Supplementary material

Jennifer L. Cardona and John O. Dabiri

S1. Model sensitivity to turbulence intensity, sway amplitude definition, and averaging period

The results presented in section 3.2 assumed constant I_u in order to directly relate $\bar{U}$ and the structural sway, since I_u would be unknown in most engineering applications of the presently proposed anemometry method. However, the derived physical model (equation 16) suggests that sway amplitude should depend on I_u. Section S1.1 discusses the results of including the variable I_u. Model sensitivity is also evaluated with respect to other parameters including the definition of sway amplitude (section S1.2), and the time averaging window (section S1.3). A summary of these results is given in table S1 and is described in section S1.4.

S1.1. Incorporating turbulence intensity

Figure S1 shows the distributions of I_u (a-c), and plots of I_u versus $\bar{U}$ (d-f) for the trees in each of the three data logger groups. The most common value of turbulence intensity in the forest was approximately 25%, and it decreased with increasing wind speed. These trends are expected in comparison with the lower turbulence intensity measured for higher winds in the open field. Nonetheless the scaling predicted by the model in equation 12 which assumes $u' << \bar{U}$ remains effective when applied to the forest data. To analyze the effects of a non-constant turbulence intensity, I_u was allowed to remain variable in equation 16 ($\bar{U} \propto \sqrt{\sigma(\varepsilon)/I_u}$). Figure S2b shows the results for a representative tree (tree #18) with the known values of I_u incorporated. These results can be compared to the baseline case assuming constant I_u (figure S2a). R^2 values are reported for all trees in table S1.

Allowing for variable I_u did not appear to improve model agreement compared to the baseline case. One possible explanation is offered by the range of wind speeds for these experiments, which is relatively low ($\bar{U} < 4$ ms^{-1}). This means that fluctuations have small magnitudes in dimensional terms and therefore a smaller effect on the tree structure dynamics. The higher values of I_u occurred at lower wind speeds (figure S1d-f), which would further contribute to this effect. Prior work also suggests that gusts at low wind speeds have little effect on tree sway for trees within forest canopies because of a lack of gust penetration into the canopy (Gardiner, 1994; Gardiner et al., 1997).

S1.2. Median absolute deviation as an alternative amplitude definition

As discussed in section 2.1, the standard deviation was chosen as a measure to represent the sway amplitude for the trees analyzed in this study. However, deflection or strain measurements over an averaging period do not follow perfectly normal distributions (figures 1e and 2b). It has been suggested that the median absolute deviation (MAD) may a be more robust measure of dispersion for non-normal data distributions, since it is less sensitive to long tails than σ (Ruppert, 2010). The median absolute deviation is calculated as:

$$\text{MAD} = \text{median}(|X_i - \text{median}(X)|) \tag{24}$$

where X_i are the population samples. MAD(ε) was applied to the strain gage measurements as an alternative measure of sway amplitude. Model agreement was robust to the choice of measure, as demonstrated in figure S2c and table S1, which show that results using MAD were very similar to the baseline case.

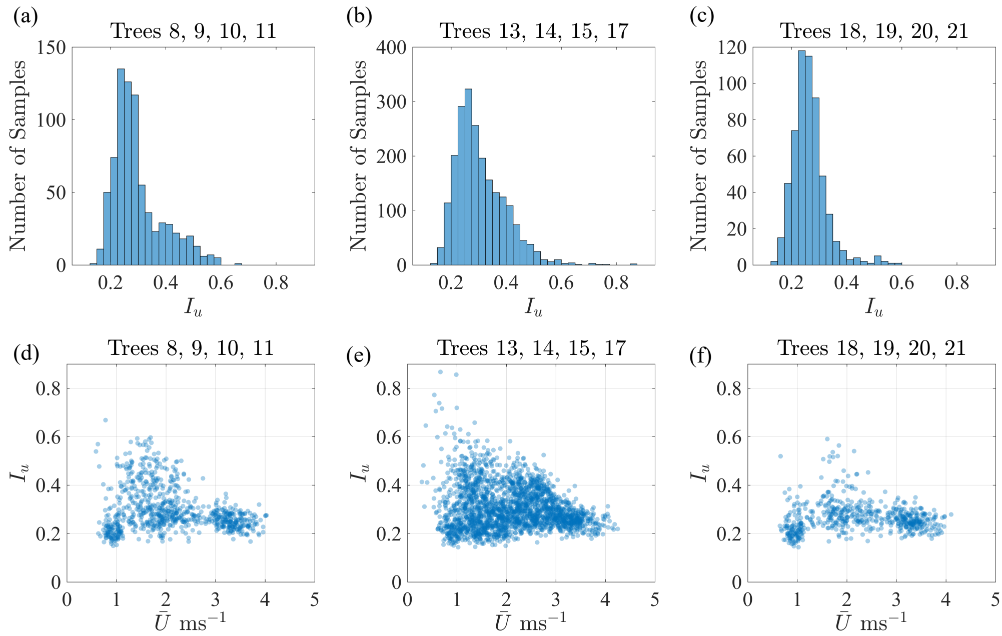

Figure S1. *(a-c) Histograms of I_u and (d-f) plots of I_u vs. $\bar{U}$ for trees grouped by data logger (i.e. separate panels show trees in subsets [8, 9, 10, 11], [13, 14, 15, 17], and [18, 19, 20, 21]).*

S1.3. Temporal averaging period length

The temporal averaging period is both a practical consideration in terms of data collection and processing time, as well as an important factor based on the potential applications. For the video dataset analysis described in section 2.2.1, a 1-minute averaging window was used, and model agreement was observed (figure 3). The abundance of data available in the Jackson (2018) dataset allowed for the selection of a longer time averaging period (10-minute periods were used in the baseline results shown in figures 4 and S2). The results from the application of 1-minute averaging windows are shown in figure S2d and table S1. The longer 10-minute averaging periods led to better agreement than 1-minute averaging periods. Model agreement with the shorter 1-minute averaging periods may have suffered due to the spatial separation between the anemometer used to measure $\bar{U}$ and the structures of interest (for many of the trees, it is located approximately 230 m away as detailed by Jackson et al. (2019)). The trees were also located within a forest, where hyper-local conditions may be spatially variable, especially over shorter timescales.

The choice of a 10-minute averaging window is still an appropriate averaging window to provide useful measurements of mean wind speed in the context of engineering applications. For instance, 10-minute averaging windows are common in wind speed measurements for wind energy applications (Mathew, 2006).

S1.4. Summary of results from model parameter changes

The results of adjusting model parameter choices are summarized in table S1, and a representative example is shown for tree #18 in figure S2. Including the variable turbulence intensity, I_u, did not appear to have a large impact on the results. However, as discussed in section S1.1, the range of mean wind speeds (and hence, the magnitude of fluctuations) was relatively low, which may have made effects difficult to detect in the swaying of trees of this size. The effect of I_u should be further considered in future studies, especially in cases where there is a substantial range of I_u at higher wind speeds. Model performance was also consistent with the baseline case when median absolute deviation (MAD) was used as an alternative to standard deviation in characterizing the sway amplitude. Model agreement was sensitive to the choice of time averaging period. The 10-minute averaging period proved to be a better choice compared to shorter 1-minute averaging periods in this case.

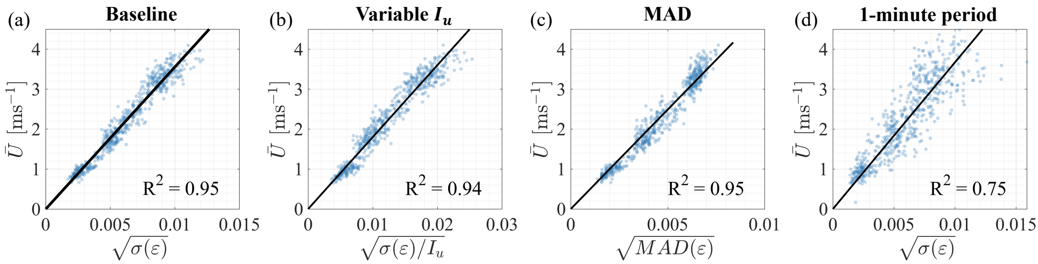

Figure S2. *Representative example showing experimental results compared to model relationship for tree #18 considering (a) the baseline case (constant I_u, σ defining sway amplitude, and 10-minute averaging windows); (b) the case allowing for variable I_u; (c) the case using median absolute deviation (MAD) to define sway amplitude instead of σ; and (d) the case using 1-minute time averaging periods instead of 10-minute averaging periods.*

Table S1. *R^2 values for best-fit line compared to experimental data for each tree. Results are reported for the model applied in the baseline case (constant I_u, σ defining sway amplitude, and 10-minute averaging periods), the case allowing for variable I_u, the case using median absolute deviation (MAD) to define sway amplitude, and the case using 1-minute time averaging period instead of 10-minute averaging period.*

Tree ID #	Species	R^2 (Baseline)	R^2 (Variable I_u)	R^2 (MAD)	R^2 (1-min. avg. period)
8	Ash	0.89	0.90	0.90	0.56
9	Ash	0.88	0.83	0.90	0.47
10	Ash	0.91	0.87	0.91	0.56
11	Ash	0.90	0.87	0.90	0.53
13	Ash	0.11	0.24	0.09	0.18
14	Ash	0.80	0.71	0.81	0.43
15	Sycamore	0.69	0.83	0.74	0.37
17	Ash	0.85	0.89	0.86	0.47
18	Birch	0.95	0.94	0.95	0.75
19	Birch	0.94	0.91	0.94	0.79
20	Birch	0.95	0.95	0.96	0.74
21	Birch	0.94	0.95	0.96	0.71