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Seasonal variations of oscillation and vibration parameters of *Acer platanoides*

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Abstract: This article describes an investigation into the seasonal variations of frequency, damping ratio and amplitude of swaying and vibration of Norway maple *Acer platanoides* L. The study was carried through a series of pull and release experiments *in situ* and on branches in the laboratory using an artificial air flow. It was found that foliated trees had a natural sway frequency that was on average 1.6±0.2 times greater than in the out-of-leaf state. In contrast, the damping ratio of maple increased by 1.5±0.3 times in the summer period. The stem swaying initiated vibrations, i.e. elastic wave, in the roots with frequencies in the range of 45–50 Hz. Laboratory tests showed that the vibration amplitude of branches depended linearly on leaf mass for an air flow velocity of 1.94 m/s.

Additional key words: maple, swaying, frequency, damping ratio

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Introduction

Mechanical properties of plants are determined by the interaction of genetic factors and growth conditions. The chronic wind action and other mechanical factors cause morphological changes, which lead to reinforcement of tissues and an increase in mechanical stability of tree or their certain parts (Telewski 2006). However, few mechanisms of energy dissipation exist for a tree under mechanical load. Thus, the most significant dynamic mechanical factor that influences a tree is wind, which leads to swaying of the stem and branches. This energy is dissipated in the plant tissues as heat and into environment as a result of friction of the plant parts with air and soil. Clashing of tree branches is also an effective mechanism of energy transfer. It converts the energy into an elastic wave that spreads along the tree as vibration and is partially transferred into the environment as sound. Another mechanism of vibration initiation also exists – deformation of tree tissues while swaying at the points of flexure. Apparently, tree vibrations appear very important in interaction of tree with organisms, which inhabit it (Cocroft and Rodriguez 2005) and, probably, influence on the pedogenic processes (Netsvetov et al. 2009).

Thereby, investigation of swaying and vibrations of arborous plants is important not only from economic position, i.e. for the purpose of damage prevention of tree-stand by a wind, but also from ecological position as ecologic factor. The aim of the present work has been study of seasonal variations of parameters (frequency, damping ratio and amplitude) of swaying and vibration, which they induce using the example of Norway maple *Acer platanoides* L.

Methods

The influence of leaves on frequency and oscillation damping was investigated for four Norway maple

Table 1. The main morphological indices of *Acer platanoides* trees

Tree	$d_{0.3}$ (cm)	$d_{1.3}$ (cm)	$d_{к}$ (cm)	l (m)
A1	9.0	7.5	2.2	8.5
A2	10.5	10.0	2.5	9.0
A3	19.0	16.0	3.6	9.5
A4	13.0	11.5	3.2	10.0

Notes: $d_{0.3}$ – diameter of stem on the height of 0.3 m; $d_{1.3}$ – diameter of stem on the height of 1.3 m; $d_{к}$ – diameter of crown; l – tree height.

(*Acer platanoides* L.) trees. Experiments took place in the arboretum of Donetsk Botanical Garden, the National Academy of Sciences of Ukraine during 2009. The trees that were chosen for the investigation were 20–25 years old and grew in stands with no obstacles to prevent the experimental swaying tests from being done. The main morphological indices are presented in the Table 1.

Tree swaying test

The trees oscillations were initiated by successive pulling of the stem at a height of 1.3 m. Several replications of the tests were done on each tree and trees were swayed in two perpendicular directions. After excitation, the trees returned to their rest position under damped free vibration, and their oscillations were measured using a piezoelectric cartridge and oscilloscope (HP-10 Villeman enterprise, Belgium). The sensor was placed on the stem at a height of 30–35 cm to record the swaying, while a second sensor was placed on the top of the root plate to record vibrations. The signal was processed using a fast Fourier transform within the MathCad 2001 program to determine the amplitude-oscillation characteristics (AOC) – the dependence of signal amplitude on the frequency (or period). The basic frequency of oscillations f was determined by AOC, and damping ratio of oscillation $\hat{\imath}$ from the equation of free damped oscillations (Moore and Maguire 2005):

$$x(t) = X_0 \cdot e^{\zeta\omega t} \cos(\omega_d \cdot t + \varphi)$$

where $x(t)$ – value of the point displacement at the time moment t,
X_0 – displacement at the initial time moment,
ω – circular frequency of oscillations, $\omega=2\pi f$, T, T – period,
ω_d – circular frequency of damped oscillations, which calculates by the formula (2),
φ – phase shift.

$$\omega_d = \omega \cdot (1-\xi)^{1/2}$$

The influence of leaves on the amplitude of branch vibrations

The experiment took place in the laboratory using five 4–5-year-old sprouts of Norway maple. Branches with similar morphological indices, amount of foliage, height of attachment to the stem and insertion angle to a stem were chosen for the experiment. These branches had a basal diameter of 11 cm, ranged in length from 1.10–1.15 m, and ranged in mass from 32–36 g. The experiment took place in the in-leaf state and after a few stages of defoliation (Table 2). The leaf surface area projected toward the air flow was determined from photographs of the branches taken during the experiment. The air flow was created by a fan with the controllable speed of fan rotation. The velocity of the air flow in front of the branches was $V1$=0.58; $V2$=0.89; $V3$=1.94 m/s. Oscillations of the branches under the air flow were measured using the same method employed for tree oscillations (see above), with the piezoelectric sensor placed 5 mm above the point of branch fixation.

Table 2. Relative values of leaves mass m and leaves surface area projected to the wind flow A under successive defoliation of *Acer platanoides* branches

	Stages of defoliation						
	0	1	2	3	4	5	6
m, r.u.	1.00	0.83	0.68	0.59	0.32	0.01	0.00
A, r.u.	1.00	0.87	0.75	0.67	0.46	0.05	0.00

Note: mass and leaves area are attributed to the maximal values in the intact state at the 0 stage of defoliation. The standard deviation at each stage was not more than 0.15.

Results

Frequencies of stem oscillations

The frequency of stem oscillations of maples in February, 2009 (i.e., during the dormancy period) ranged between 0.50 and 0.56 Hz for trees A1, A2, and A4, but was significantly lower ($p<0.05$) for tree A3 (0.39 Hz) (Table 3). At the end of May, 2009 when the trees were in-leaf, their natural frequencies were significantly lower ($p<0.05$) than in the dormancy period (Table 3). Foliated trees sway with a natural frequency that is on average 1.6 times greater, than in the out-of-leaf state during dormancy (Fig. 1 A). During the fall period at the beginning of defoliation in October, 2009, when yellowed leaves remained only partially, substantially on the top of trees, the values of frequencies of stem oscillations were almost indistinguishable from the spring period except for tree A3, where significant differences were observed. Overall, this decrease in the amount of foliage and the change in mechanical properties of the stem in fall,

Table 3. Seasonal variations of frequencies (mean±sd) of *Acer platanoides* stem oscillations

Tree	Date of the experiment			
	24.02.2009	22.05.2009	13.10.2009	24.11.2009
A1	0.50±0.033	0.29±0.014	0.29±0.033	0.45±0.015
A2	0.56±0.021	0.35±0.028	0.35±0.029	0.55±0.009
A3	0.39±0.014	0.29±0.017	0.31±0.012	0.37±0.020
A4	0.54±0.015	0.33±0.007	0.35±0.029	0.52±0.016
Average	0.50±0.077	0.31±0.032	0.32±0.030	0.48±0.081

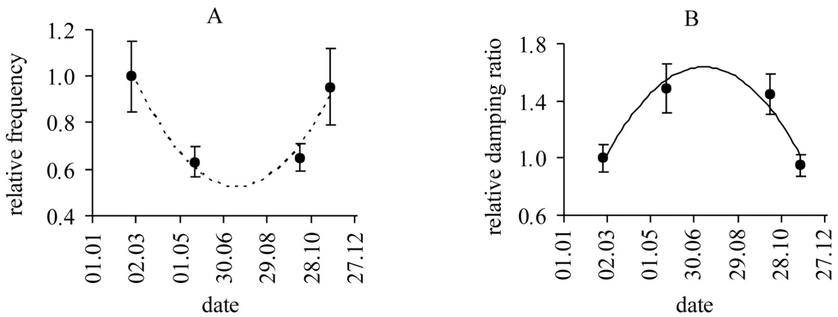

Fig. 1. Seasonal variation of relative frequency (A) and relative damping ratio (B) of *Acer platanoides* oscillations in 2009. Data are normalized by the values measured on 24.02.2009

when residual leaves remained in the upper third of the tree didn't lead to a significant change in frequency. However, after complete defoliation at the end of November, 2009 frequencies of the stem oscillations increased back up to the winter values. Only for tree A1 are the frequency differences in the dormancy period in winter and fall, 2009 statistically significant.

Damping ratio of stem oscillations

In the dormancy period in February, 2009 the damping ratio of stem oscillations of maples varied from 0.133±0.0201 (À1) to 0.168±0.0198 (À3). After completion of forming leaves at the end of May the damping ratio significantly increased (P>0.95) for all trees by an average of 1.5±0.3 times (Fig. 1 B). Its minimum value was 0.194±0.0058 (À3) and its maximum was 0.252±0.0094 (À1). During defoliation the values of damping ratio remained almost constant, except for A1, where î decreased to 0.209±0.0200 (P>0.95). After completion of leaf fall the damping ratio decreased to a level that was statistically indistinguishable from the winter values.

Vibration of roots from the tree swaying

The measurements were made on windless days under swaying initiated by successive stem pulling together with measurement of stem oscillations for exclusion of vibration of roots, which was caused by collisions and flexing of branches. The natural vibration frequency of the base of roots was between 45 and 50 Hz for all trees (Fig. 2). On the amplitude spectra the two additional peaks appear on both sides of the main peak at the same distance, and may be interpreted as

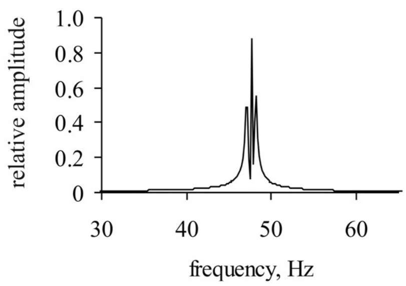

Fig. 2. Amplitude spectrum of vibration of *Acer platanoides* root, induced by the stem swaying

the amplitude modulation (Kelly 2006). The modulation frequency is equal to the distance between the main and additional peaks and represents the stem swaying frequency ~0.5 Hz. Thus, the root vibration is modulated by the stem oscillations and increases while its deviation from the equilibrium position. Comparison of oscillograms from different seasons indicates that in summer the duration of vibration is less affected by the rapid attenuation of swaying (Fig. 3).

Influence of leaves on the amplitude of branch vibration

At different levels of defoliation in the absence of air flow from the fan the amplitude of branches vibrations was almost zero and did not differ significantly. The smallest vibration amplitude from the swaying of branches under the air flow was observed after the full defoliation.

The largest branch vibration amplitude in the intact in-leaf state was not observed under the highest air flow velocity, but actually occurred when the air

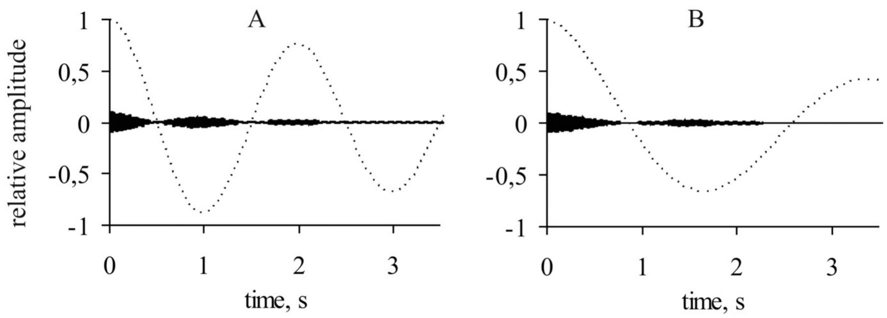

Fig. 3. Oscillograms of vibration at the base of an *Acer platanoides* root (firm line), caused by stem swaying at the height of 30 cm from the base (dashed line) at the dormancy period (A) and vegetation (B)

flow was 0.58 m/s (i.e. *V1*) and after removal of 68% of leaves mass (or 54% of surface area projected to the wind). A significant decrease of vibration amplitude occurred only after removal of all the leaf mass. The presence of even a single leaf at the end of the branch reduced the amplitude to 83 % of the value that is typical for the intact in-leaf state (Fig. 4).

The increase of speed of the air flow up to *V2*=0.89 m/s resulted in an increase in the amplitude of vibration by an average of 1.5 times compared with *V1*; however, the relationship between amplitude of vibration and leaf mass or the frontal area presented to the air flow is nonlinear. A more significant change of amplitude of vibration and a relationship with leaf mass and frontal area was found when the air flow velocity was increased to 1.94 m/s (i.e. *V3*). On average the amplitude increased by 2.3 times in comparison with *V1*. The following linear relationships were found between amplitude and relative mass (M) and relative area (A) of removed leaves:

$y= -7.1M+20.1$ ($R^2=0.82$)

$y= -7.8A+19.9$ ($R^2=0.88$).

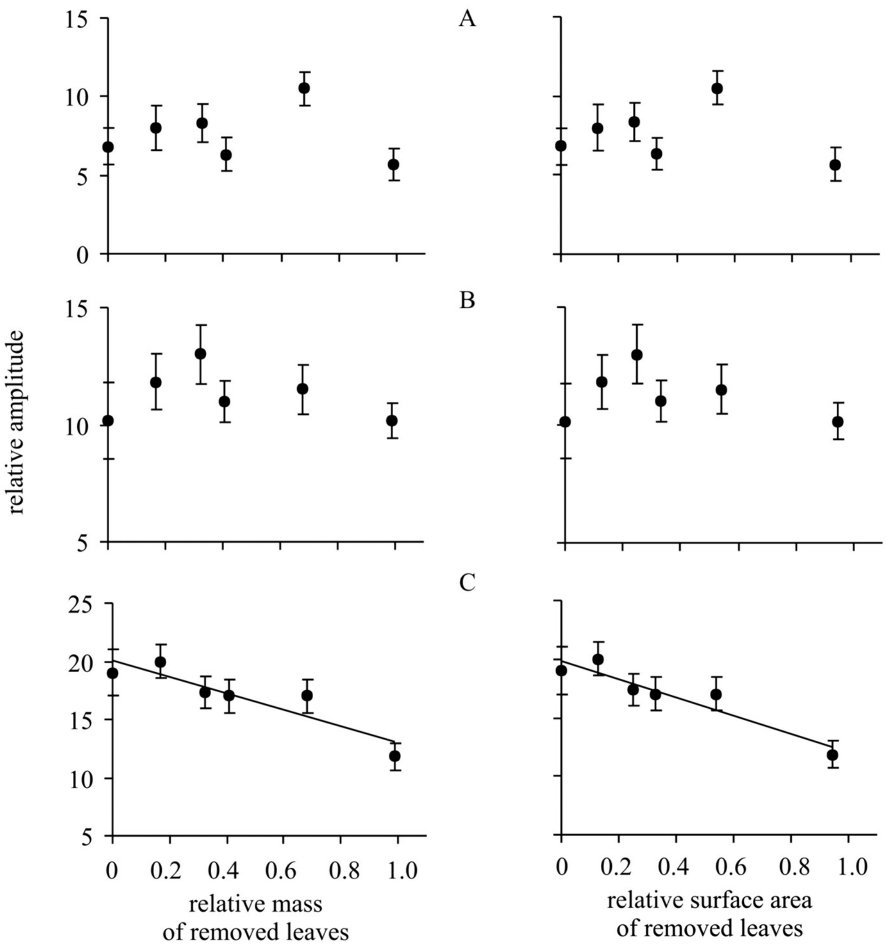

Fig. 4. Dependence of relative amplitude of vibrations of *Acer platanoides* branches on the relative mass and relative surface area of removed leaves under the air flow speed of 1,94 m/s (A); 0,89 m/s (B); 0,58 m/s (C). The value «1» corresponds to the full defoliation stage

Table 4. Seasonal variations of damping ratio (mean±sd) of the *Acer platanoides* stem oscillations

Tree	Date of the measuring			
	24.02.2009	22.05.2009	13.10.2009	24.11.2009
A1	0.133±0.0201	0.252±0.0094	0.209±0.0200	0.148±0.0690
A2	0.156±0.0202	0.246±0.0077	0.245±0.0169	0.138±0.0074
A3	0.168±0.0198	0.194±0.0058	0.200±0.0050	0.162±0.0094
A4	0.160±0.0158	0.225±0.0298	0.240±0.0267	0.138±0.0074
Average	0.154±0.0150	0.229±0.0264	0.224±0.0221	0.147±0.0118

The correlation of amplitude of vibration with a mass and area of leaves surface, blowing round by the air flow, which is expressed in terms of Pierson's correlation coefficient, rises with increase of velocity of air flow (Table 5). While using product of relative total leaf area projected to the air flow and relative leaf mass, the values of correlation coefficient increased to 0.9.

Table 5. Linear coefficient of correlation between amplitude of vibration of *Acer platanoides* branches and relative leaf mass m, leaf surface area A projected to the air flow and their product $A{\cdot}m$ under the different speed V of air flow

V, m/c	m	S	$A{\cdot}m$
0.58	0.58	0.49	0.66
0.89	0.65	0.58	0.72
1.94	0.88	0.83	0.90

Discussion

The decrease of frequency of tree swaying in the in-leaf state is due to the increase of crown mass and, therefore, the inertia moment of a tree as an oscillating system. This is consistent with previous experiments that have been carried out on deciduous tree species (e.g. Roodbaraky et al. 1994, Baker 1997, Smiley and Kane 2006, Netsvetov and Nikulina 2009). The leaf mass located at the uppermost part of crown has the greatest influence on the increase of inertia moment of a tree, which also agrees with basic theory for the oscillation of a pendulum. It is also possible that a decrease in vibration frequency in some way affected the aerodynamic resistance of the leaves (Vogel 2009). Earlier experiments with plasticine spheres instead of leaves for seedlings of Norway maple, which significantly decrease the frontal area of the crown, but not the moment of inertia, enabled the contribution of leaf area to the decrease of frequency to be estimated. It was shown that the aerodynamic resistance of leaves have a small effect on the natural frequency but influences substantially on damping ratio (Netsvetov and Nikulina 2009). The oscillation damping is also caused by coupled oscillation of branches (Spatz et al. 2007), branches collisions (Rudnicki et al. 2001), wood viscosity (Niklas 1992, Spatz et al. 2007), frictions between soil and root elements (England et al. 2000) and affected by crown architectonics (Sellier and Fourcaud 2009, Moore and Maguire 2005).

Low frequencies are invariably reported in the literature regarding wind induced tree swaying. Our study clearly shows that low-frequency swaying of tree stem is accompanied by sound range vibrations, caused by plant tissue deformation. The possibility of high-frequency vibration is sustained by the work of Casas et al. (2007), affirming the impact on rush stem induces the vibration with frequencies up to 5 kHz. The other work (Castro-García et al. 2008) shows the forced vibration of olive trees causes the branches' vibration at 20–30 Hz.

Seasonal variations of aerodynamic resistance of crown and frequency of oscillations have an effect on the character of vibrations, which were induced by deformations of tree tissues in the region of the stem where bending occurs. The influence of parameters of swaying consists in the modulation of vibration and its duration. The increase of leaf surface area at the part of crown by the wind flow has a significant impact on amplitude of vibrations because of the presence of leaves. According to the theoretical views (Vogel 2009) the aerodynamic load on the leaf increases proportionally to its area and deflection of the branch proportionally to its loaded mass. While the observing linear dependence of amplitude of vibration from the mass and blowing round area of leaves is in agreement with this theory, the linear dependence of amplitude of vibration from the blowing round area of leaves is only observed at higher air flow velocities. When the speed is lower the relationship is nonlinear. This might be connected to the aerodynamic resistance, which is proportional to the square of the air flow velocity, as well as to the fact that at lower velocities other factors have a bigger impact on the amplitude of oscillations. For example, it was not possible to achieve successive leaf removal evenly along the whole branch length, and this non-uniform leaf distribution may have contributed to an irregularity of loading at low wind speeds.

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