Gust effect factors and natural sway frequencies of trees for wind load estimation

***Seunghoon Shin[1], Ilmin Kang[1], Seonggeun Park[1], Yuhyun Lee[1], Kyungjae Shin[1], Whajung Kim[1], and †Hongjin Kim[1]**

[1]Department of Architectural Engineering, Kyungpook National University, Korea

*Presenting author: ssh10004ok@knu.ac.kr
†Corresponding author: hjk@knu.ac.kr

Abstract

Strong winds have caused increasing wind damages for fruit trees such as uprooting and fruit drop in orchards worldwide. In order to prevent these wind damages, the various prop systems or support systems have been introduced for fruit trees. When a prop system is designed against strong winds, it is essential to calculate the wind load acting on each tree for accurate evaluation of wind resistance of prop system.

It is often to treat the applied wind load acting on a tree as a static load and to use beam theory to determine the maximum bending moment at the base of the tree. However, the response of a tree is frequency dependent and is affected mostly by wind gusts at frequencies close to its resonant frequency. In this situation, the dynamic effects are likely to increase the bending of stems and hence the maximum bending moment at the base of the tree. These dynamic effects are likely significant and cannot be ignored when the natural sway frequency of a tree is relatively small, that is, the tree is flexible.

There are two approaches to quantifying the response of a tree to a given fluctuating wind load. First, the wind load and tree response spectra are experimentally measured and a transfer function from the wind load to tree response is developed. Alternatively, if the information on the dynamic properties such as natural sway frequency and damping ratio of trees are available, then it is possible to characterize their response to any fluctuating wind load by employing a wind engineering theory. In many design codes or standards, this dynamic effect is considered adopting the gust effect factor and empirical formulae for the factor are given as functions of the natural sway frequency and damping ratio. The threshold natural sway frequency in most design codes that the dynamic effect against fluctuating wind load needs to be considered carefully is 1.0 Hz.

This paper presents the system identification method to measure the natural sway frequencies and damping ratios of fruit trees for the evaluation of the wind load acting on the trees. Both the ambient vibration test and free vibration test are performed and the identified dynamic properties are compared. It is found the average natural frequency of fruit trees is less than 1.0 Hz, and thereby the dynamic effect against fluctuating wind load needs cannot be ignored. Further, it is found that the damping ratios of fruit trees are quite larger than those of civil and building structures due to the soil-structure interaction. Therefore, a special care is required when the prop systems for fruit trees are designed against strong winds.

Keywords: Tree Supporting system, Wind load, Gust effect factor, Ambient vibration test, System identification.

Introduction

Typhoon has caused increasing wind damages for fruit trees at the orchard such as uprooting and fruit drop in Korea recently. The resistance to uprooting moment of the tree is typically the weakest mechanical link for shallow-rooted trees subjected to strong winds (Lundström et al. 2007). In order to prevent these wind damages and to enhance the uprooting moment capacities of trees in orchards, the wind break forest and the various prop systems, or supporting systems, have been introduced to fruit orchards (He and Hoyano, 2010). Three most typical types of apple tree prop system used in Korea are 1) individual prop system, 2) steel pipe fence prop system, and 3) concrete column fence prop system.

However, most of these prop systems were originated from the regions where the strong tropical storm like a typhoon does not occur (Lespinasse and Delort, 1986). Further, the most of studies on the apple tree prop system has focused on the annual yield and profits (Robison et al., 2007, Palmer et al., 1992). Therefore, it is required to evaluate the wind resisting performance of fruit tree prop systems which are frequently used in Korea.

When a prop system is designed against strong winds, it is essential to calculate the wind load acting on each tree for accurate evaluation of wind resistance of the prop system. It is often to treat the applied wind load acting on a tree as a static load and to use beam theory to determine the maximum bending moment at the base of the tree. However, the response of a tree is frequency dependent and is affected mostly by wind gusts at frequencies close to its resonant frequency (Hu et al., 2009). In this situation, the dynamic effects are likely to increase the bending of stems and hence the maximum bending moment at the base of the tree. These dynamic effects are significant and cannot be ignored when the natural frequency of a tree is relatively small, that is, the tree is flexible.

There are two approaches to quantifying the response of a tree to a given fluctuating wind load (Moore and Maguire, 2004). First, the wind load and tree response spectra are experimentally measured and a transfer function from the wind load to tree response is developed. Alternatively, if the information on the dynamic properties such as natural frequency and damping ratio of trees are available, then it is possible to characterize their response to any fluctuating wind load by employing a wind engineering theory. In many design codes or standards, this dynamic effect is considered adopting the gust effect factor and empirical formulae for the factor are given as functions of the natural frequency and damping ratio. The threshold natural frequency in most design codes that the dynamic effect against fluctuating wind load needs to be considered carefully is 1.0 Hz (AIJ, 2009, ASCE, 2010).

This paper presents the system identification to measure the natural frequencies and damping ratios of fruit trees for the evaluation of the wind load acting on the trees. Both the ambient vibration test and free vibration test are performed and the identified dynamic properties are compared. The dynamic properties obtained using the previously reported empirical formulae are also compared to experimentally identified ones. Next, the gust effect factors for each tree are evaluated using the formula given in Korean Building Code, which is termed as KBC2009 hereafter (AIK, 2009).

Wind Load on the tree supporting system

Wind load on a tree

Figure 1 shows the steel pipe fence type prop system, which is most commonly used for apple orchards in Korea. Three or more trees are planted between two vertical pipes that are spaced 6 m, and the wind load acting on trees are transferred to vertical supports by horizontal wires installed at every 80 cm. Since the stiffness in the longitudinal direction is much larger than that in the normal direction, uprooting damages generally occurs in the normal direction and most trees connected to a fence are damaged simultaneously.

Figure 1. Steel pipe fence type prop system

The wind load acting on a tree, P, is calculated as (Simiu and Scanlan, 1996)

$$P = q_w A \tag{1}$$

where q_w is the wind pressure (N/m^2). The wind pressure q_w is given by

$$q_w = 0.5 \rho C_D G_f V_z^2 \tag{2}$$

where ρ is the air density (kg/m^3), C_D is the drag coefficient (dimensionless), G_f is the gust effect factor (dimensionless), and V_z is the design wind velocity at height z (m).

The drag coefficients C_D of trees in Eq. (2) are generally obtained experimentally using a wind tunnel and some typical values are given for various tree types (Mayhead, 1973, Vollsinger et al., 2005). On the contrary, only limited studies have been performed on the gust effect factor G_f of trees since it is affected by many features such as tree species, age, height, stem diameter, and spacing (Gardiner et al., 2000). In this study, the gust effect factor is obtained and analyzed applying empirical formulae provided in literatures and design codes that are obtained based on a wind engineering theory.

Gust effect factor

The gust effect factor is defined as a ratio of the maximum response to mean response of a structure and is given as (Simiu and Scanlan, 1996)

$$G_f = \frac{X_{\max}}{\bar{X}} = 1 + g_f \frac{\sigma_X}{\bar{X}} \tag{3}$$

where X_{max} is the maximum response, $\overline{X}$ is the mean response, g_f is a peak factor, and σ_x is the standard deviation of the response.

Gardiner et al. (2000) proposed the following empirical formula obtained from a wind tunnel test using scaled tree models.

$$G_{\max} = \left(2.7193\frac{s}{H} - 0.061\right) + \left(-1.273\frac{s}{H} + 0.9701\right)\left(1.1127\frac{s}{H} + 0.0311\right)^{x/H}$$

$$G_{mean} = \left(0.68\frac{s}{H} - 0.0385\right) + \left(-0.68\frac{s}{H} + 0.4875\right)\left(1.7239\frac{s}{H} + 0.0316\right)^{x/H}$$

$$G_f = \frac{G_{\max}}{G_{mean}} \qquad \text{(3.a, b, and c)}$$

where s is the tree spacing (m), H is the tree height, and x is the distance from the forest edge (m).

Davenport and Surray (1990) defined the gust effect factor for low rise structures as

$$G_f = 1 + \psi\varphi\sqrt{k_1 + k_2} \qquad (4)$$

where ψ is the peak factor (dimensionless), φ is the exposure factor (dimensionless), k_1 is the background turbulence factor (dimensionless), and k_2 is the gust resonant factor.

Peak factor ψ depends on the natural frequency of the structure, that is, it increases as a logarithmic function of natural frequency of the structure increases. Further, the gust resonant factor k_2 also is a function of the natural frequency of the structure. The damping ratio of the structure affects the gust resonant factor as well. Consequently, the accurate evaluation of the natural frequency and damping ratio is critical for the gust factor calculation.

Eq. (4) is adopted in many design codes including KBC2009. The peak factor ψ and the exposure factor φ in KBC2009 are given as

$$\psi = \sqrt{2\ln(600\nu_f) + 1.2} \qquad (5)$$

$$\varphi = \left(\frac{3+3\alpha}{2+\alpha}\right) I_z \qquad (6)$$

where α is the power law exponent of mean wind speed profile for a given terrain roughness category, υ_f and I_z are , respectively, the level crossing number and turbulence density at the reference height and given as

$$\nu_f = n_0\sqrt{\frac{k_2}{k_1 + k_2}} \qquad (7)$$

$$I_z = 0.1\left(\frac{z}{Z_g}\right)^{-\alpha-0.05} \tag{8}$$

where n_0 is the natural frequency of the structure (Hz) and Z_g is the nominal height of the atmospheric boundary layer.
The background turbulence factor k_1 and the gust resonant factor k_2 in KBC2009 are defined as

$$k_1 = 1 - \left[\frac{1}{\left\{1+5.1\left(L_H/\sqrt{HB}\right)^{1.3}\left(B/H\right)^{0.33}\right\}^{1/3}}\right] \tag{9}$$

$$k_2 = \frac{\pi}{4\varsigma_f} S_f F_s \tag{10}$$

where B is the width of the structure, ζ_f is the damping ratio, L_H is turbulence density at the reference height, and S_f and F_s are, respectively, the size reduction factor and the spectral energy factor given as

$$S_f = \frac{0.84}{\{1+2.1(n_0 H/V_H\}\{1+2.1(n_0 B/V_H\}} \tag{11}$$

$$F_s = \frac{4(n_0 L_H/V_H)}{\{1+71(n_0 L_H/V_H)^2\}^{5/6}} \tag{12}$$

where V_H is the design wind speed at the top of the structure.
For the structure with a natural frequency of less than 1.0 Hz, the structures is classified as a rigid structure and its gust effect factor is simply given as Eq. (13) omitting the gust resonant factor k_2 and letting the value of and the exposure factor φ to be 4 from Eq. (4)

$$G_f = 1 + 4\varphi\sqrt{k_1} \tag{13}$$

Natural frequency and damping ratio of trees

From Eqs. (7), (11), and (13), it can be noticed that the natural frequency is required for the gust effect factor calculation. Further, it can be noted from Eq. (10) that the damping ratio needs to be known as well.

Moore and Maguire (2004) investigated previously reported natural frequency measurement from 602 trees, which belong to eight different species, and showed that natural frequency is strongly and linearly related to the ratio of diameter at breast height to total height squared. They presented the following empirical formula based on a regression analysis.

$$n_0 = 0.0766 + 3.1219\frac{D_{bh}}{H^2} \tag{14}$$

where D_{bh} is the diameter at breast height (cm).

They proposed another empirical formula to consider the species difference given by Eq. (15) where I_p is an indicator variable.

$$n_0 = 0.0948 + 3.4317\frac{D_{bh}}{H^2} - 0.7765 I_p \frac{D_{bh}}{H^2} \tag{15}$$

The value of I_p is 1.0 if the genus is Pinus and 0.0 otherwise.
Moore and Maguire also investigated the damping ratio of trees from the previous researches and classified it into two categories; 1) internal damping is due to the friction of the root-soil connection, structural damping resulting from the movement of branches and the internal friction of the wood, and 2) external damping due to the aerodynamic drag of the crown and also to collisions between crowns of neighboring trees. They concluded that the internal damping ratios are generally less than 0.05 and do not appear to be related to tree size, while the external damping is wind velocity dependent and much larger than the internal one.

Field measurement of natural frequencies and damping ratio

Test specimens and methods

A field vibration test was performed to measure the natural frequencies and damping ratios of orchard trees. The apple trees were used for the test. Both the ambient vibration test and free vibration test were performed and the identified dynamic properties were compared.

The trees were supported by the steel pipe fence type prop system and four to five trees were planted between two vertical steel pipes. The test was performed when trees were heavy with clusters of apples since the typhoon damages occur mostly before and during harvest season. Total of 20 trees were used in the test.

In order to analyze the effect of the prop on the dynamic properties of trees, a half of specimens were tested after cutting all horizontal wires connected to the trees while the prop for the rest of specimens remained intact.

Two piezoelectric accelerometers were installed at 1.5 m high, one in the longitudinal direction (x-direction) and another in the normal direction (y-direction) to measure the accelerations of trees without a steel pipe prop. On the contrary, only one accelerometer was used in the y-direction for trees with a prop because the frequency in the x-direction is considerably affected by the prop due to large stiffness.

The ambient vibration test was carried out for 10 minutes with a sampling frequency of 360 Hz. The free vibration test was performed by simply pushing trees about 30 cm slowly by human and letting trees vibrate freely. Five human-induced free vibrations were performed continuously for both x- and y-directions for trees without a steel pipe prop, while those were performed for the y-direction only for trees with a prop. The only acceleration measured in the same direction to the free vibration direction is utilized for the identification of dynamic properties for the free vibration test.

Identified natural frequencies and damping ratio

The power spectrum densities (PSDs) of measured accelerations from two test methods were obtained to identify the natural frequencies of trees. Then the half-power band-width method was applied to the obtained PSDs for damping ratio estimation (Clough, R. W. and Penzien, J, 1995, Xiong et al., 2011).

The peaks of PSDs are considerably noticeable at the fundamental natural frequencies in both ambient and free vibration tests, while the values of PSDs in the ambient vibration test contains the higher modes and DC contents. The distinction of PSDs near the fundamental frequency in the free vibration test is mainly due to the fact that trees oscillate at their fundamental frequency under a free vibration.

The identified natural frequencies of the test specimens are summarized in Tables 1 and 2. Note that the only natural frequencies in the y-direction are identified in Table 2 for trees with a prop since the acceleration were measured in that direction only.

It can be seen from Table 1 that the natural frequencies of trees in the x- and y-directions are almost same except the test specimen T3, T8, and T9. It can be also seen that the identified natural frequencies from the free vibration tests are generally smaller than those from the ambient vibration tests. This is because the natural frequency of a structure is generally inversely proportional to its response amplitude and the amplitudes of measured accelerations in the free vibration test are significantly larger than those in the ambient vibration test. In average, the natural frequencies obtained from the free vibration test are 3.90 % and 6.06% smaller in the x- and y-directions, respectively, than those from the ambient vibration test.

The natural frequencies of the trees with a prop are found to be increased compared to those without a prop. Those with a prop are 15.73 % and 13.70 % larger than those without a prop in average (Table 2). This concludes that the stiffness of the steel pipe fence prop helps to increase the stiffness of trees in the y-direction. That is the overall uprooting moment resistance capacities of trees are increased due to the installation of the prop.

Table 1. Identified natural frequencies of trees without a prop

Specimen	Ambient vibration test		Free vibration test	
	x-dir. (Hz)	y-dir. (Hz)	x-dir. (Hz)	y-dir. (Hz)
T1	0.807	0.807	0.779	0.791
T2	0.907	0.907	0.908	0.870
T3	0.807	0.630	0.756	0.655
T4	0.857	0.882	0.807	0.857
T5	0.907	0.958	0.907	0.907
T6	0.958	1.058	0.958	1.008
T7	1.134	1.046	1.008	1.008
T8	1.210	1.411	1.159	1.109
T9	1.084	0.958	1.008	0.907
T10	1.109	1.159	1.109	1.109
Average	0.978	0.982	0.922	0.922

Table 2. Identified natural frequencies of trees with a prop in the y-direction

Specimen	Ambient vibration test (Hz)	Free vibration test (Hz)
T11	0.958	0.907
T12	0.857	0.756
T13	0.807	0.756
T14	1.512	1.411
T15	1.445	1.336
T16	0.907	0.832
T17	1.498	1.210
T18	1.033	1.008
T19	1.159	1.109
T20	1.184	1.159
Average	1.136	1.048

In Table 3, the calculated natural frequencies of trees using the empirical formulae provided in Eqs. (14) and (15) are presented for comparison with experimentally identified ones. Compared with identified natural frequencies provided in Tables 1 and 2, the empirical formulae proposed by Moore and Maguire overestimate the natural frequencies up to 234 %

in average. Therefore, it can be concluded that the empirical formulae do not cover every genus of trees even though they are obtained from more than 600 experimental data.

Table 3. Natural frequencies of trees from empirical formulae

Specimen	Eq. (14) (Hz)	Eq. (15) (Hz)	Specimen	Eq. (14) (Hz)	Eq. (15) (Hz)
T1	4.169	4.593	T11	2.612	2.881
T2	2.497	2.755	T12	2.375	2.622
T3	2.358	2.603	T13	2.301	2.540
T4	2.351	2.595	T14	1.545	1.709
T5	2.892	3.190	T15	3.046	3.359
T6	3.193	3.521	T16	2.455	2.709
T7	2.723	3.048	T17	2.443	2.696
T8	4.063	4.477	T18	2.825	3.116
T9	2.618	2.888	T19	2.682	2.959
T10	2.083	3.092	T20	2.945	3.248
Average	2.971	3.276	Average	2.523	2.784

Table 4. Identified damping ratios of trees without a prop

Specimen	Ambient vibration test		Free vibration test	
	x-dir. (%)	y-dir. (%)	x-dir. (%)	y-dir. (%)
T1	6.53	7.68	4.63	3.05
T2	6.56	7.08	11.10	16.41
T3	7.35	6.10	7.42	8.90
T4	7.18	3.79	8.62	7.03
T5	6.86	7.21	9.73	7.03
T6	6.48	7.05	7.82	11.10
T7	3.54	5.60	9.52	9.61
T8	7.92	6.62	6.98	14.59
T9	3.49	6.36	9.84	7.78
T10	4.15	5.74	5.95	5.06
Average	6.01	6.32	8.16	9.06

Table 5. Identified damping ratios of trees with a prop in the y-direction

Specimen	Ambient vibration test (%)	Free vibration test (%)
T11	5.31	10.91
T12	2.64	17.27
T13	8.97	8.72
T14	2.48	14.19
T15	8.30	12.41
T16	6.30	10.55
T17	6.73	20.61
T18	19.43	21.79
T19	6.98	11.15
T20	9.29	8.17
Average	7.64	13.58

Tables 4 and 5 present the identified damping ratios of trees with and without a prop from the ambient and free vibration test. It can be seen from Table 4 that the identified damping ratios of trees without a prop from the free vibration test were significantly larger than those from the ambient vibration test. They are 35.88% larger in the x-direction and 43.22 % larger in the y-direction in average. This is because the external damping as well as internal damping plays a role when the trees are oscillating with large magnitudes as Moore and Maguire reported. The average damping values of 6.01 % and 6.32 % obtained from the ambient vibration test match well to the internal damping of 5 % reported by Moore and Maguire.

Compared to the damping ratio of trees without a prop, those with a prop in Table 5 are 20.88 % and 49.92 % larger in the ambient and free vibration tests, respectively. Consequently, it can be concluded that the wires attached to the trees in the steel pipe fence prop increase not only stiffness but also damping ratios of trees.

Gust effect factor evaluations

The gust effect factors are calculated and summarized in Tables 6 and 7. Both formulae for non-rigid structures in Eq. (3) and rigid structures in Eq. (4) are utilized since the identified natural frequencies of trees are almost 1 Hz. For comparison, the results of the empirical formula in Eq. (13) proposed by Gardiner et al. are also presented in Tables 6 and 7. For Eqs. (3) and (4), the identified natural frequencies and damping ratio from the ambient vibration test were used because the smaller damping ratios produce more conservative wind load estimation. For Eq. (13), the tree spacing is set to be 1.5 m, and the distance from the forest edge is assumed to be zero for conservative condition.

Table 6. Gust effect factors of trees without a prop

Specimen	Eq. (3)	Eq. (4)	Eq. (13)
T1	2.925	2.493	3.992
T2	2.938	2.494	3.985
T3	3.101	2.468	3.827
T4	3.312	2.473	3.859
T5	2.865	2.469	3.827
T6	2.922	2.508	4.054
T7	2.962	2.469	3.840
T8	2.875	2.514	4.095
T9	2.963	2.485	3.920
T10	2.961	2.491	3.955
Average	2.982	2.486	3.935

Table 7. Gust effect factors of trees with a prop

Specimen	Eq. (3)	Eq. (4)	Eq. (13)
T11	2.783	2.362	3.330
T12	3.490	2.422	3.588
T13	2.746	2.435	3.631
T14	3.207	2.425	3.565
T15	2.629	2.433	3.652
T16	2.910	2.450	3.726
T17	2.685	2.426	3.597
T18	2.506	2.467	3.802
T19	2.740	2.428	3.616
T20	2.602	2.413	3.547
Average	2.830	2.426	3.606

It can be noticed that the gust effect factors obtained using Eq. (4) are 14.27 % to 16.63 % smaller than those obtained using Eq. (3). Therefore, if the flexible nature of trees is neglected, the total wind load can be underestimated noticeably.

The empirical formula proposed by Gardiner et al. yields 27.41 % to 31.96 % lager gust effect factors compared to those by the formula for non-rigid structures, and 48.62 % to 58.29 % lager ones compared to those by the formula for rigid structures Therefore, it can be concluded that the empirical formula that does not require the exact values of natural frequency and damping ratio overestimates the gust effect factor considerably.

Conclusions

The gust effect factors of trees are analyzed for the wind load estimation of the tree supporting system. Since the value of gust effect factor depends on the natural frequency and damping ratio, the field experiment was performed to identify the accurate dynamic properties of the trees.

The 20 apple trees were used for the field test, in which a half of them were tested after cutting all horizontal wires connected to the trees while the prop for the rest of specimens remained intact. Both the ambient vibration test and free vibration test were performed and the identified dynamic properties were compared.

It was found that the average natural frequency of fruit trees is about 1.0 Hz, and thereby the dynamic effect against fluctuating wind load needs cannot be ignored. Further, it is found that the damping ratios of fruit trees are quite larger than those of civil and building structures due to the external damping effect. The wires attached to the trees in the steel pipe fence prop increase both stiffness and damping ratios of trees.

The gust effect factor analysis results indicate that the total wind load can be underestimated noticeably if the flexible nature of trees is neglected. If the empirical formula that does not require the exact values of natural frequency and damping ratio is used, the gust effect factor was overestimated considerably.

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