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Response spectrum of the Jugo wind force

Ante Mihanović, **Željana Nikolić** and **Hrvoje Smoljanović**
University of Split, Faculty of Civil Engineering and Architecture,
Matice hrvatske 15, HR-21000 Split, CROATIA
e-mail: ante.mihanovic@gradst.hr; zeljana.nikolic@gradst.hr; hrvoje.smoljanovic@gradst.hr

SUMMARY

This paper presents the response spectrum for Jugo, a strong wind blowing from the south-eastern quadrant over the Adriatic Sea region. The response spectrum is constructed on the basis of classical elastic and resonant response spectra of a single-degree-of-freedom (SDOF) system, which are calculated from the data of the wind force measured at the location near Split. The spectra are constructed for different intensities of the dynamic wind force, i.e., for a wind with different average velocities. After presenting the spectra in a non-dimensional form, their reciprocal similarity can be observed irrespective of the intensity of the wind force. A non-dimensional shape of the response spectrum for the observed wind named Jugo is constructed by a non-dimensional comparison based on the envelopes of the averaging values. It can be observed from the presented results that the ordinates of response spectra are constant. The response spectrum of the Jugo wind is compared with the response spectrum of the north-eastern Bora wind measured at the same location.

Key words: *Jugo wind, response spectra, dynamic wind force.*

1. INTRODUCTION

In calculating the action of horizontal forces on structures the dominant loads include the earthquake and wind action. In earthquake analysis the most often used method is the spectrum analysis wherein the seismic load is modelled on the basis of the response spectrum. It is possible to use either the response spectrum of an actual earthquake recording or a spectrum defined by respective regulations. Spectrum analysis is not frequently applied for the computation of wind action upon structures although the wind load can be significant. One of the reasons for this is that the response spectra for winds are not available. The present literature on this topic includes only one attempt of construction artificial spectra [1].

This paper presents the construction of elastic spectra for a series of recordings of the wind force on the basis of experimental measurements of the wind action. Elastic spectra are presented in a non-dimensional form and an average elastic spectrum was defined.

This paper also presents an application of the windows-wavelet transform [2] for the analysis of the wave properties for the wind acting on a single-degree-of-freedom (SDOF) system, for determining the wind response spectrum. The dynamic along-wind action on the SDOF can be extracted on the constant and the fluctuating components [3]. The constant component represents the rectangular type of load in the dynamic sense. The fluctuating component in a limited time period has the form of a harmonious function. The combination of the effects of the constant and fluctuating components results in a resonant response spectrum which presents the response of the SDOF system for a measured wind force. The resonant response spectra are described for nine measured wind forces and are reduced to a non-dimensional form in order to construct an average resonant response spectrum for all analyzed recordings.

The obtained average elastic resonant response spectrum is appropriate for a given location and for the selected SDOF system.

2. MEASURED WIND FORCE

This paper is based on the data related to a strong wind, blowing from the south-eastern quadrant over the Adriatic Sea region, named Jugo, measured at the location near Split (*210 m* above sea level) at several time periods during 2007.

The experimental measurements of the wind action were performed on the SDOF system consisting of a smooth steel bar, *620 mm* in length and *4.2 mm* in diameter, clamped in a fixed metal base, with a steel sphere of *80 mm* in diameter placed on top (Figure 1). The equivalent mass of the SDOF was *0.25 kg* and the flexural stiffness was *32.6 N/m*. The value of the measured equivalent viscous damping was *0.55%*. An accelerometer with a resolution of 10^{-5} seconds was installed in a lee of the steel sphere. The measurements were carried out in such a way that the horizontal acceleration of the metal sphere centre was measured in the direction of the wind acceleration.

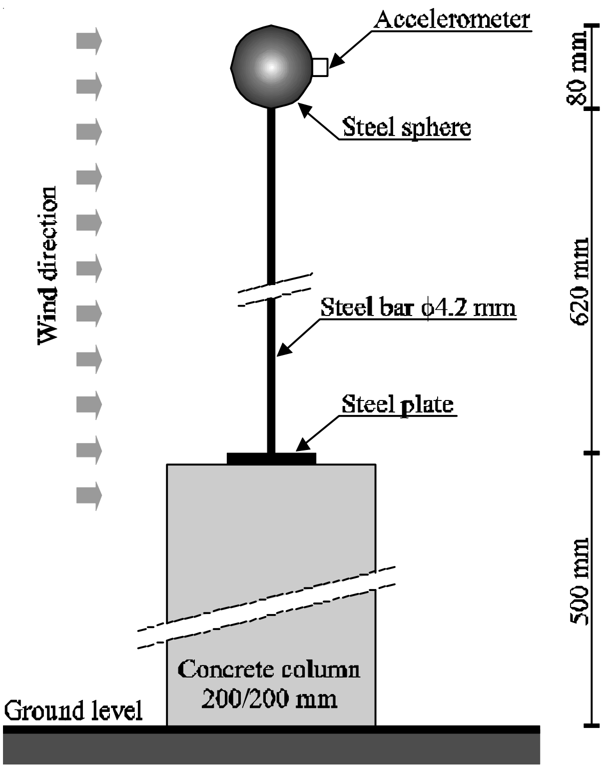
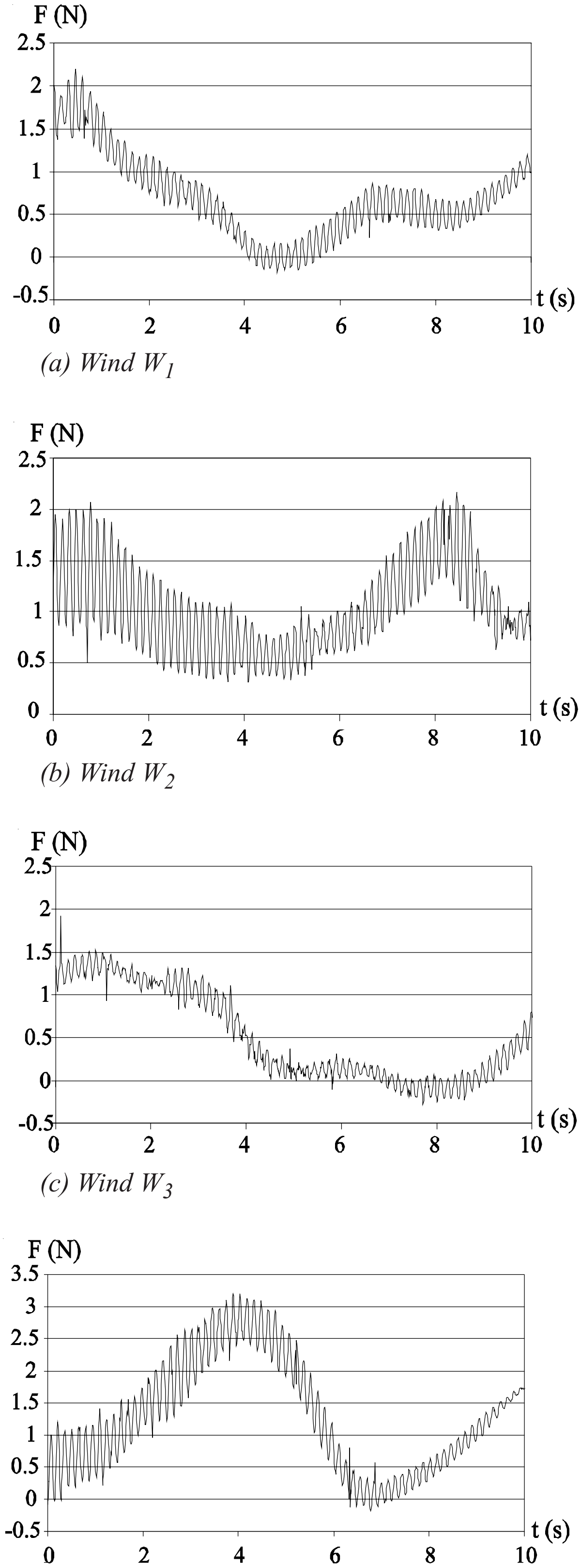


Fig. 1 Experimental SDOF system

The number of measurements on the SDOF system was registered. The results of the acceleration have been translated into the wind force using standard dynamics methods [4, 5]. The analysis was performed for nine records of the wind force with time resolutions of $\Delta t = 0.01\ s$. Figure 2 presents the record of the wind force for winds $W_1, W_2, \ldots, W_9$.



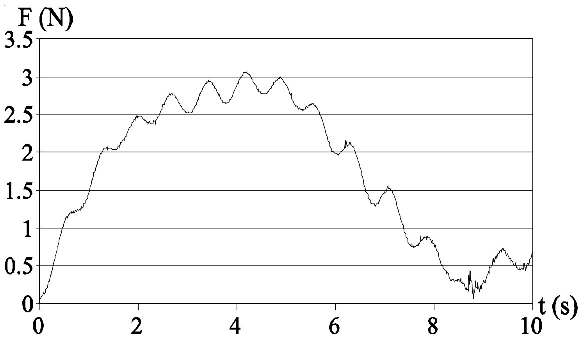
(a) Wind W_1

(b) Wind W_2

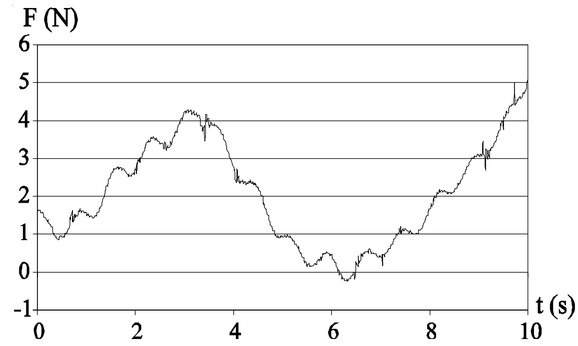
(c) Wind W_3

(d) Wind W_4

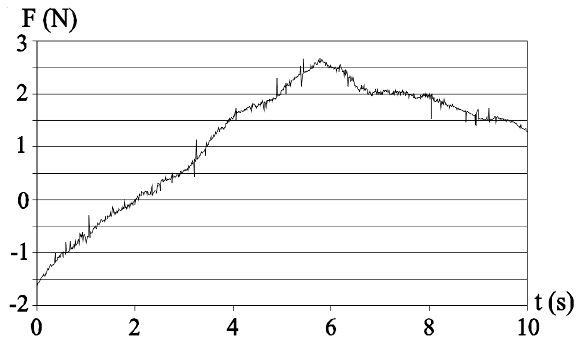
Fig. 2 Measured wind force records (a), (b), (c) and (d)



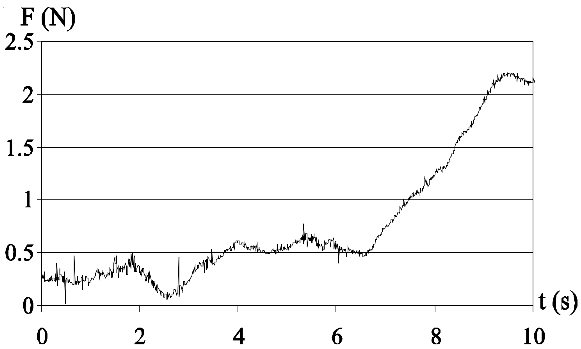
(e) Wind W_5



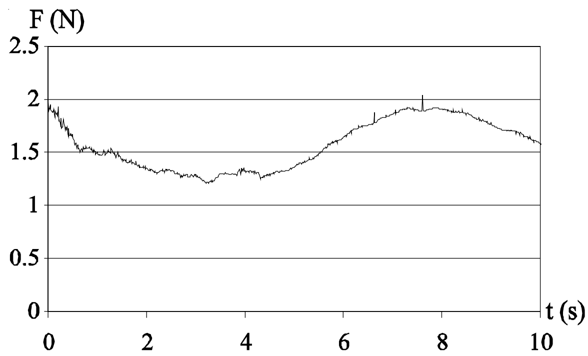
(f) Wind W_6



(g) Wind W_7



(h) Wind W_8



(i) Wind W_9

Fig. 2 Measured wind force records (e), (f), (g), (h) and (i)

3. ELASTIC RESPONSE SPECTRUM OF THE WIND FORCE

The elastic response spectrum S_{e1} of wind W_2, calculated using standard dynamic methods [4, 5], is shown in Figure 3.

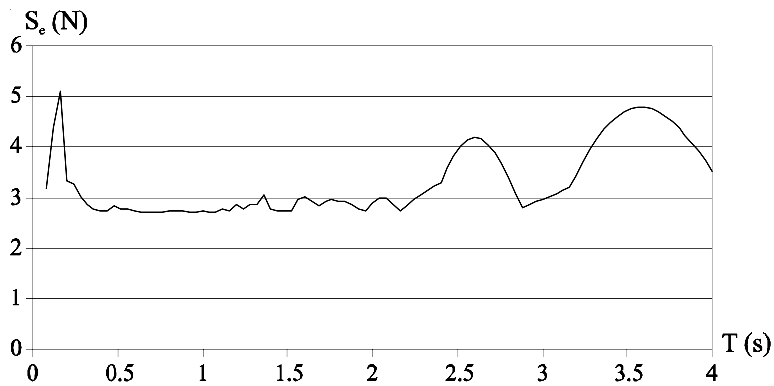


Fig. 3 Elastic response spectrum of wind W_2

Elastic response spectra $S_e(W_1)$, $S_e(W_2)$, …, $S_e(W_9)$ of all nine wind records are shown in Figure 4.

The obtained elastic response spectra were used for the construction of a non-dimensional response spectrum. A scale of the spectra is taken so that the spectrum force of the unit value of $1\ N$ is associated to the period $T=1\ s$. Non-dimensional response spectra $S_{e,nd}(W_1)$, $S_{e,nd}(W_2)$, …, $S_{e,nd}(W_9)$ of winds are shown in Figure 5.

The average value of non-dimensional elastic spectra is presented in Figure 5 and expressed as $\bar{S}_{e,nd}$.

4. RESONANT RESPONSE SPECTRUM OF THE WIND FORCE

The wave properties of the wind action on structures are analyzed by a wavelet analysis [2]. The dynamic along-wind action on the SDOF system can be extracted on the constant and the fluctuating components [3]. The constant component in a limited time period has a constant value and represents the rectangular type of load in the dynamic sense. The fluctuating component in a limited time period has the form of a harmonious function. When the rectangular impulse type of the function is chosen for the wavelet transform, the transformation of a given wind force has the meaning of the average value of the wind action, i.e., the average force with the average interval being equal to the duration of the impulse. If the harmonious type of the function is chosen for a wavelet transform, e.g. the sinusoidal form, the wavelet transform of the wind force extracts the intensity of the harmonious action that at the same time shows the possible resonant effect on the SDOF system with the period being equal to the period of the chosen sinusoidal function.

The windows-wavelet transform is given by the following expression [3]:

$$a_\alpha(\alpha,T)\big|_{max} = \int_{-\infty}^{\infty} F_w(\tau) I(\tau - t)\, d\tau, \quad \alpha > 0 \qquad (1)$$

where $F_w(\tau)$ is the measured wind force, and:

$$I(\tau - t) = N(\alpha T, \tau - t) \sin\frac{2\pi}{T}(\tau - t) \qquad (2)$$

is the sinusoidal impulse with the duration of $t=\alpha T$, while N is a function of the impulse normalization given by the following expression:

$$N(\alpha T, t) = \begin{cases} 1/\alpha T & 0 < t < \alpha T \\ 0 & other \end{cases} \qquad (3)$$

Expression (1) with the application of the sinus impulse function (2) gives the fluctuating component of the wind action. If a rectangular impulse function is chosen for the windows-wavelet transform in expression (1), then the transformation of the given wind force gives the constant component of wind action.

The wavelet analysis of the dynamic incitement for wind W_2 is shown in Figure 6. The component a_0 shows the intensity of a constant wind component which depends on a time of averaging. The time of averaging is taken as a function of the natural period T of a particular SDOF. Component a_1 shows the amplitude of the first fluctuating component of the wind force of one full sinusoidal wave during the natural period T, while component a_2 shows the amplitude of the second fluctuating component.

The wave analysis of the dynamic incitement for wind W_2 showed that the constant wind component has the greatest intensity, the intensity of the first fluctuating component is approximately three times smaller while the intensity of second fluctuating components is negligibly small. A similar conclusion is valid for other analyzed winds.

Constant components for all nine recordings of the wind force for $a_{0,nd}(W_1)$, $a_{0,nd}(W_2)$, …, $a_{0,nd}(W_9)$, and their average value in a non-dimensional form are presented in Figure 7. The first fluctuating components $a_{1,nd}(W_1)$, $a_{1,nd}(W_2)$, …, $a_{1,nd}(W_9)$ and their average value in a non-dimensional form are presented in Figure 8.

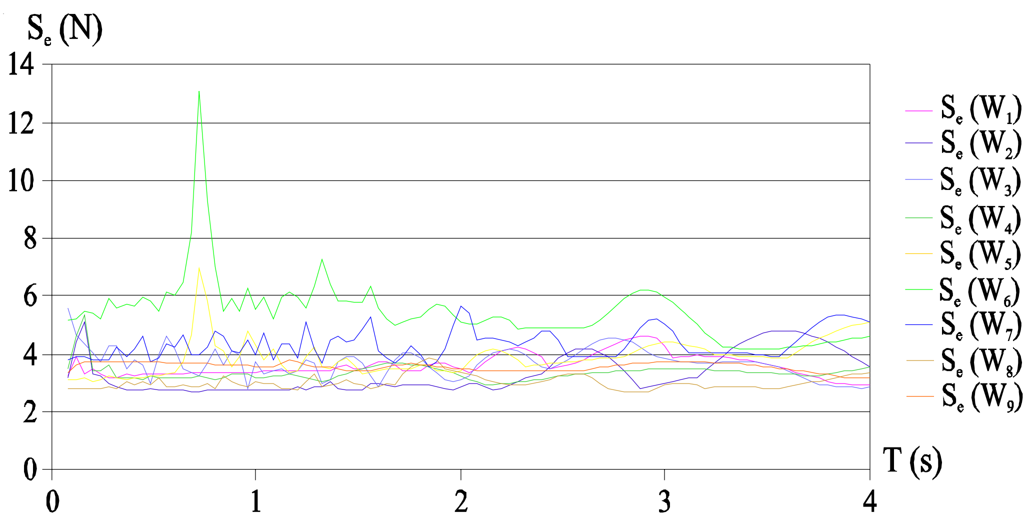


Fig. 4 Elastic response spectra of winds W_1, W_2, …, W_9

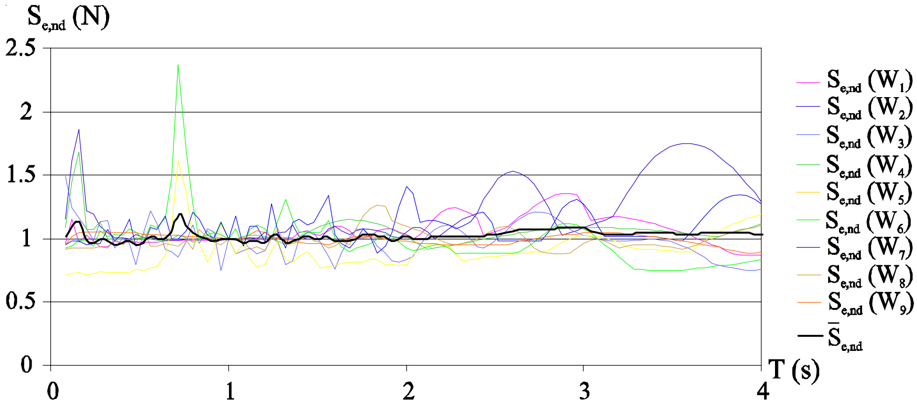


Fig. 5 Non-dimensional elastic response spectra of winds $W_1, W_2, \ldots, W_9$

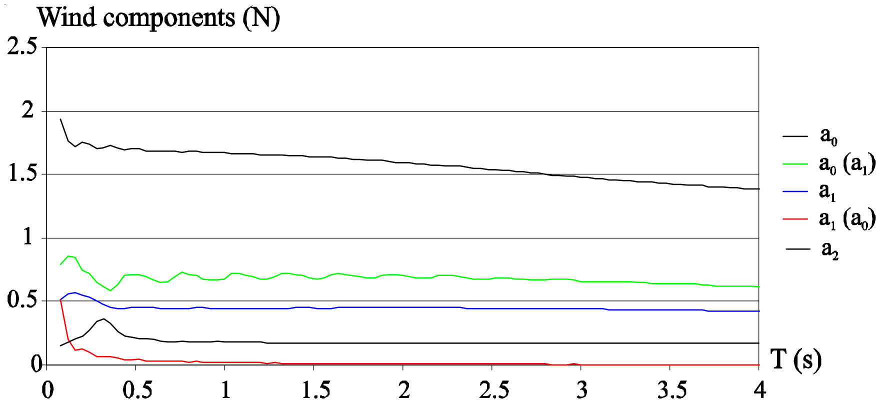


Fig. 6 Constant and fluctuating components of wind W_2

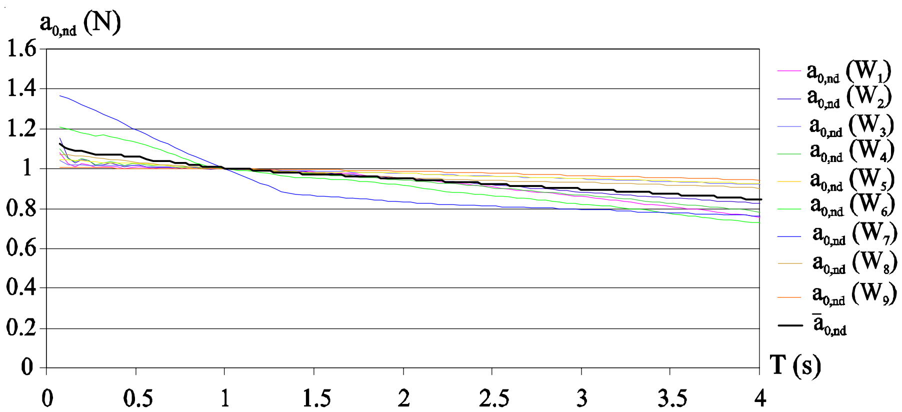


Fig. 7 Constant components of winds $W_1, W_2, \ldots, W_9$ in a non-dimensional form

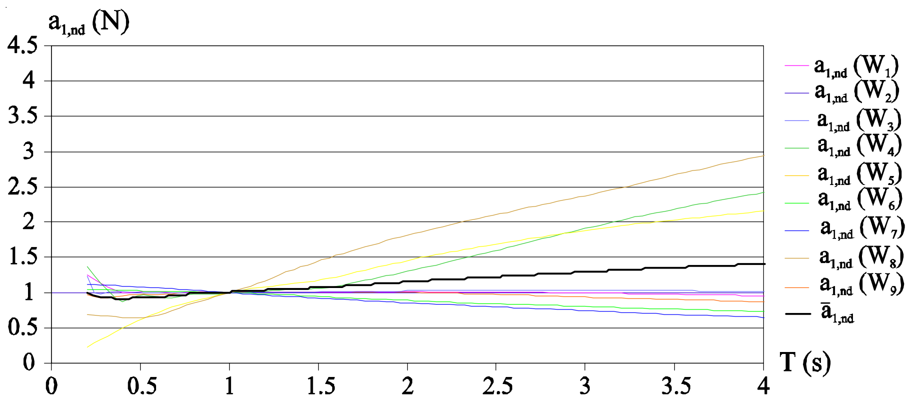


Fig. 8 The first fluctuating components of winds $W_1, W_2, \ldots, W_9$ in a non-dimensional form

The combination of the effects of the constant and fluctuating components yields a resonant response spectrum which presents the response of the SDOF system for the measured wind force. All components do not reach extreme values at the same point in time.

Therefore the resonant spectra are obtained as a combination of the constant component a_0 with the respective fluctuating components $a_1(a_0)$, $a_2(a_0)$, …, $a_n(a_0)$, which occurred at the same point in time as a_0 or as a combination between given fluctuating component a_i ($i=1, ..., n$) and the respective constant component and other fluctuating components $a_1(a_i)$, $a_2(a_i)$, …, $a_{i-1}(a_i)$, $a_{i+1}(a_i)$, …, $a_n(a_i)$. The dynamic factor for the constant component is 2 while for the fluctuating components it is π [3].

Since the wave analysis for the dynamic wind incitement showed that the second component and all other fluctuating components are negligibly small with respect to the constant component and the first fluctuating component, the resonant spectra will be analyzed in the form of the following combinations:

$$S_{r1} = 2a_0 + \pi a_1(a_0)$$
$$S_{r2} = 2a_0(a_1) + \pi a_1 \qquad (4)$$

In expression (4), a_0 is a constant component, a_1 is the first fluctuating component, $a_1(a_0)$ is the respective first fluctuating component which occurred at the same point in time as the constant component, while $a_0(a_1)$ is the respective constant component which occurred at the same point in time as the first fluctuating component a_1.

Figure 9 presents the elastic spectrum S_{el} and the resonant spectra S_{r1} and S_{r2} for wind W_2. Since the constant component of the wind force is dominant with respect to fluctuating components, the resonant spectrum S_{r1} describes the elastic spectrum better than spectrum S_{r2}. A similar conclusion can be drawn for other measured wind forces.

Figure 10 presents the resonant spectra $S_{r1}(W_1)$, $S_{r1}(W_2)$, …, $S_{r1}(W_9)$ for all nine measured wind forces. Figure 11 presents the spectra $S_{r1,nd}(W_1)$, $S_{r1,nd}(W_2)$, …, $S_{r1,nd}(W_9)$ in a non-dimensional form and the average value of the non-dimensional spectra $\overline{S}_{r1,nd}$.

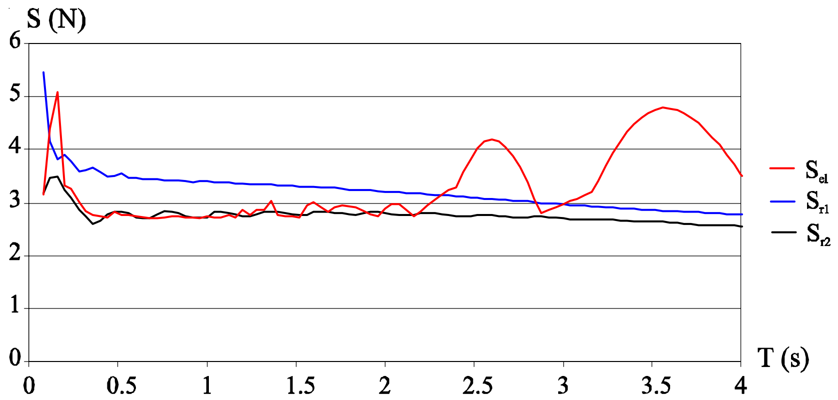


Fig. 9 Elastic and resonant response spectra of wind W_2

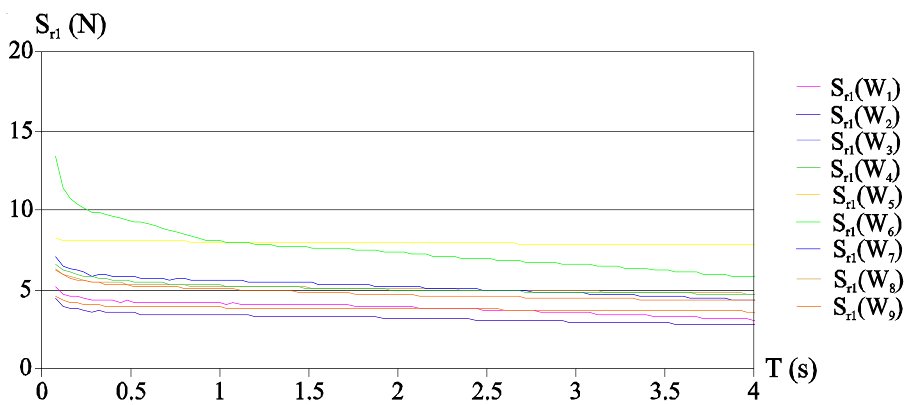


Fig. 10 Resonant response spectra S_{r1}

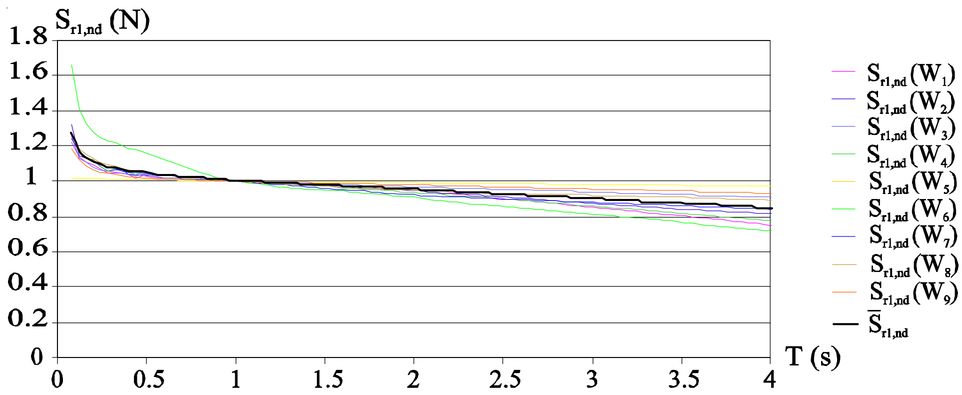


Fig. 11 Resonant response spectra in non-dimensional form

5. COMPARISON OF ELASTIC AND RESONANT RESPONSE SPECTRA

The average values of the elastic spectrum $\overline{S}_{e,nd}$ and of the resonant spectrum $\overline{S}_{r1,nd}$ are presented in Figure 12. It can be noted that the average elastic response spectrum is almost constant for the period $0.2\ s < T < 4.0\ s$ and that it can be very well approximated by the resonant response spectrum $\overline{S}_{r1,nd}$. The obtained data for the average spectra can be used for constructing a non-dimensional response spectrum for the Jugo wind by using the function:

$$S_{nd}(T) = 1, \quad 0.2s < T < 4.0s \tag{5}$$

6. SPECTRAL POWER DENSITY

The curves for the spectral power density SPD were constructed for the described wind forces. Figure 13 presents the SPD for wind W_2. The duration of the records was 19 seconds.

The SPD curves of all nine winds were normalized and presented in Figure 14. The normalization was performed by reduction to the basic wind W_2 with the same ratio as the reduction of elastic response spectra.

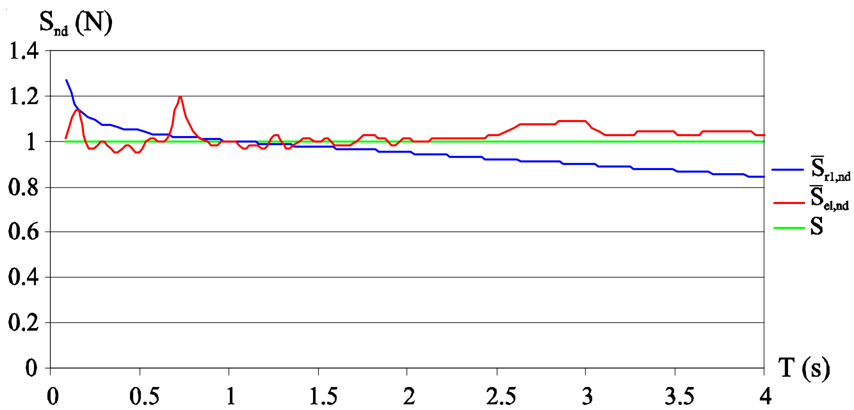


Fig. 12 Comparison of elastic and resonant response spectra

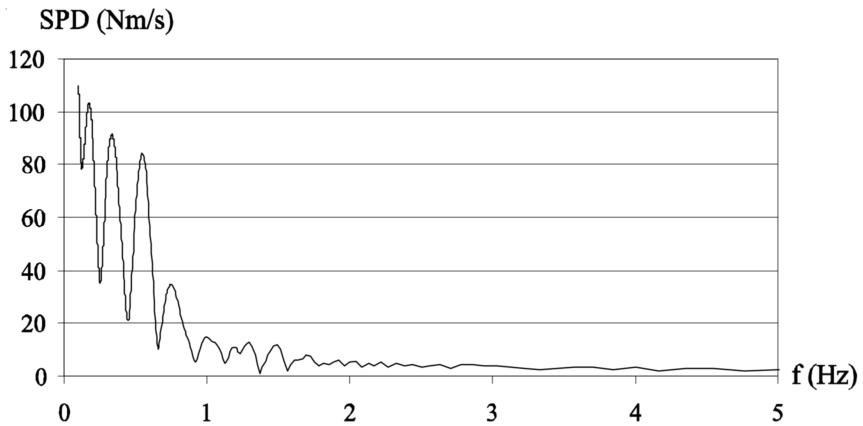


Fig. 13 Spectral power density for wind force W_2

The normalization enabled the computation of the average spectral power density $\overline{SPD}_{nd}$ which is presented in Figure 15. The same figure presents the analytical approximation of the normalized average SPD, which has the following form:

$$SPD(f) = 1.25 e^{-1.1 \log(0.002 f)} - 10 \qquad (6)$$

7. COMPARISON OF RESPONSE SPECTRA FOR JUGO AND BORA WINDS

Mihanović et al. [6] presents a proposal for the approximation of the wind spectrum for the Bora wind measured at the same location and with the same instrument. By comparing the two spectra (Figure 16), a significant difference is observed between the spectra for the Bora and the Jugo winds for the periods $0.2\,s < T < 1.0\,s$. While the Bora spectrum in that period is best described by the exponential curve $e^{-\log T}$, the Jugo spectrum can be described as constant in that location. However, for the periods $1.0\,s \leq T \leq 4.0\,s$ both winds can be described by the same spectrum.

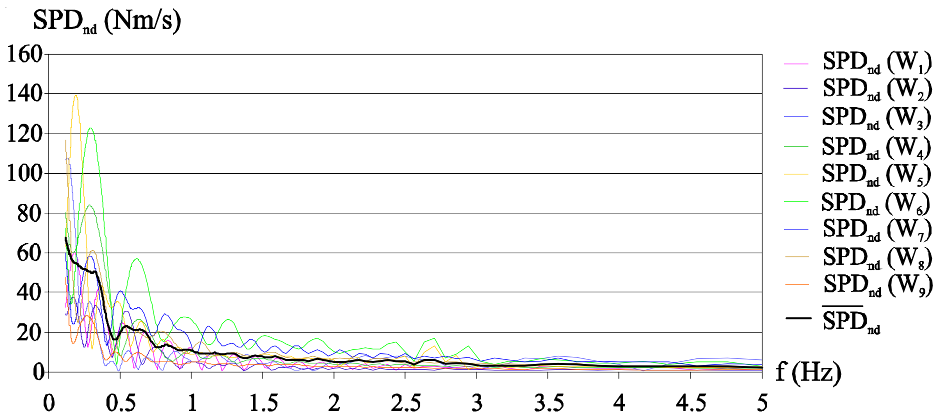


Fig. 14 Normalized spectral power density for nine wind force

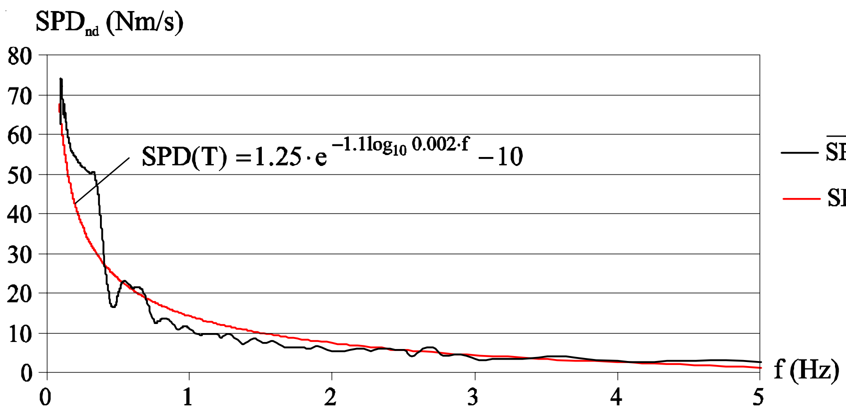


Fig. 15 Average spectral power density and its analytical approximation

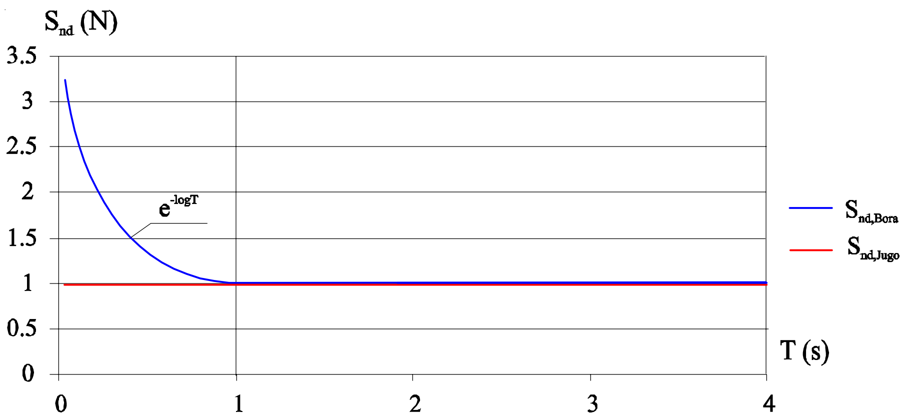


Fig. 16 Response spectra of the Jugo and Bura winds measured at the same location

8. CONCLUSION

This paper presents the response spectrum for the south-eastern wind Jugo. The response spectrum is constructed on the basis of classical elastic and resonant response spectra of a single-degree-of-freedom (SDOF) system, which are calculated from the data of the wind force measured at the location near Split. After the presentation of the spectra in a non-dimensional form, it was noted the action of the Jugo wind for the periods $0.2\ s < T < 4.0\ s$ can be described as a constant spectrum.

By comparing the obtained spectrum with the spectrum of the north-eastern wind Bora [6], constructed on the basis of measurements taken at the same location, a significant difference can be observed for the spectrum ordinate for period $0.0\ s < T < 1.0\ s$. For the Jugo wind the spectrum is constant, while for the Bora it is described by the exponential function. For the periods $T \geq 1.0\ s$ the spectrum is constant and is the same for both winds.

The application of the spectrum analysis for analyzing the dynamic incitements of wind upon structures requires a comprehensive insight into the shapes of the wind force spectra, which can be obtained by measuring wind forces at different locations.

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SPEKTAR ODGOVORA VJETRA JUGO

SAŽETAK

U ovome radu je prikazan spektar odgovora za jugo, jaki jugoistočni vjetar koji puše preko Jadranskog mora. Spektar odgovora je konstruiran na osnovu klasičnog elastičnog i rezonantnog spektra odgovora jednostupnjevnog sustava koji su izračunati iz podataka sile vjetra izmjerenih na lokaciji u blizini Splita. Spektri su konstruirani za različite intenzitete dinamičke sile vjetra, odnosno za vjetar različitih srednjih brzina. Svođenjem spektara na bezdimenzionalni oblik pokazuje se njihova velika sličnost neovisno o intenzitetu sile vjetra. Bezdimenzionalnom usporedbom na temelju približne anvelope srednjih vrijednosti konstruiran je bezdimenzionalni oblik spektra odgovora promatranog vjetra jugo. Iz prikazanih rezultata vidljivo je da su ordinate spektra odgovora konstantne. Spektar odgovora vjetra jugo je uspoređen sa spektrom odgovora vjetra bura izmjerenog na istoj lokaciji.

Ključne riječi: *vjetar jugo, spektar odgovora, dinamičke sile vjetra.*