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Long term simulation of wind-induced fatigue loadings

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ABSTRACT

This paper deals with the fatigue analysis of slender structures subjected to the wind action. A 50-year conditioned Monte Carlo simulation of the bending moment at the base of a steel lighting pole is performed. Long-term simulations of the static part of the bending moment, related to the mean wind speed, are combined with short-term fluctuations due to the turbulence. Multiple time series of the stress at the base of the pole, with length ranging between 10 min and 3 days, are generated and processed by means of the Rainflow counting algorithm. The resulting large size data set of the fatigue damage is analyzed in order to clarify some cloudy issues related to the fatigue analysis: the contribution to the damage of the low-frequency, large-amplitude cycles in the stress-time series; the contribution of the transition cycles between consecutive wind states; the length of the stress-time series necessary to get a reliable stress cycle histogram in the framework of the classical state approach; the variability of the damage resulting from a given mean wind speed; the variability of the annual damage.

1. Introduction

The wind loading on structures is a non-stationary, non-Gaussian random process. Typically, the fatigue analysis is based on the 'state approach', which breaks down the wind loading process into independent loading conditions characterized by given magnitude and incoming direction of the wind speed. For each loading condition, the fluctuating part of the effect induced by the wind turbulence is modeled as a stationary Gaussian process superimposed to the static part of the effect induced by the mean wind velocity. The long-term time variability of the mean static effect is lost when the wind loading process is broken down into the loading conditions; however, this variability is recovered through the probability distribution of the wind states.

Two approaches may be used to evaluate the structural effect due to a given wind loading condition. The first approach is an analytical method in the frequency domain. For a given wind loading condition, the structural effect in each loading condition is modeled as a stationary Gaussian processes, while the relative fatigue damage is evaluated through an analytical cycle-counting method. To this aim a suitable power spectrum of the load has to be chosen consistently with narrow-band hypothesis [1,2], or wide band hypothesis [3–6] or bi-modal hypothesis [7–9]. This approach is usually applied to derive engineering procedures for simple structures [10] but it is still enable to provide good results in the design of complex structures. The second approach is based on numerical methods in the time domain. The wind-induced structural effects in each loading condition are described through real measurements or synthetic time series of the stress of limited length. The fatigue damage is evaluated by processing the stress time series by means of numerical algorithms such as the Rainflow cycles counting algorithm (RCCA). Even though this approach is numerically time-consuming, it is widely used in different structural fields [11–15] and standards codes [16–18]. Time-domain approaches are commonly used as benchmark against which frequency-domain approaches are measured.

Regardless of the approach used to evaluate the wind-induced structural effect, some questionable issues affect the use of the state approach in the evolution of the fatigue damage. Firstly, as it is highlighted by Sutherland [19], the state approach decomposes the continues wind loading process into a series of independent loading conditions. Therefore, the low-frequency large-amplitude cycles, related to the macro-meteorological fluctuation of the wind speed, are completely disregarded as well as the transition cycles from two consecutive loading conditions. A second issue concerns the fatigue damage cumulated over 1 year, which is typically used to derive the fatigue lifetime of the structure. The annual damage should be modeled as a random variable [22,23], because of the large uncertainty [20,21], but a suitable probability distribution of the annual damage has not been identi-

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fied yet. A third issue concerns specifically the use of the state approach in combination with time-domain approaches. The real observed damage is usually smaller than the one evaluated by time-domain approaches [19,24], because the cycles counting algorithms are applied to stresses time series limited in length (duration). Furthermore, the total damage is affected by the stochastic variability of the partial damage related to a given loading condition [25,26]. Sutherland [19] demonstrated that the damage associated to the same loading conditions, stationary on 10-min time interval, can vary by two orders of magnitude. Finally, the width of the wind speeds and stress classes defined in the state approach is still under discussion [14].

It is worth noticing that several of the open issues listed above are applicable not only to wind-induced fatigue but also to others fatigue assessment methodologies based on random loading (e.g. [27]). In light of these points, and considering the strong non-linearity of the fatigue phenomenon, it is difficult to judge the effectiveness of the state approach usually adopted in practical applications without detailed studies.

Long-term simulations of the wind loading have been used to measure the effectiveness of the state approach. Kelley et al. [28] generated a series of 144, 10-min wind speed loading conditions that are likely to occur individually within 24-h at two distinct locations, discussing the effects of the diurnal loading variation on a wind turbine. Moriarty [29] simulated 5 years of operational wind turbine loading conditions, to test the techniques usually used in wind turbine design for loads extrapolation; he found out that discrete load cases currently represented in the standard can be reproduced by stochastic simulations as long as they are run for a sufficient length of time. More recently Barone et al. [30] generated 96 years of operational wind turbine load simulations. This huge amount of data has been used to assess extreme loads in design standards [31] but they still have not been used to analyze fatigue procedures.

In the line of these publications, this paper presents the assessment of the wind-induced fatigue damage at the base of a steel lighting pole, based on the generation of 50-year synthetic stress time series. Section 2 provides a short summary of the state approach. Previous research on wind simulation associated with the synoptic wind climatology of the central part of Italy [32] is then applied in Section 3, to realize a two-step Monte Carlo simulation of the bending process at the base of the pole a conditional Monte Carlo (MC) simulation [33] able to include both the micro- and macro-meteorological fluctuations of the wind speed into the stress time series are used for the macro-meteorological fluctuations. Section 4 deals with the evaluation of the wind-induced fatigue damage. Firstly, a benchmark estimate of the annual damage is created: the RCCA is applied to 122 serially concatenated 3-day time series and the resulting individual damages are cumulated in order to estimate the annual damage. Then, the open issues concerning the state approach are discussed on the base of such a benchmark.

In particular, the contribution to the damage given by the long-term large-amplitude cycles related to macro-meteorological fluctuations of the mean wind speed is investigated. Beside the benchmark, resulting from the concatenation of 3-day time series, the annual damage is reevaluated by concatenating also 1-day, 6-h and 10-min long time series, so as to highlight the contribution to the damage given by the transition cycles between consecutive loading states. Finally, the paper discusses the high variability of the annual damage in the classical application of the state approach, putting in evidence the role of the loading conditions in the accumulation of the annual damage. In light of the derived outcomes, some conclusions about the length of time series of stresses representative of the loading conditions experienced by the structures are provided. Section 5 summarizes the main conclusions of this study and the perspectives for the future work.

2. The state approach in the fatigue analysis

The evaluation of the wind-induced fatigue damage on the structure through the state approach requires the knowledge of the stress-cycle histogram as well as the knowledge of the local wind climate.

The wind speed in the atmospheric boundary layer is usually modeled as the superposition of the macro- and micro-meteorological components, respectively associated with the mean wind speed and turbulence. The two components are treated as independent of one another. If the wind speed is sampled at discrete time intervals $\Delta T = 10$–60 min long, the mean speed varies so slowly that it can be regarded as constant in intensity $\bar{V}$ and direction φ. On the other hand the turbulence $V'(t)$ can be modeled as a stationary Gaussian process over ΔT-intervals, having nil mean and standard deviation depending on $\bar{V}$. However, the time variability of the mean wind speed $\bar{V}(t)$ should be taken into account over an epoch $T \gg \Delta T$.

The state approach breaks down the loading process into a series of independent conditions, each characterized by a constant value of mean wind speed and direction, therefore the chronological order of the loading conditions (ΔT) over the T epoch is lost. However, the long-term variability of the process, related to the macro-meteorological part of the wind speed, is taken into account in probabilistic terms, as frequency of occurrence of the independent conditions. This concept is described mathematically by defining equally spaced speed intervals (bins) $\Delta\bar{V}_i$ $(i = 1, 2, \ldots)$ and directional sectors $\Delta\varphi_j$ $(j = 1, 2, \ldots)$. P_{ij} is the probability of occurrence of the ij-th loading condition, associated to the case $\bar{V} \in \Delta\bar{V}_i$ and $\varphi \in \Delta\varphi_j$; therefore $T_{ij} = T \cdot P_{ij}$ is the fraction of the T-epoch during which the structure experiences the ij-th loading condition.

For structures with linear behavior, the stress induced in a fixed position by the ij-th loading condition, associated with the mean wind speed $(\Delta\bar{V}_i, \Delta\varphi_j)$, is given by:

$$s_{ij}(t) = \bar{s}_{ij} + s'_{ij}(t); \qquad \text{for } t \in \Delta t \tag{1}$$

where $\bar{s}_{ij}$ is the mean stress due to the mean component of the load, while $s'_{ij}(t)$ is the nil-mean fluctuating stress due to the fluctuating component of the load.

The accumulated damage over the entire lifetime is evaluated by applying suitable cycle counting methods to the fluctuating part of the stress process $s'_{ij}(t)$, in order to consider all the loading conditions experienced by the structure. Frequency-domain methods usually apply analytical formulae based on the properties of the power spectrum of $s'_{ij}(t)$, while time-domain methods apply numerical technique to count cycles directly on the measured or simulated time-history of $s'_{ij}(t)$. A series of equally spaced intervals of stress-cycle amplitude Δ_k $(k = 1, 2, \ldots)$ is defined. The cycle histogram counts the number of the stress cycles n_{ijk} with amplitude Δ_k around the mean stress $\bar{s}_{ij}$. It is stressed that n_{ijk} is proportional to the duration of the ij-th loading condition T_{ij}. If the Palmgren-Miner linear rule is used, the fraction of damage associated with the ijk-th block of the cycle histogram is given by:

$$d_{ijk}(T) = n_{ijk}(T)/N_{ijk} \tag{2}$$

where N_{ijk} is the number of stress cycles to failure with amplitude Δ_k around $\bar{s}_{ij}$ given by the fatigue strength curve for a given structural detail.