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On the calibration of the logarithmic mean wind profile based on experimental data

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SUMMARY:
This paper investigates the uncertainty associated with the calibration of the logarithmic mean wind profile based on wind Lidar measurements, and its propagation to the base shear and moment of medium- to high-rise buildings. First an absolute minimum problem is solved to find the optimum parameters z_0^{opt} and d^{opt} . Then a constrained minimum problem is also solved to build a skeleton curve of the possible pairs z_0 and d well fitting the experimental measurements. It is found that the uncertainty of the measured profiles with respect to the optimum one is low, and it reduces when it propagates to the loads. Finally a probabilistic model is set up to account for the randomness of the optimum parameters along the skeleton curve, and of its effect on base shear and moment.

Keywords: mean wind profile, calibration with full scale data, uncertainty in wind loads

1. INTRODUCTION

Different analytical models are available to describe mean wind speed profiles, some of which have been borrowed by codes of practice. The current version of Eurocode 1, EN1991-1-4:2005 (CEN, 2005), for example, prescribes the use of a logarithmic profile; in flat orography, this is governed by three parameters: an intensity parameter given by the basic wind velocity v_b, a roughness parameter z_0, and, for buildings in terrain category IV, a displacement height d. While calibration of the basic wind velocity requires statistical analyses of historical records and therefore contains aleatory uncertainty, both z_0 and d are expected to be constant with time and vary with direction. Their experimental calibration, therefore, can be again attempted based on experimental data, but with a relatively small number of recorded profiles for each direction, provided these are all associated with sufficiently high winds, such to guarantee neutral conditions. To this aim, in a recent paper (Sepe et al., 2023) the ability of available wind Lidars to provide data useful for the calibration of the parameters z_0 and d of the logarithmic law, was discussed by use of pseudoexperimental profiles.

This paper deals with the uncertainties arising from calibration of the logarithmic law based on wind Lidar measurements, and on how these propagate to the resultant loads on medium- to high-rise buildings in urban area. What emerges when recorded 10-minutes wind profiles nominally equivalent, i.e. selected with close intensities and mean wind directions in the same meteorological strong event, are used to identify the shape parameters of a logarithmic law. A procedure is then proposed to obtain the optimal values of z_0 and d, and their confidence interval.

2. EXPERIMENTAL CAMPAIGN AND AVAILABLE DATA

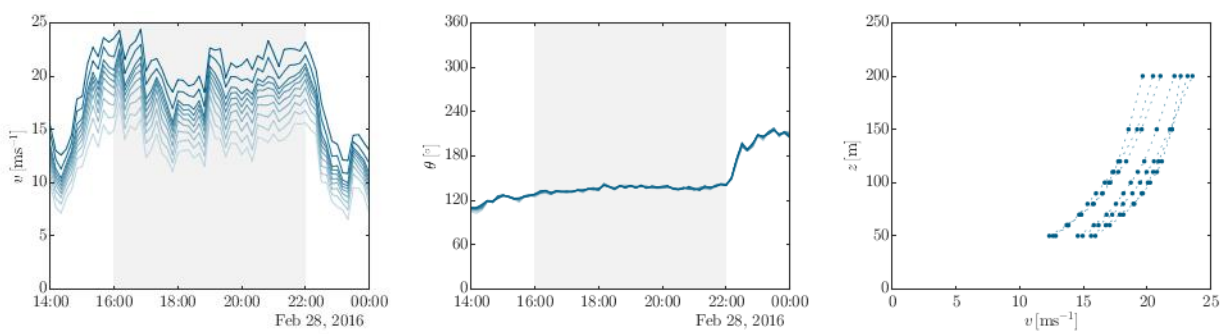
The experimental campaign was performed using a Leosphere WindCube® V2 wind Lidar, operating as a pulsed Doppler anemometer. The laser beam is inclined by 30° from the vertical direction and rotates in about 6 seconds around the vertical axis taking measures at four different azimuth angles, each separated by 90°, that are then used to derive the wind velocity vector; for a given angle, simultaneous measurements were taken at twelve different heights z_i = 50, 60, 70, 80, 90, 100, 110, 120, 150, 200, 220 and 250 m above ground. The device was located on the roof of a 2-story building of the University of Campania "L. Vanvitelli" in Aversa, Italy (40°58'00''N, 14°12'00''E). Measurements were taken with a sampling rate of 1 Hz. The experimental campaign lasted between October 2015 and December 2016. From the recorded time histories, 10-min averaged wind speeds and directions were obtained at the selected heights.

Purpose of this paper is to illustrate a procedure for calibrating the mean wind profile, and for assessing the associated uncertainty. To this aim, only one storm was considered in the analyses, characterized by two features. First is about intensity, high enough to ensure neutral conditions, i.e. the validity of the logarithmic profile:

$$v(z) = \frac{u^*}{k} \cdot \ln\left(\frac{z-d}{z_0}\right) \quad (1)$$

$\kappa = 0.4$ being the von Karman constant. According to the Pasquill stability classes (Wieringa, 1973), when wind speed at 10 m from ground is larger than approximately 6 m/s, then the atmosphere is in neutral conditions irrespective of cloud cover, time of day or season of the year. Roughly, this corresponds to 10 m/s at 50 m from the ground in urban roughness class. Second feature of the selected profile is a small variation of direction from one height to another.

According to these criteria, data from a storm occurred on February 28th, 2016 were used, whose time histories of wind speed and direction are shown in Figure 1a and 1b, respectively. The hatched area, spanning 6 hrs, contains 37 values of the 10-min averaged wind speed and direction; wind speed at 50 m ranged between 11.0 m/s and 17.5 m/s; mean direction was 125° at beginning of the event and 143° at the end of the event, respectively, and the difference between the maximum θ_{max} and the minimum θ_{min} directions within the same profile was always lower than 5°. As an example, seven of the recorded profiles are also shown in Figure 1c.



(a) (b) (c)

Figure 1. Time histories of the 10 min averaged wind speed (a) and direction (b) at 12 measurement heights; seven out of the 37 measured profiles (c).

3. UNCERTAINTY IN THE MEAN WIND PROFILE AND RESULTANT LOADS

In order to calibrate the optimum pair of values (z_0, d), an optimization problem is set up. This is based on the assumption that all the wind profiles belonging the same event, and to other events having the same mean wind direction must have the same roughness length z_0 and the same displacement height d, therefore only epistemic uncertainty is considered in their evaluation. Under this hypotheses, the wind speeds $v_i(z_j)$ at height z_j for the i-th of N profiles belonging to the selected event are proportional to the friction velocity u_i^*. The solution of the optimization problem is:

$$\left(z_0^{opt}, d^{opt}\right) = \arg\min \frac{1}{N}\frac{1}{M}\sum_{i=1}^{N}\sum_{j=1}^{M}\left(u_i^*(z_0, d) - k\,\frac{v_{ij}}{\zeta_j(z_0,d)}\right)^2 \tag{2}$$

where M is the number of measurement heights, $\zeta_j(z_0, d) = \ln\left(\left(z_j - d\right)/z_0\right)$, and where u_i^* is a function of the pair (z_0, d), evaluated for the i-th wind profile by solving:

$$\arg\min \frac{1}{M}\sum_j^M\left(u^* - k\,\frac{v_{ij}}{\zeta_j(z_0,d)}\right)^2 \tag{3}$$

The above optimization problem is found to correspond to the problem of optimizing the parameters (z_0, d) for the standardized mean wind profile $\eta(z) = \bar{v}(z)/\bar{v}(z_{ref}$, being $\bar{v}(z) = \sum_N v_i(z)/N$. The reference height z_{ref} can be chosen equal to the lowest measurement height, i.e. 50 m for the dataset used in this paper. The optimization problem is thus set up:

$$\left(z_0^{opt}, d^{opt}\right) = \arg\min \frac{1}{N}\frac{1}{M}\sum_{i=1}^{N}\sum_{j=1}^{M}\left(\eta_{ij} - \frac{\zeta_j(z_0,d)}{\zeta_{50}(z_0,d}\right)^2 \tag{4}$$

where $\eta_{ij}(z) = v_i(z_j)/v_i(z_{50})$.

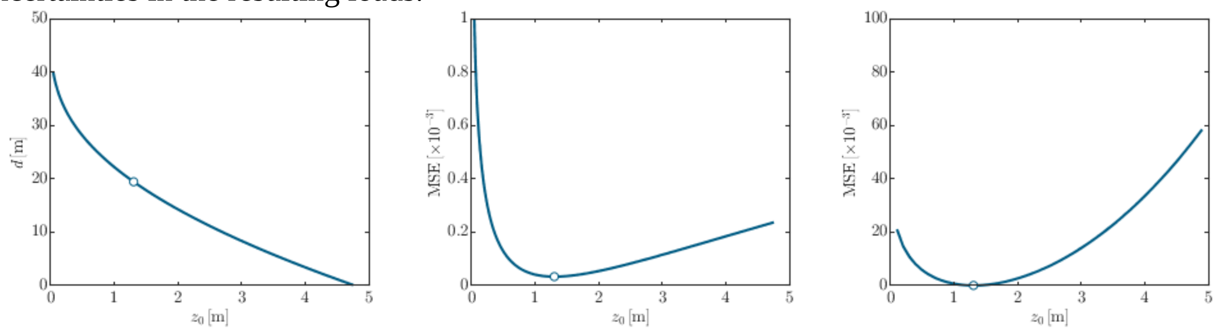
For a given d^* different from the optimum value of eq. (4), the objective function attains a constrained minimum, $z_0^* = f(d^*)$. The points (z_0^*, d^*) define a curve denoted in the following as *skeleton curve* (figure 2a) that contains the point (z_0^{opt}, d^{opt}). It is observed that the gradient of the objective function (i.e. the Mean Squared Error) along the skeleton curve (figure 2b, as a function of z_0^*), is much smaller than the gradient in the direction orthogonal to the skeleton curve (figure 2c). This introduces an intrinsic uncertainty in the identification of the absolute minimum (corresponding to $z_0 = 1.30$ m and $d = 19.5$ m in figure 2b), whose accuracy depends on the number N of available profiles, but also suggests that only the uncertainty along the skeleton curve is considered in the analyses.

Propagation of the uncertainty to the mean non-dimensional base shear and moment:

$$\tau^* = \frac{1}{H}\cdot\int_0^H c_r^2(z)\,\mathrm{d}z \tag{5}$$

$$m^* = \frac{1}{H^2}\cdot\int_0^H c_r^2(z)\cdot z\,\mathrm{d}z \tag{6}$$

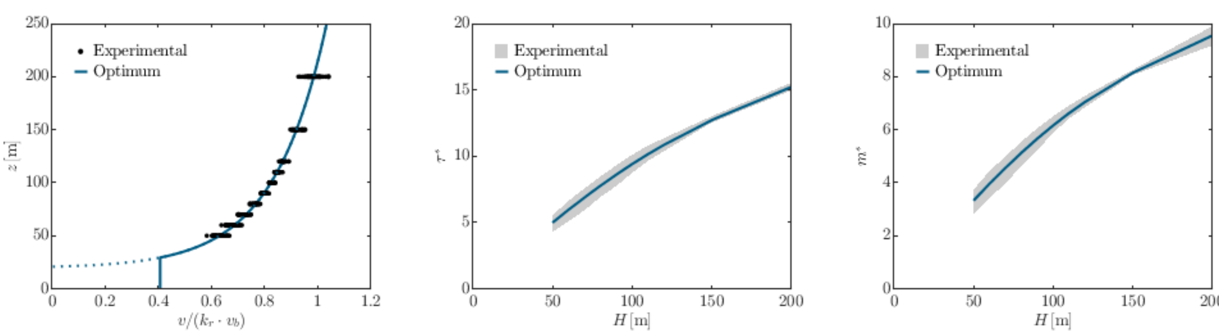
is first evaluated considering only the randomness of each measured profile with respect to optimum profile (z_0^{opt}, d^{opt}), see figure 3a. The difference between the optimum and the measured profiles is a measure of the uncertainty arising from the experimental calibration of z_0 and d. Propagation of this uncertainty to base shear and moment of tall buildings for a given value of v_b is shown in figures 3b and 3c, respectively, as a function of the building height. It appears that the small uncertainty on the wind profile of figure 3a translates in even lower uncertainties in the resulting loads.



(a) (b) (c)

Figure 2. Skeleton curve (a), gradient of error along (b) and orthogonal (c) to the skeleton curve.

Second step is that of investigating the effects of the uncertainty on the optimum values of z_0 and d along the skeleton curve; this is done by calibrating a probabilistic model for the optimum profile parameters, and investigating the effect of their randomness on the resulting load.



(a) (b) (c)

Figure 3. Uncertainty in the wind profile (a) and in the mean nondimensional base shear (b) and moment (c).

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