3311^{++}
Vicking	–	–	7.6557^{+++}	6.5774^{+++}	0.3168^{-}
Riale	–	–	–	10.7352^{+++}	7.6332^{+++}
Peto	–	–	–	–	11.8816^{+++}

$^{+}$LSD = 0.1%; $^{++}$LSD = 0.05%; $^{+++}$LSD = 0.01%; $^{-}$LSD < 0.1%

Table 5. Results of t-test between average strength coefficients in bending k_2

Variety	Rimpaus Braun	Pepital	Roetelstein	Peragis
Hana	10.6591^{+++}	1.3466^{-}	5.9215^{+++}	10.5861^{+++}
Nougat	8.2148^{+++}	1.9236^{+}	4.3315^{+++}	8.2132^{+++}
Vicking	6.7812^{+++}	5.1337^{+++}	1.4673^{-}	6.7613^{+++}
Riale	10.8669^{+++}	3.5816^{+++}	8.4419^{+++}	10.8798^{+++}
Pero	0.7452	9.6931^{+++}	5.2036^{+++}	0.9402^{-}
Penaceja	5.5763^{+++}	5.1199^{+++}	0.9923^{-}	5.5972^{+++}
Rimpaus Braun	–	9.8449^{+++}	5.4822^{+++}	0.2228^{-}
Pepital	–	–	6.2496^{+++}	9.8344^{+++}
Roetelstein	–	–	–	5.4765^{+++}

$^{+}$LSD = 0.1%;$^{++}$LSD = 0.05%; $^{+++}$LSD = 0.01%; $^{-}$LSD < 0.1%

RESULTS AND DISCUSSION

The measured values of resonance frequencies as well as the obtained damping factors (δ) are introduced in Table 1.

Table 2 contains the measured values obtained for variety (DEU) Rimpaus Braun.

The mean measured values and the calculated data for wheat stems of various varieties are given in Table 3.

The values of t-test between the mean measured values of the strength coefficients in bending k_2 of various wheat varieties are given in Tables 4 and 5. Sign + marks a significant difference between the mean values of the strength coefficients in bending k_2 between the measured for different varieties at LSD = 0.10. The same Sign ++ marks the LSD = 0.05 and the Sign +++ marks the LSD = 0.01% (Nepraš 1986). The results of the t-test show significant differences in the strength properties of wheat stems of different varieties. The strength properties are the variety properties. The strength properties play an important role as a characteristic controlling at least partly the variety resistance to lodging.

CONCLUSIONS

In this work, the mean measurement values and the evaluation of the mechanical values of the elasticity and strength characteristics of the stems of various varieties of wheat are introduced. A formula is derived for the calculation the strength coefficient of bending k_2. The resonance frequency was found out by a modified resonance dynamic method of the transversal oscillations.

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Abstrakt

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Práca sa zaoberá meraním rezonančných frekvencií stebiel pšenice rôznych odrôd. K meraniu bola použitá dynamická rezonančná metóda priečnych kmitov. V práci je odvodený vzorec pre výpočet koeficientu pevnosti stebiel v ohybe. Ďalej je uvedené vyhodnotenie pomocou *t*-testu koeficientov pevnosti v ohybe vzoriek stebiel pšenice rôznych odrôd. Dosiahnuté výsledky sa využijú pri riešení otázok odolnosti proti poliehaniu.

Kľúčové slová: steblá pšenice; rezonančná frekvencia; koeficient pevnosti v ohybe; modul pružnosti; mechanické vlastnosti stebla pšenice

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