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Development of software based on spectral characteristics for wind load

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Abstract. A method is proposed for processing data from experimental or numerical simulation of wind loads and impacts in order to obtain spectral characteristics, which will make it possible to more correctly calculate the response of a structure, in particular, take into account the resonant and turbulent components that affect the stress-strain state of structures. In the Python programming language, the WIND SPECTRUM software module was written, designed to process simulation data based on spectral characteristics, which implements the developed technique. Examples of processing the wind effect obtained from the results of numerical simulation in the ANSYS CFX software package are also given.

1 Introduction

Wind action is one of the important factors that make a significant contribution to the stress-strain state of building structures. The impact of the wind is a random and non-stationary process, therefore, to study its qualitative and quantitative characteristics, spectral analysis is currently used, which is especially important for describing the pulsating component of the wind flow. The pulsation component is determined by the presence of wind flow turbulence, which greatly complicates the calculations and requires extended research in this area. Modern approaches to the description of wind flow turbulence are described in the regulatory documents of various countries.

There are a large number of spectral functions to describe the wind flow. Energy spectra are widely used in Russian building codes [1] and Eurocodes [2]. In the normative documents under consideration, they are represented by the Davenport (1) and Solari (2) spectra [3]:

$$S_{Vp}(\omega) = \frac{4u^2}{3f(1+u^2)^{4/3}}; \tag{1}$$

$$S_{Vp}(\omega) = \frac{6.8u}{f(1+u)^{5/3}}, \tag{2}$$

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where: $f = \omega/2 \cdot \pi$ is the frequency (Hz), $u = Lf/v_{10}$ is the dimensionless frequency, $L = 1200$ m is the integral scale of turbulence, v_{10} is the average wind speed at a height of 10 m.

In (2), for the dimensionless frequency, the expression $u = L(z)f/v(z)$ is taken, where the scale of turbulence depends on the height above ground level, and the wind speed is also taken at this height.

The spectral characteristics were obtained as a result of long-term measurements of the wind flow with subsequent processing of the results. However, they were obtained in the generalized case of flow and do not take into account how the building will respond to wind action. For such an individual approach to determining the spectral wind effect on buildings and structures, it is necessary to develop a processing program based on spectral characteristics.

The basis for obtaining spectral characteristics is full-scale measurement, experimental (physical) or numerical modeling of wind flows and effects, determined individually for each building or structure. This approach allows us to study the spectral effects of wind on buildings and structures, which depends on many factors, which include: the architectural form of the building or structure, the height of the object, as well as the surrounding buildings and terrain. The obtained spectral characteristics of the wind action can later be used for computational studies of the strength and deformability of buildings and structures.

On the basis of the identified issues of individualization of the spectral characteristics of wind effects on buildings and structures, the goal of this study was formulated, which is to develop a program for processing wind effects based on spectral characteristics, called "WIND SPECTRUM", on the basis of which some spectra of wind effects on buildings will be analyzed. and structures obtained from the results of numerical simulation of CFD problems in the ANSYS CFX software package.

2 Methods

Currently, there are many methods for processing time signals, of which the following can be distinguished:

- Fourier transform [4], divided into: fast Fourier transform (FFT) [5], fast discrete Fourier transform [6], inhomogeneous discrete Fourier transform [7,8];
- Wavelet transforms [9];
- Chirplet transform [10];
- Hilbert-Huang transformation [11];
- Wigner-Ville transformation [12];
- two-sided Laplace transform [13];
- Hartley transform [14];
- Laguerre transformation [15];
- S-transform [16].

The most common transformation, at the moment, is the Fourier transform, namely, the Fast Discrete Fourier Transform (BDFT) algorithms, which are characterized by high computational efficiency with a sufficiently high quality of signal processing with the ability to embed "filters" of spurious signals. When developing software codes for processing wind effects, this approach is used.

The basic approach of the discrete Fourier transform is to calculate according to the following formula:

$$X(k)=\sum_{n=0}^{N-1}x(n)\cdot W^{kn}, \quad (3)$$

where: $W=exp\left(-j\frac{2\pi}{N}\right)$ – turning coefficient, $x(n)$ – number of readings, k = 0, 1, …, N-1 – number of matrix rows, n = 0, 1, …, N-1 – number of matrix columns

Since the signal values are a subset of the complex number field C, it is necessary to implement the arithmetic operations of the field. To calculate the discrete Fourier transform (DFT) at $x(nT)$, it is required for each k to have $N-1$ the operation of addition and multiplication of complex numbers. For real numbers, we get $4N-4 \Leftrightarrow 4(N-1)$ multiplication operations and $2N-2 \Leftrightarrow 2(N-1)$ addition operations. Therefore, the algorithm has complexity close to N^2.

The implementation of the fast algorithm is that the original sequence is divided into two smaller ones $(N/2)$, for which the DFT is calculated, therefore the number of arithmetic operations will be reduced to $N\cdot Log_2(N)$:

$$X(k)=\sum_{n=0}^{N/2-1}x(n)W_N^{nk}+\sum_{n=0}^{N/2-1}x(n+N/2)W_n^{(n+N/2)k}, \quad (4)$$

where $x(n)$, $x(n+N/2)$ is two input parts of the original sequence.

Program can also use multithreading technologies. Threads are created that have priorities for performing certain operations. All algorithms are written in the C++ programming language.

To study the energy component of the spectrum of wind action, the concept of power spectral density is used. Consider the principle of transforming the power spectral density.

Let be $x(t)$ a signal considered on the time interval $\left[-\frac{T}{2},\frac{T}{2}\right]$. Then the signal energy in this interval is equal to:

$$E_T=\int_{-T/2}^{T/2}x^2(t)dt. \quad (5)$$

In accordance with the Parseval theorem E_T based on the transformation into the frequency domain of the signal, it can be represented as:

$$E_T=\int_{-\infty}^{+\infty}\left|F_T(\omega)\right|^2 d\omega, \quad (6)$$

where: $F_T(\omega)=\frac{1}{\sqrt{2\pi}}\int_{-T/2}^{T/2}x(t)e^{-i\omega t}dt$ is Fourier transform of $x(t)$.

At $T\to+\infty$, the average power has the form:

$$W=\lim_{T\to+\infty}\frac{E_T}{T}=\int_{-\infty}^{\infty}\lim_{T\to+\infty}\frac{\left|F_T(\omega)\right|^2}{T}d\omega, \quad (7)$$

where: $S(\omega)=\lim_{T\to+\infty}\frac{\left|F_T(\omega)\right|^2}{T}$ is the power spectral density (power spectrum density function) or the energy spectrum of the signal. For the problem under consideration, this spectral characteristic shows the distribution of wind energy per unit frequency.

The power spectral density of the wind action saves information only about the amplitudes of the spectral components. Information about the oscillation phases is lost. For

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spectral characteristics, the hydro-gas-dynamic parameter Strouhal number is also used, which is a dimensionless quantity that describes the ratio of the additional dynamic force and inertia forces, and allows one to make an assessment of resonance phenomena:

$$Sh = \frac{fL}{V}, \tag{8}$$

where: f is the characteristic frequency of the process, L is the characteristic size of the streamlined body, V is the characteristic flow velocity.

This parameter allows to make an assessment of resonance phenomena. On the basis of the developed program for processing the wind effect based on the spectral characteristics, we will analyze some spectra of the wind effect obtained on the basis of numerical modeling of the wind effect.

The shell of the WIND SPECTRUM program is written in the Python programming language, using the NumPy, SciPy, Pandas, Matplotlib, Kivy, KivyMD libraries, which are Open-source solutions on the software market and are supported by the global programming community. The initial wind action data defined in the table are read from the xlsx format using Pandas and converted into the program's internal data array. The resulting raw data can then be processed using NumPy. To obtain the spectral characteristics of the wind flow, RFFT from the SciPy library is used. The power spectral density describing the energy component of the wind forcing spectrum is obtained using SciPy. The resulting graphs of the original non-stationary signal, as well as the spectral characteristics and power spectral density (energy spectrum of the signal) are built in Matplotlib, the display occurs through the GUI (Graphical User Interface) written in Kivy and KivyMD.

3 Results

The first example of processing wind action is a flow around a two-dimensional prism 42 × 42 m, which is a section of a high-rise building 201 m high (Figure 1) [17]. The wind flow speed is V=20 m/s.

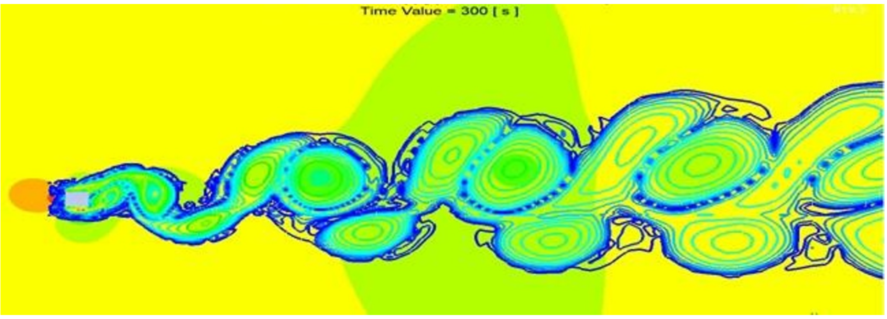

Fig. 1. Vortex wake behind a prism section.

As the studied parameters of the wind impact on a high-rise building, we will consider the aerodynamic coefficients C_x and C_y, defined along and across the flow, respectively. The initial non-stationary signal (Figure 2) is the time change of the aerodynamic coefficients, which, by multiplying by the active wind pressure, determined as $\frac{\rho V^2}{2}$ and the area of the streamlined section A, determines the total wind loading.

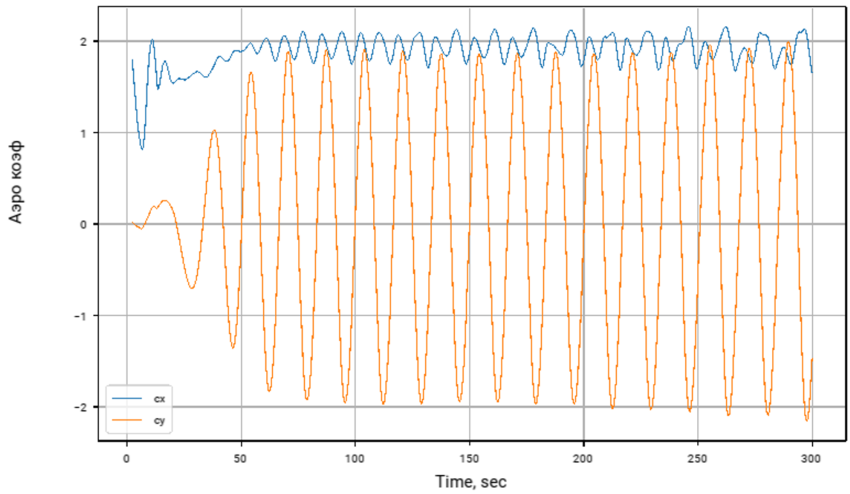

Fig. 2. Aerodynamic coefficients C_x and C_y.

Based on the developed program of the RFFT algorithm, the initial graphs of aerodynamic coefficients are converted into spectral characteristics in the form of a spectrum and spectral density of the wind power (Figure 3).

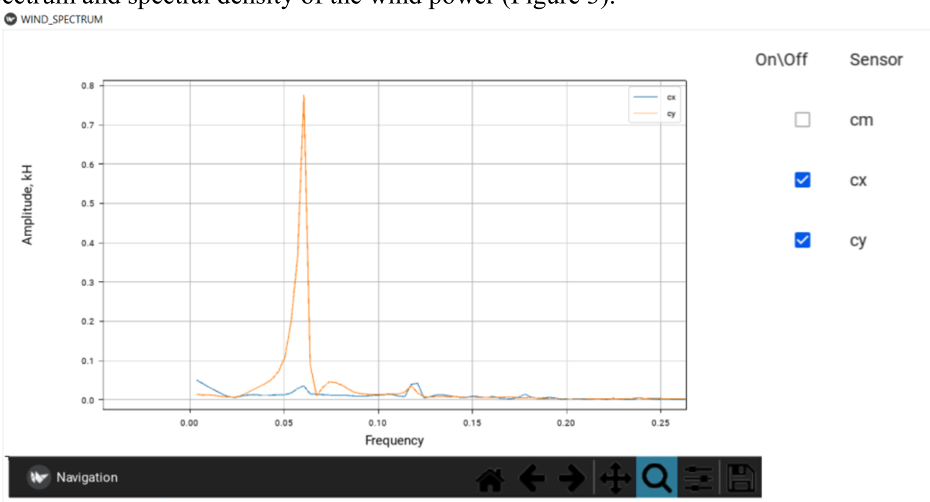

Fig. 3. Spectra of C_x and C_y.

The second example is the flow around an I-column, which is a free-standing steel frame profile. The characteristic size along the wind flow is L=0.4 m, the characteristic speed of the wind flow is V = 5 m/s (Figure 4).

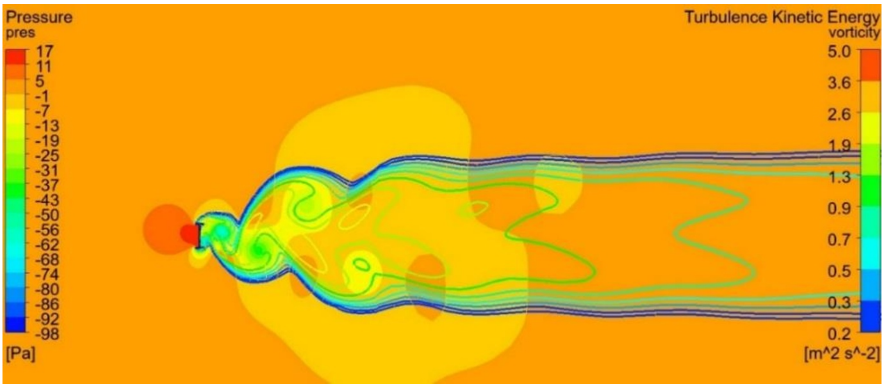

Fig. 4. Vortex aerodynamic wake behind the section of an I-column

As the studied parameters of the wind effect on the I-section, we will consider the aerodynamic forces F_x and F_y, defined along and across the flow, respectively (Figure 5).

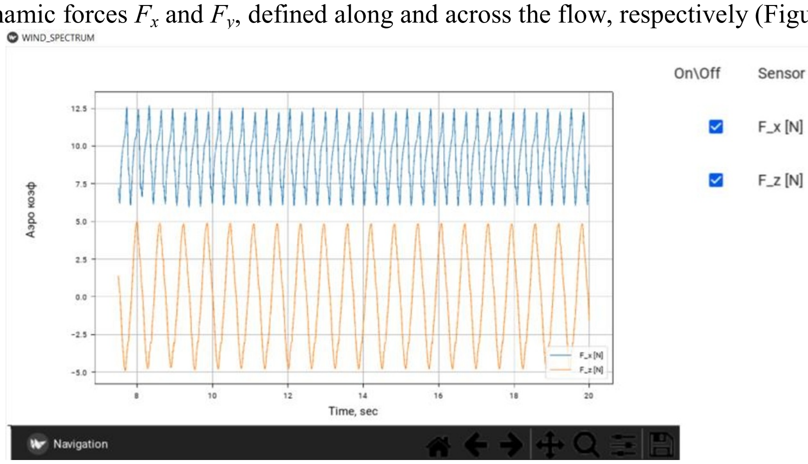

Fig. 5. Unsteady aerodynamic forces F_x and F_y.

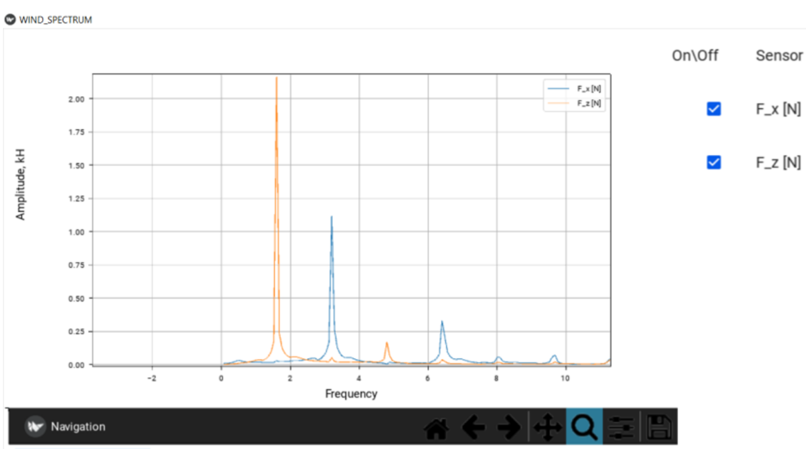

Fig. 6. Spectrum of aerodynamic forces F_x and F_y.

The third example is a flow around a two-dimensional cylinder, which is a section of a high-rise cylindrical tower (Figure 7). The characteristic size along the wind flow is L=4 m, the characteristic speed of the wind flow is V=30 m/s.

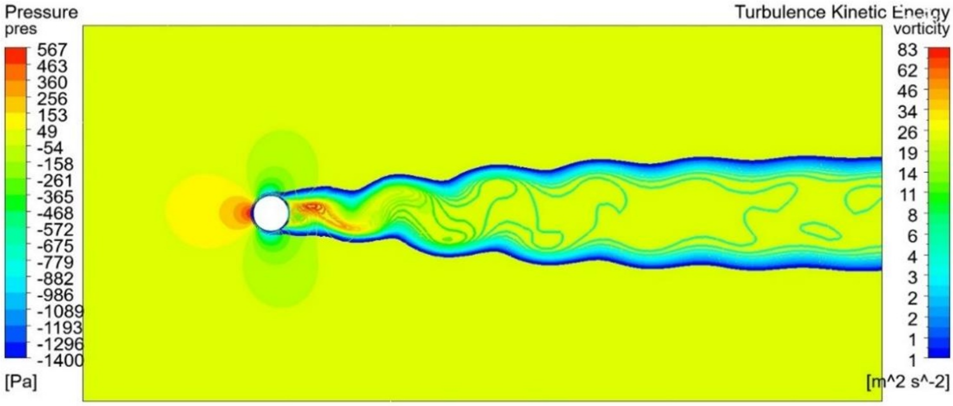

Fig. 7. Vortex aerodynamic wake behind the cylinder section

As the studied parameters of the wind effect on the cylinder, we will consider the aerodynamic forces F_x and F_y, defined along and across the flow, respectively (Figure 8).

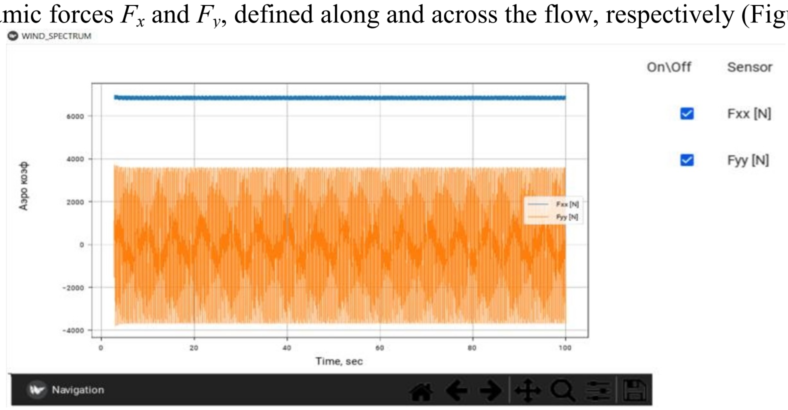

Fig. 8. Unsteady aerodynamic forces F_x and F_y.

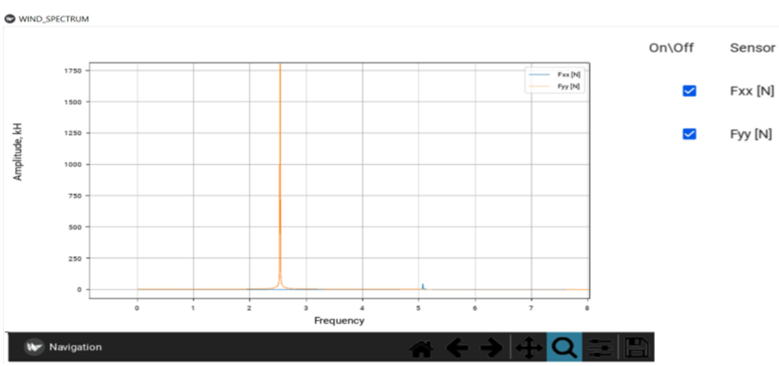

Fig. 9. Spectrum of aerodynamic forces F_x and F_y.

The obtained spectral characteristics describe the wind action falling on streamlined objects, spaced apart by the oscillation frequencies of the original signal. Knowing the natural vibration frequencies of a building or structure, it is possible to determine the possibility of resonant effects. Using the obtained individual spectral characteristics, they can be used for computational studies of the dynamic response of buildings and structures under wind action.

4 Conclusions

Based on the study, the following conclusions can be drawn:

1. A wind forcing processing program has been developed to determine spectral characteristics based on input data on wind forcing, which can be obtained by field measurement, experimental (physical) or numerical simulation.
2. The review of the existing methods for the spectral transformation of non-stationary signals made it possible to substantiate the effective use of the Fast Discrete Fourier Transform in the developed program for solving the problem of the spectral characteristics of the wind effect.
3. On the basis of the developed program for processing the wind effect, based on the spectral characteristics, the spectra of the wind effect were investigated. Their analysis made it possible to conclude that the frequency characteristics of the wind effect in relation to the flow around buildings and structures, depending on many factors, which include: the architectural form of the building or structure (the aerodynamic shape of the streamlined object), the height of the object, as well as the surrounding buildings and relief terrain.

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