Gust Effect Factor for Wind Load Estimation of Tree Supporting Systems

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Abstract

Strong winds have caused an increasing amount of damage to fruit trees, such as uprooting and fruit drop, and various prop systems or support systems have been introduced to prevent this wind damage. When a prop system is designed against strong winds, it is essential to calculate the wind load acting on each tree in order to accurately assess the wind resistance of the prop system. In particular, the fluctuating effect is significant and cannot be ignored when the natural frequency of a tree is relatively small. In this study, vibration tests were performed to measure the natural frequencies and damping ratios of trees in order to evaluate the wind load acting on the trees. Both ambient and free vibration tests were performed, and the dynamic properties were identified and compared. It was found that the average natural frequency of trees was approximately 1.0 Hz, and therefore the dynamic effect against fluctuating wind load needs to be considered. The analysis results of the gust effect factor indicated that the wind load may be underestimated or overestimated considerably if the flexible nature of trees is neglected, or if the exact values of natural frequency and damping ratio are not available.

Keywords: wind load; tree supporting system; gust effect factor; ambient vibration test; system identification

1. Introduction

Typhoons have caused an increasing amount of wind damage to fruit trees in orchards, such as uprooting and fruit drop, in Korea. 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 this wind damage and to enhance the uprooting moment capacities of trees in orchards, the windbreak forest and various prop systems, or supporting systems, have been introduced in fruit orchards (He and Hoyano, 2010). The three most common types of apple tree prop systems used in Korea are: 1) the individual prop system; 2) the steel pipe fence-type prop system; and 3) the concrete column fence-type prop system.

However, for the most part, these prop systems have not been developed for trees subjected to strong tropical storms such as typhoons (Lespinasse and Delort, 1986). Further, most studies on fruit tree prop systems have focused mainly on annual yield and profits (Robison et al., 2007, Palmer et al., 1992). Therefore, it is necessary to evaluate the wind resisting performance of fruit tree prop systems that are frequently used in Korea.

When a prop system is designed to withstand strong winds, it is essential to calculate the wind load acting on each tree in order to accurately evaluate the wind resistance of the prop system. The applied wind load acting on a tree is often treated as a static load and beam theory is used 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). Under these conditions, the dynamic effects are likely to increase the bending of stems and hence the maximum bending moment at the base of the tree. Therefore, they need to be considered carefully when the natural frequency of a tree is relatively small, that is, when 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 the wind
engineering theory. In many design codes or standards, this dynamic effect is considered by incorporating the gust effect factor in the wind load calculation, and empirical formulae for the factor are given as functions of the natural frequency and damping ratio. The threshold natural frequency used in most design codes to take into account the dynamic effect of fluctuating wind load is 1.0 Hz (AIJ, 2009, ASCE, 2010).

In this paper, experiments to measure the natural frequencies and damping ratios of fruit trees were carried out in order to evaluate the wind load acting on the trees. Both ambient vibration tests and free vibration tests were performed, and the dynamic properties were identified and compared. The dynamic properties were also calculated using empirical formulae provided in the literature, and these were compared with the experimental results. Next, the gust effect factors for each tree were calculated using the formula provided in the Korean Building Code, hereinafter referred to as KBC2009 (AIK, 2009), and compared with calculation results using an empirical formula provided in the literature.

2. Wind Load on the Tree Supporting System

2.1 Wind Load on a Tree

Fig. 1. (a) shows a schematic drawing of the steel pipe fence-type prop system used in this study, which is the type of prop system most commonly used in apple orchards in Korea, and Fig. 1. (b) shows the key dimensions of the prop system. Three to five trees are planted between two vertical pipes spaced 6 m apart, and the wind load acting on the trees is transferred to the vertical supports by means of horizontal wires installed at 80 cm height intervals. As the stiffness in the longitudinal direction (the direction of the wires and row of trees) is much larger than that in the normal direction (at 90 to the direction of the wires and row of trees), uprooting damage generally occurs in the normal direction and most trees connected to a fence are damaged simultaneously.

The overall wind-induced uprooting moment resisting capacity, $M_{ut}$, of the steel pipe fence-type prop system is given by

$$ M_{ut} = \sum M_i + \sum M_p $$

(1)

where $M_i$ and $M_p$ are the uprooting moment resisting capacities of the trees and vertical pipes, respectively. The wind-induced uprooting moment resisting capacity required of the steel pipe fence-type prop is decided such that the prop resists the difference between the wind-induced moment acting on trees and the uprooting moment resisting capacities of trees.

Values of the uprooting moment resistance capacities of trees, $M_i$, are commonly obtained from winching experiments, in which a cable attached to a tree is pulled by a winch measuring the tensile force of the cable (Crook and Ennos, 1996). The wind-induced moment acting on a tree, $M_w$, can be calculated using the following equation, assuming that the wind load acting on the tree is transferred to the wires in the form of point loading (Fig. 2.).

$$ M_w = P_1l_1 + P_2l_2 + P_3l_3 + P_4l_4 $$

(2)

where $P_1$, $P_2$, $P_3$, and $P_4$ are the wind loads (N) acting on the wires, and $l_1$, $l_2$, $l_3$, and $l_4$ are the heights above the ground (m) of the corresponding wires.

As the wind loads transferred to the wires are proportional to the allotted area of the tree, the formula for the wind-induced moment acting on a tree, $M_{ut}$, in Eq. (2) can be re-written as

$$ M_{ut} = P \times \frac{A_1l_1 + A_2l_2 + A_3l_3 + A_4l_4}{A} $$

(3)

where $P = P_1 + P_2 + P_3 + P_4$ is the total wind load acting on the tree, and $A = A_1 + A_2 + A_3 + A_4$ is the total...
projected area (m²) of the tree.

The total wind load acting on a tree, \( P \), can be calculated using the following formula (Simiu and Scanlan, 1996)

\[
P = q_w A \quad (4)
\]

where \( q_w \) is the wind pressure (N/m²). The wind pressure, \( q_w \), is given by

\[
q_w = 0.5 \rho C_D G_f V_z^2 \quad (5)
\]

where \( \rho \) is the air density (kg/m³), \( C_D \) 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/s).

The drag coefficient of a tree used in Eq. (5), \( C_D \), is generally obtained experimentally by using a wind tunnel, and some typical values have been provided for various tree types (Mayhead, 1973; Vollsinger et al., 2005). On the contrary, few studies have been carried out to determine the gust effect factor of trees, \( G_f \), as it is affected by many factors including tree species, age, height, stem diameter, and spacing (Gardiner et al., 2000). In this study, the gust effect factor was obtained and analyzed using empirical formulae provided in the literatures as well as design codes based on wind engineering theory.

**2.2 Gust Effect Factor**

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

\[
G_f = \frac{X_{\text{max}}}{X} = 1 + g_f \frac{\sigma_y}{X} \quad (6)
\]

where \( X_{\text{max}} \) is the maximum response, \( X \) is the mean response, \( g_f \) is a peak factor, and \( \sigma_y \) is the standard deviation of the response.

Gardiner et al. (2000) proposed the following empirical formula to calculate \( G_f \) obtained from the wind tunnel tests by using scaled tree models.

\[
G_{\text{max}} = \left( 2.7193 \frac{S}{H} - 0.061 \right) + \left( -1.273 \frac{S}{H} + 0.9701 \right) \left( 1.1127 \frac{S}{H} + 0.0311 \right)^{x/H}
\]

\[
G_{\text{mean}} = \left( 0.68 \frac{S}{H} - 0.0385 \right) + \left( -0.68 \frac{S}{H} + 0.4875 \right) \left( 1.7239 \frac{S}{H} + 0.0316 \right)^{x/H}
\]

\[
G_f = \frac{G_{\text{max}}}{G_{\text{mean}}} \quad (7, \ a, \ b, \ and \ c)
\]

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

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

\[
G_f = 1 + \psi \sqrt{k_1 + k_2} \quad (8)
\]

where \( \psi \) is the peak factor (dimensionless), \( \phi \) is the exposure factor (dimensionless), \( k_1 \) is the background turbulence factor (dimensionless), and \( k_2 \) is the gust resonant factor (dimensionless).

The peak factor, \( \psi \), depends on the natural frequency of the structure, i.e., it increases as a logarithmic function of the natural frequency of the structure increases. Further, the gust resonant factor, \( k_2 \), is also a function of the natural frequency of the structure. In addition, the damping ratio of the structure affects the gust resonant factor. Consequently, accurate evaluations of the natural frequency and damping ratio are critical for the gust factor calculation.

Eq. (8) has been adopted for many design codes, including KBC2009. The peak factor, \( \psi \), and the exposure factor, \( \phi \), in KBC2009 are given as

\[
\psi = \sqrt{2 \ln(600v_f) + 1.2} \quad (9)
\]

\[
\phi = \frac{3 + 3 \alpha}{2 + \alpha} I_z \quad (10)
\]

where \( \alpha \) is the power law exponent of mean wind speed profile for a given terrain roughness category, and \( v_f \) and \( I_z \) are, respectively, the level crossing number and turbulence intensity at the reference height given as

\[
v_f = n_0 \sqrt{\frac{k_2}{k_1 + k_2}} \quad (11)
\]

\[
I_z = 0.4 \left( \frac{z}{Z_g} \right)^{a-0.05} \quad (12)
\]

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

\[
k_1 = 1 - \frac{1}{\left[ 1 + 5.1L_H \sqrt{HB}/H \right]^3 (B/H)^{0.33}} \quad (13)
\]

\[
k_2 = \frac{\pi}{4 \varepsilon_f} S_f F_s \quad (14)
\]

where \( B \) is the width of the structure, \( \varepsilon_f \) 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

\[
S_f = \frac{0.84}{[1 + 2.1(n_0 H/V_H)] [1 + 2.1(n_0 B/V_H)]} \quad (15)
\]
where $V_H$ is the design wind speed at the top of the structure.

A structure with a natural frequency of greater than 1.0 Hz is classified as a rigid structure with the gust resonant factor, $k_s$, being omitted and the value of the exposure factor, $\varphi$, as the value 4 from Eq. (8). The resulting formula for the rigid structure is

$$G_f = 1 + 4\varphi_0\sqrt{FS_k}$$  \hspace{1cm} (17)

2.3 Natural Frequency and Damping Ratio of Trees

From Eqs. (11), (15), and (17), it can be seen that the natural frequency is required for the gust effect factor calculation. Further, it can be seen from Eq. (14) that the damping ratio is also required.

Moore and Maguire (2004) investigated the natural frequency measurement of 602 trees belonging to eight different species reported in the literatures, 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 for the natural frequency of trees, $n_{01}$, based on a regression analysis.

$$n_0 = 0.0766 + 3.1219 \frac{D_{bh}}{H^2}$$  \hspace{1cm} (18)

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

They proposed another empirical formula to consider the difference in species of tree, given by Eq. (19).

$$n_0 = 0.0948 + 3.4317 \frac{D_{bh}}{H^2} - 0.7765 I_p \frac{D_{bh}}{H^2}$$  \hspace{1cm} (19)

where $I_p$ is an indicator variable. 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, and divided it into two categories: 1) internal damping due to the friction of the root-soil connection, the movement of branches, and the internal friction of the wood, and 2) external damping due to the aerodynamic drag of the crown and 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 dependent on the wind velocity and much larger than the internal damping.

3. Field Measurement of Natural Frequencies and Damping Ratio

3.1 Test Specimens and Methods

Vibration tests were performed in the field to measure the natural frequencies and damping ratios of orchard trees. The specimen trees consisted of apple trees. Both ambient vibration tests and free vibration tests were performed and the dynamic properties were identified and compared.

Fig. 3. is a photograph showing the tree specimens used for the field vibration test. The trees were supported by a steel pipe fence-type prop system and four to five trees were planted between two vertical steel pipes. The test was performed when the trees were heavy with clusters of apples as typhoons occur mostly before and during the harvest season. A total of 20 tree specimens underwent testing.

| Specimen  | $D_{bh}$ (cm) | $B$ (m) | $H$ (m) |
|-----------|--------------|--------|--------|
| T1        | 8.59         | 1.93   | 2.56   |
| T2        | 5.12         | 1.69   | 2.57   |
| T3        | 5.73         | 1.60   | 2.80   |
| T4        | 5.51         | 1.63   | 2.75   |
| T5        | 7.07         | 1.47   | 2.80   |
| T6        | 6.14         | 1.48   | 2.48   |
| T7        | 6.65         | 1.71   | 2.78   |
| T8        | 7.54         | 1.49   | 2.43   |
| T9        | 5.76         | 1.48   | 2.66   |
| T10       | 5.95         | 1.55   | 2.61   |
| Average   | 6.41         | 1.55   | 2.64   |

Table 1. Dimensions of Unsupported Trees

| Specimen  | $D_{bh}$ (cm) | $B$ (m) | $H$ (m) |
|-----------|--------------|--------|--------|
| T11       | 12.35        | 2.12   | 3.90   |
| T12       | 7.73         | 1.67   | 3.24   |
| T13       | 7.07         | 1.32   | 3.15   |
| T14       | 5.09         | 1.12   | 3.29   |
| T15       | 9.20         | 1.81   | 3.11   |
| T16       | 6.72         | 1.58   | 2.97   |
| T17       | 7.86         | 1.47   | 3.22   |
| T18       | 7.10         | 1.29   | 2.84   |
| T19       | 8.44         | 1.65   | 3.18   |
| T20       | 10.19        | 1.74   | 3.33   |
| Average   | 8.17         | 1.58   | 3.22   |

Table 2. Dimensions of Supported Trees

In order to analyze the effect of the prop on the dynamic properties of trees, half of the trees were tested after cutting all horizontal wires connected to the trees, while the prop for the rest of specimens remained intact. Tables 1. and 2. summarize the important tree dimensions for all specimens.

For the unsupported trees without a prop, two piezoelectric accelerometers were installed at a height 1.5 m, one placed in the longitudinal direction (x-direction hereinafter) and the other placed in the normal direction (y-direction hereinafter) to measure
the accelerations experienced by the trees. On the other hand, only one accelerometer was used in the y-direction for the supported trees with a prop, because the frequency in the x-direction is considerably affected by the prop because of its large stiffness.

The ambient vibration tests were carried out for 10 min at a sampling frequency of 360 Hz. The free vibration tests were performed by simply pushing the trees slowly by hand to a distance of approximately 30 cm, and then releasing them so that they vibrated freely. Five human-induced free vibrations were performed continuously in both the x- and y-directions for the unsupported trees, while these were performed only in the y-direction for supported trees. To identify the dynamic properties from the free vibration test, only the acceleration measured in the same direction as the free vibration direction was used.

### 3.2 Identified Natural Frequencies and Damping Ratios

Fig.4. shows, for unsupported tree specimen T5, the measured acceleration time histories from the ambient vibration test for the first 20 s. Fig.5. shows, also for T5, those from the free vibration test for the entire test period. As can be seen from Figs.4. and 5., the magnitudes of accelerations measured in the ambient vibration test are significantly smaller than those measured in the free vibration test.

![Fig.4. Acceleration Time Histories from the Ambient Vibration Test for Specimen T5](image)

![Fig.6. PSDs of Accelerations from the Ambient Vibration Test for Specimen T5](image)

![Fig.5. Acceleration Time Histories from the Free Vibration Test for Specimen T5](image)

The power spectrum densities (PSDs) of the measured accelerations from the two test methods were obtained to identify the natural frequencies of trees. Subsequently, 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). Figs.6. and 7. present the PSDs of measured accelerations from the ambient vibration test and free vibration test, respectively, for the test specimen T5.

It can be seen from Figs.6. and 7. that the peaks of PSDs were clearly evident at the fundamental natural frequencies for both ambient and free vibration tests, while the values of PSDs for the ambient vibration test contain the higher modes and direct current contents. The clear distinction of PSDs near the fundamental frequency apparent in the graph for 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 obtained for all test specimens are summarized in Tables 3. and 4. Note that for the supported trees in Table 4., only results of natural frequencies in the y-direction are given as acceleration was only measured in that direction.

As can be seen from Table 3., the natural frequencies of trees in the x- and y-directions were similar, other
The natural frequencies of the supported trees were found to be higher than those for the unsupported trees. They were, on average, 15.73% and 13.70% higher (Table 4.). These results show that the stiffness of the steel pipe fence-type prop helped in increasing the stiffness of trees in the y-direction. That is, the overall uprooting moment resistance capacities of trees were increased because of the installation of the prop.

The natural frequencies of trees calculated using the empirical formulae provided in Eqs. (18) and (19) are presented for comparison with the natural frequencies identified by experiment. The dimensions presented in Table 1. were used for the calculation. Compared with the natural frequencies identified by experiment provided in Tables 3. and 4., the empirical formulae proposed by Moore and Maguire overestimated the natural frequencies by up to 234%. Therefore, it can be concluded that the empirical formulae are not relevant for every genus of tree even though they were obtained from more than 600 experimental data.

**Table 3. Identified Natural Frequencies of Unsupported Trees in x- and y-directions**

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

**Table 4. Identified Natural Frequencies of Supported Trees in 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 5., the natural frequencies of trees found to be higher than those for test specimens T3, T8, and T9. The trunks of test specimens T3, T8, and T9 are bent considerably, and thereby the natural frequencies of those trees in the x- and y-directions were slightly different to each other. It can also be seen that the identified natural frequencies obtained from the free vibration tests were generally lower than those obtained from the ambient vibration tests. This is due to the fact that the natural frequency of a structure is generally inversely proportional to its response amplitude, and the amplitudes of the measured accelerations in the free vibration test were significantly larger than those identified by experiment provided in Tables 3. and 4.. The identified natural frequencies from the ambient vibration tests are 3.90% and 6.06% lower in the x- and y-directions, respectively, than those obtained from the ambient vibration test.

The natural frequencies of trees identified by experiment provided in Tables 3. and 4., the empirical formulae proposed by Moore and Maguire overestimated the natural frequencies by up to 234%. Therefore, it can be concluded that the empirical formulae are not relevant for every genus of tree even though they were obtained from more than 600 experimental data.

**Table 5. Natural Frequencies of Trees Obtained from Empirical Formulae**

| Specimen | Eq. (18) (Hz) | Eq. (19) (Hz) | Specimen | Eq. (18) (Hz) | Eq. (19) (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 6. Identified Damping Ratios of Unsupported Trees in x- and y-directions**

| Specimen | Ambient vibration test x-dir. (%) | y-dir. (%) | Free vibration test x-dir. (%) | y-dir. (%) |
|----------|----------------------------------|------------|-------------------------------|------------|
| T11      | 6.53                            | 7.68       | 4.63                          | 3.05       |
| T12      | 6.56                            | 7.04       | 11.10                         | 16.41      |
| T13      | 7.35                            | 6.10       | 7.42                          | 8.90       |
| T14      | 7.18                            | 3.79       | 8.62                          | 7.03       |
| T15      | 6.86                            | 7.21       | 9.73                          | 7.03       |
| T16      | 6.48                            | 7.05       | 7.82                          | 11.10      |
| T17      | 3.54                            | 5.60       | 9.52                          | 9.61       |
| T18      | 7.92                            | 6.62       | 6.98                          | 14.59      |
| T19      | 3.49                            | 6.36       | 9.84                          | 7.78       |
| T20      | 4.15                            | 5.74       | 5.95                          | 5.86       |
| Average  | 6.01                            | 6.32       | 8.16                          | 9.06       |

Tables 6. and 7. present the damping ratios identified by experiment for the unsupported and supported trees, respectively, from the ambient and free vibration tests. As can be seen from Table 6., the identified damping ratios for the unsupported trees obtained in the free vibration tests were significantly higher than those obtained in the ambient vibration test. They were, on
average, 35.88% higher in the x-direction and 43.22% larger in the y-direction. This is due to the fact that external damping as well as internal damping plays a role when trees are oscillating with large magnitudes, as predicted by Moore and Maguire. The average damping values of 6.01% and 6.32% obtained from the ambient vibration tests closely match the internal damping value of 5% provided by Moore and Maguire.

Furthermore, the damping ratios for the supported trees, shown in Table 7., were 20.88% and 49.92% higher than the damping ratios of the unsupported trees, shown in Table 6., 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-type prop increase not only the stiffness but also the damping ratios of trees.

### 3.3 Gust Effect Factor Evaluations

The gust effect factors were calculated for the unsupported and supported trees, and the results are summarized in Tables 8. and 9., respectively. The formula for non-rigid structures in Eq. (8) was utilized as the identified natural frequencies of trees were approximately 1 Hz.

#### Table 7. Identified Damping Ratios of Supported Trees in 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                  |

For comparison, both the results of the empirical formula provided in Eq. (7), proposed by Gardiner et al., and rigid structures in Eq. (17) are also presented in Tables 8. and 9. For Eq. (8), the natural frequencies and damping ratios identified from the ambient vibration test were used, as the smaller damping ratios yield a more conservative wind load estimation. For Eq. (7) the tree spacing was set to 1.5 m, and the distance from the forest edge was assumed to be zero, also for a conservative estimation.

The empirical formula proposed by Gardiner et al. (Eq. (7)) yielded 27.41% to 31.96% larger gust effect factors compared to those provided by the formula for non-rigid structures (Eq. (8)). These discrepancies of empirical formulae may be due to the fact that these formulae must cover various species and include some allowance.

It was also found that the gust effect factors obtained using Eq. (17) were 14.27% to 16.63% smaller than those obtained using Eq. (8). Therefore, if the flexible nature of trees is neglected as in Eq. (17), which is for rigid structures, the total wind load can be underestimated considerably.

It is known that Eq. (8) for non-rigid structures by Davenport and Surray is most accurate for estimating gust effect factor because it reflects the exact values of natural frequency and damping ratio. Therefore, it can be concluded that empirical formula and the formula approximated for rigid structures, by not taking into account the exact values of natural frequency and damping ratio of the specific tree species, may overestimate or underestimate the gust effect factors of trees considerably.

#### 4. Conclusions

The gust effect factors of trees were analyzed in order to estimate the wind load of the tree supporting system. As the value of the gust effect factor depends on the natural frequency and damping ratio, field experiments were performed to identify these dynamic properties of the trees accurately.

The field test conducted on 20 apple trees, of which half of the specimens were tested without a prop (unsupported), while the other half of specimens were tested with a prop (supported). Both ambient vibration tests and free vibration tests were performed and the dynamic properties were identified and compared.

It was found that the average natural frequency of fruit trees was approximately 1.0 Hz, and therefore the dynamic effect against fluctuating wind load needs to be considered carefully. Further, it was found that the damping ratios of fruit trees were significantly larger than those of civil and building structures because of the external damping effect. For the supported trees, the wires attached to the trees increased both the stiffness and damping ratios of trees.
The results of the gust effect factor analysis indicated that the total wind load could be underestimated significantly if the flexible nature of trees was not taken into account. If the empirical formula not requiring the exact values of natural frequency and damping ratio was used, the gust effect factor was overestimated considerably.

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