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SOIL–STRUCTURE INTERACTION IN CASE OF A WIND TURBINE

BY

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Abstract. In Romania the wind turbine construction is extending. It is known that our country is located in a seismic area. Therefore it is necessary to consider wind as well as the seismic action when analysing the towers of wind turbines. Knowing the natural modes of vibration of the structure is an evaluation method of structural response under dynamic actions. This aspect becomes of a high interest in a wind turbine analysis because it is necessary to avoid entering the resonance range. There are two methods used to highlight the soil structure interaction effects, namely the substructure method when the soil stiffness is modeled through springs and the finite element method which analyses the entire structure including the foundation soil. A comparison of a dynamic analysis of a 70 meters tall wind turbine considering both above mentioned methods, is presented.

Key words: wind turbines; soil–structure interaction; FE analysis; dynamic analysis; resonance.

1. Introduction

The construction of wind turbines has accelerated in the last decade all over Europe, as well as in Romania. This growth of wind turbines construction

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has revealed some design and building difficulties because care need to be taken when dealing with some particularities of these structures.

One of the aspects that should be treated carefully during the functioning of a wind turbine is the necessity to avoid entering the resonance range. This implies the knowledge and control of the natural frequencies of vibrations of the tower which should not coincide with the rotor and blade-passing frequencies.

In order to control the natural frequency of the tower, particular solutions for the tower as well as for the foundations has to be chosen. In this situation considering a rigid base for the tower can outcome misleading results. Studies have proved that when soil stiffness is taken into account in analyses the natural frequencies of the structures differ (usually are smaller) from the case when a rigid base is considered (Olariu, 2011). Therefore, in order to choose the best design solutions as to avoid the resonance range it is necessary to consider soil–structure interaction.

In what follows some theoretical aspects in order to avoid entering resonance ranges and a comparison of the dynamic results of a soil–foundation–wind turbine system with the soil modeled are presented using both springs and finite element method.

2. Theoretical Background

The International Standard IEC 61400-1 (Wind turbines, Part **1**: *Design Requirements*) was published in order to ensure the safety of wind turbines against damage for the entire life span. In 2005 it was reevaluated and it became the European Standard EN 61400-1: 2005. This standard provides safety requirements and specifies the essential design requirements to ensure the engineering integrity of wind turbine.

In Romania the European Standard was completed with national design requirements and in 2006 it became the national standard SR EN 61400-1:2006. Wind turbines. Part **1**: *Design Requirements*. This standard includes also other parts which deal with different aspects of the wind turbines design.

2.1. Wind Turbine Modeling

The tower of a wind turbine supports the nacelle and the rotor and it provides the necessary elevation of the rotor to keep it clear off the ground and bring it up to the level where the wind resources are. Most large wind turbines are delivered with tubular steel towers, which are manufactured in sections of 20…30 m length with flanges at either end. The towers are conical, their diameters increase towards the base, and thereby increasing their strength towards the tower base, where it is needed the most, because this is where the load response due to the wind loading is largest. The tower is usually connected to its supporting foundation by means of a bolted flange connection or a weld (Guidelines…, 2002).

On the entire life span of the wind turbine the tower has to withstand the operational vibrations. The rotor and blade-passing frequencies may cause increase of the forces acting on the tower which may lead to a highly insecure level of structural integrity.

The international design codes usually require that wind turbines should be designed for wind actions. On the other hand, in countries like Romania it is necessary to take into account apart from the wind action also the seismic action. When a wind turbine is to be designed for installation on a site which may be subject to earthquakes, the wind turbine has to be designed so as to withstand the earthquake loads (Han, 2006).

It is important to analyse the wind turbine tower for the earthquake-induced accelerations in one vertical and two horizontal directions. Usually it is sufficient to reduce the analysis of two horizontal directions to an analysis in one horizontal direction, due to the symmetry of the dynamic system. The vertical acceleration may lead to buckling in the tower.

As the wind turbine blades start rotating their circular velocity is increasing and the induced vibration frequency increases too. Depending on the power output capacity of the wind turbines, the blades rotate with rotational speeds that range from 30 to 60 rpm, which correspond to some maximum operational frequencies from 0.5 to 1 Hz. Usually these operational frequencies are close to the natural frequency range of the soil–structure system (Hartmann & Katz, 2007).

The way to avoid structural failures is to attain a natural frequency of the structure different from the operational frequency of the wind turbine. Usually the operational frequency is smaller than the natural frequency of the tower. Therefore it is necessary to study and establish the resonance ranges.

2.2. Dynamic Response and Resonance

In physics the resonance represents the tendency of a system to oscillate with maximum amplitude at certain frequencies, called also *resonance frequencies*. For these frequencies even small forces can cause large vibration amplitudes and this is due to the stocked oscillating energy. When the damping is small, the resonance frequency is almost equal to the system's natural frequency, and therefore it is in free vibration.

The resonance can be found in damped or undamped forced vibrations which can be produced by a periodic (harmonic or non-harmonic) force, denoted with $F(t)$ (Stratan, 2009).

It is considered the case when the exterior force is a harmonic one according to Fig. 1 namely

$$F(t) = F_0 \sin\theta t\,, \tag{1}$$

where: F_0 is the amplitude of the exterior force, θ – circular frequency of the exterior force.

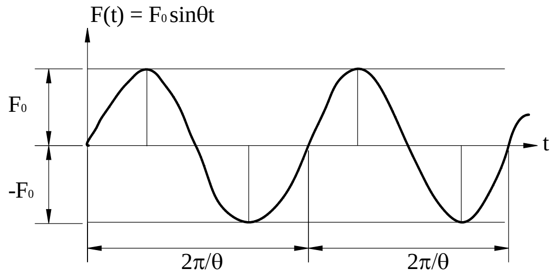

Fig. 1 – Harmonic exterior force.

In the stationary process the intensity of the dynamic response is highlighted by the dynamic coefficient denoted with *D*. In Fig. 2 is presented the variation of the dynamic coefficient, *D*, represented by the ratio between the circular frequency of the exterior force and the circular frequency of the system, namely θ/ω (Stratan, 2009; Atanasiu, 2000).

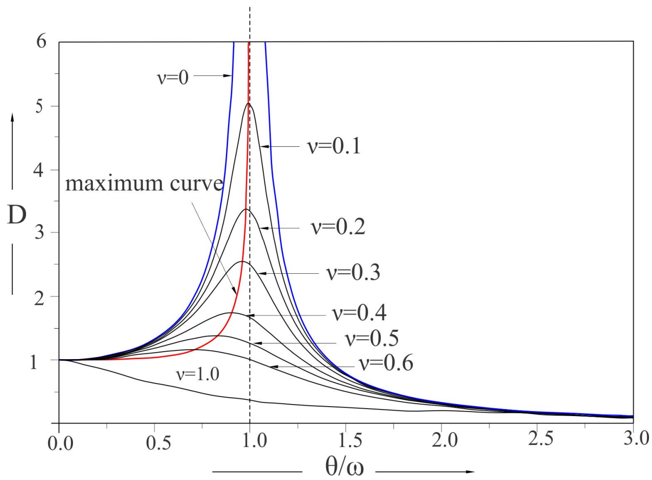

Fig. 2 – The dynamic coefficient variation under damped forced vibrations.

The resonance occur when $\theta = \omega$. In the absence of damping the dynamic coefficient has an asymptotic leap in case of resonance. However in the presence of damping the dynamic coefficient, *D*, is highly affected during resonance (Atanasiu, 2000).

In case of wind turbines, a poor design decision can involve a maximum rotational speed that is very close to the natural frequency of the structural system resulting in a high likelihood of resonant amplification causing structural instability. Another poor design may have a rotational speed not very close to yet higher than the natural frequency of the structural system. In such cases, the structure would have to endure violent near-resonance vibrations as the operational frequency approaches the natural frequency while speeding up to and down from the maximum speed. This situation would result in very high dynamic forces which could cause immediate damage to the structure. Even if these dynamic forces do not exceed the structure's strength capacity, fatigue-induced failures could also be encountered (Maunu, 2008).

A safe design would avoid allowing the operational frequency to approach the vicinity of the natural frequency by a certain safety factor. According to different specialized design codes a safety factor ranging from 5% up to 15% of the natural frequency is recommended (Olariu, 2011; Han, 2006).

2.3. Soil–Structure Interaction for Wind Turbines

Wind turbines are usually supported by either a slab foundation or a pile foundation. Soil conditions at the specific site usually govern whether a slab foundation or a pile foundation is chosen. A slab foundation is normally preferred when the foundation soil is strong enough to support the loads from the wind turbine, while a pile supported foundation is used when the foundation soil is of a softer quality and the loads need to be transferred to larger depths.

The overall foundation stiffness depends on the strength and stiffness of the soil as well as on the structural foundation elements. The foundation stiffness needs to be determined as a basis for predicting the dynamic structural response to wind, wave and earthquake loading. The foundation stiffness depends in general, on the frequency. This is particularly important when predicting dynamic response to earthquake (Al Satari & Saif Hussain, 2008; Olariu, 2011).

A common modeling and analysing method of the soil–structure interaction is using stiffness springs as to model the soil. Usually, the foundation soil has a finite stiffness. In order to represent the finite stiffness of the foundation soil there are used a set of springs that can be applied in one or several supporting points of the structure. The set of stiffness springs of the foundation can include the following: the vertical stiffness spring (k_z); the horizontal stiffness spring (k_x); the rotational stiffness spring (k_θ); the torsional stiffness spring (k_t). Fig. 3 presents a model of a wind turbine having a rigid base and a spring modeled base.

On the other hand the soils–structure interaction can be solved through the Finite Element Method (FEM), which is meshing the foundation soil and the structure, therefore solving the problem in one step.

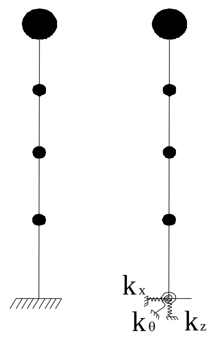

Fig. 3 – Simplified wind turbine model
with rigid base and flexible base.

FEM provides a precise computational mean for soil–structure interaction. The foundation soil can be modeled throughout finite elements instead of providing a global stiffness of the soil. Although in this method the soil parameters considered are the elastic modulus and the Poisson's ratio, the obtained results being more realistic than using stiffness springs (Hartmann & Katz, 2007; Olariu, 2011).

Various books are providing different eqs. to compute foundation stiffness depending on the shape, size and type of the foundation and on the soil properties.

3. Wind Turbine – Case Studies

In order to highlight the importance of taking in to account soil–structure interaction in a dynamic analysis for a wind turbine it was chosen a particular case. Therefore in this section there are presented the results from a dynamic analysis for a 70 m tall wind turbine considering the two methods of soil–structure interaction modeling, namely the stiffness springs and the FEM. Afterwards a comparison between the obtained results in these two cases was performed.

The analysis was realized using the computational program SAP 2000. The tower was modeled through 'shell' finite elements having variable diameter and thickness along the height of the tower. It is a 67.6 m tall tubular steel tower with a range of diameter from 4.2 m at the base to 1.85 m at the top. The mass of the tower is of 85.15 t and the weight of the rotor and the blades are 47 t. The rotor and the blades were modeled as a concentrated mass at the top of the tower. Also along the entire height of the tower the weight from interior stairs and platforms was applied.

The foundation used for this model is a circular footing having a 16 m diameter (*D*) and a 3 m thickness. The foundation soil considered for the analysis was extended around the foundation at a length of 2*D* and in depth for 6*D*.

It is considered that the wind turbine is operating with variable speed range from $n_{\min}$ = 5.5 rpm to $n_{\max}$ = 29 rpm.

In the following there are presented two case studies, namely case study *A*, where the foundation soil was modeled by the means of stiffness springs and case study *B*, where the entire soil foundation structure system was modeled by finite elements.

3.1. Case Study *A*

The model used for case *A* is presented in Fig. 4. For the foundations soil stiffness there were considered four situations, namely a rigid base and three different types of soils modeled through springs. The types of considered soils were characterized through elastic compression coefficients, denoted with c_z, as it follows:

a) Loose sand and clayey sand, clay and sandy clay with a bed coefficient, c_z = 5,000,000 N/m^3 (denoted as the support Elastic 1).

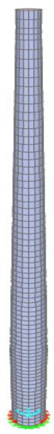

Fig. 4 – The meshed model of the wind turbine's tower with stiffness springs at the base.

b) Gravel, sand and clayey sand, clay and sandy clay with a bed coefficient, c_z = 8,500,000 N/m^3 (denoted as the support Elastic 2).

c) Gravel, sand and clayey sand, clay and sandy clay plastic stiff, with a bed coefficient c_z =50,000,000 N/m^3 (denoted as the support Elastic 3).

The values of the spring's stiffness were computed based on the bed coefficient and on the following relationships (Hegoiță, 1985):

$$c_x = 0.7c_z\,,\; c_\theta = 2c_z\,,\; c_t = 1.5c_z\,; \tag{2}$$

$$k_z = c_z A_f\,,\; k_\theta = c_\theta I_f\,,\; k_x = c_x A_f\,,\; k_t = c_t I_z\,, \tag{3}$$

where: A_f is the aria of the foundation base, connected to the foundation soil; I_f – moment of inertia of the aria A_f in relation with the horizontal rotational axis; I_z – the polar moment of inertia of the aria A_f .

Table 1 presents the values of the spring stiffness's used for modeling the three elastic supports. The spring stiffness's were computed for translational displacement, namely k_x, k_y and k_z , and for rotational displacement on the *x* and *y* direction, $k_{\theta x}$ and $k_{\theta y}$, and finally for torsion, k_t.

Table 1
Spring Stiffness Used for Elastic Base Modeling

Elastic spring	k_x N/m	k_y N/m	k_z N/m	$k_{\theta x}$ N.m/rad	$k_{\theta y}$ N.m/rad	k_t N.m/rad
Elastic 1	70,371×10^4	70,371×10^4	100,530×10^4	3.2×10^{10}	3.2×10^{10}	2.412×10^{10}
Elastic 2	12,031×10^5	12,031×10^5	171,873×10^4	5.5×10^{10}	5.5×10^{10}	4.125×10^{10}
Elastic 3	70,371×10^5	70,371×10^5	100,531×10^6	32×10^{10}	32×10^{10}	2,412×10^{11}

From the dynamic analysis the natural frequencies of the tower considering both the rigid and the elastic supports, were determined. The variation range of the frequencies was considered to be ±10%.

Table 2 presents these results obtained from the dynamic analysis, namely the frequencies for the first and second mode of vibration and their periods of vibration.

Table 2
Frequencies and Periods of Vibration of the Wind Turbine Model

Mode of vibration	Bearing	Frequency Hz	Frequency +10% Hz	Frequency –10% Hz	Period of vibration s
1	Elastic 1	0.505	0.5555	0.4545	1.979
	Elastic 2	0.513	0.5643	0.4617	1.9464
	Elastic 3	0.524	0.5764	0.4716	1.905
	Rigid	0.527	0.5797	0.4743	1.897
2	Elastic 1	3.0691	3.37601	2.76219	0.325
	Elastic 2	3.150	3.465	2.835	0.3174
	Elastic 3	3.264	3.5904	2.9376	0.306
	Rigid	3.291	3.6201	2.9619	0.3038

The diagrams of resonance presented in Figs. 5,…,8 were realized using the following relations:

$$\frac{f_R}{f_{0,1}} \le 0.90 \text{ and } \frac{f_{R,m}}{f_{0,n}} \le 0.90 \text{ or } \frac{f_{R,m}}{f_{0,n}} \ge 1.10, \quad (4)$$

where: f_R is maximum rotation frequency of the rotor in normal operation range; $f_{0,1}$ – first frequency of the tower; $f_{R,m}$ – pass frequency of the m rotor blades; $f_{0,n}$ – the n-th frequency of the tower.

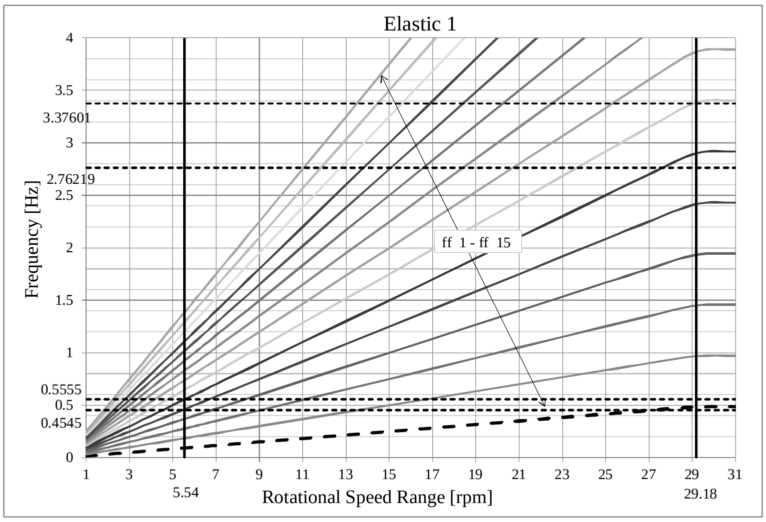

Fig. 5 – Resonance diagrams for the model with "Elastic 1" spring.

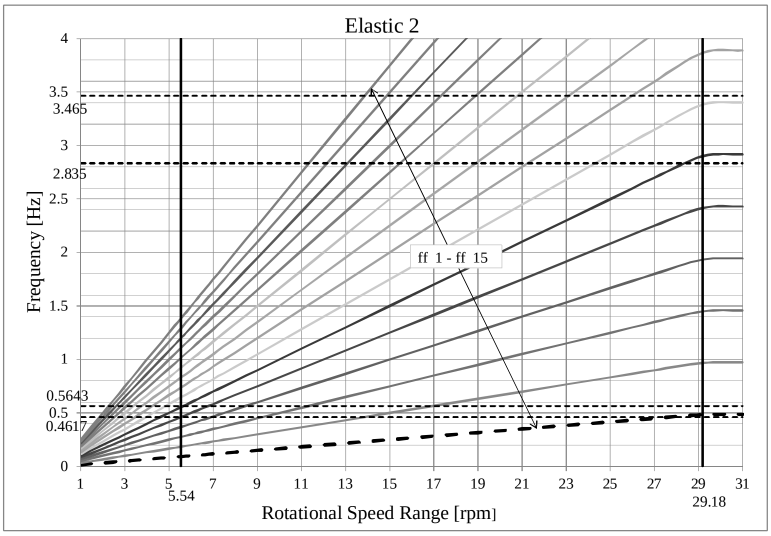

Fig. 6 – Resonance diagrams for the model with "Elastic 2" spring.

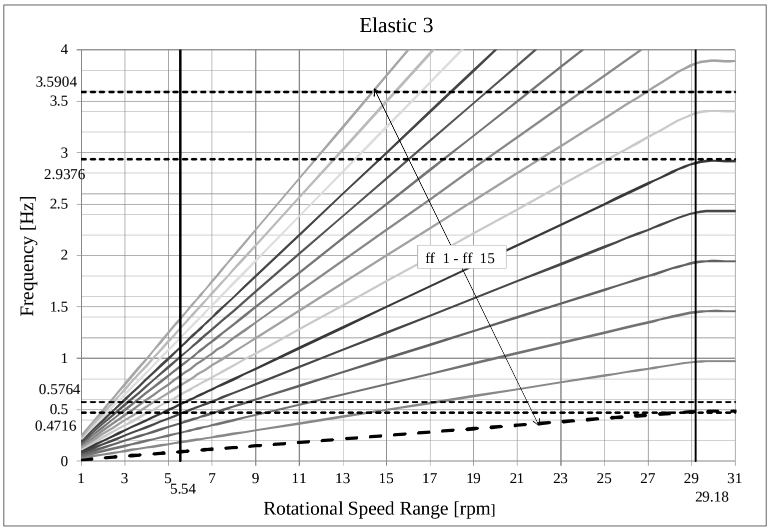

Fig. 7 – Resonance diagrams for the model with “Elastic 3” spring.

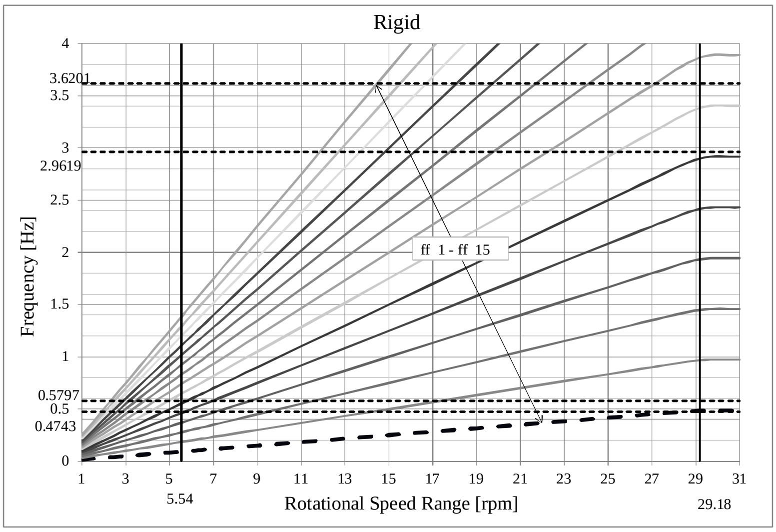

Fig. 8 – Resonance diagram for the model with rigid base.

The frequencies $f_{f1},\dots, f_{f15}$ from the resonance diagrams were computed with the following relation:

$$f_f = \frac{in}{60}, \tag{5}$$

where: $i = 1\dots15$ and n = 1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, 27, 29, 31.

It is necessary that the first frequency, f_{f1}, avoid the entering the variation range of the first frequency of the tower until the rotor reaches the speed of 29.18 rpm.

The aim of choosing three types of elastic supports was to establish a minimum stiffness limit of the foundation soil as to avoid the operational frequencies of the wind turbine in the range of the tower's frequencies.

From the resonance diagrams it can be concluded that the minimum rotational stiffness of the dynamic soil structure interaction can be: $k_\theta = 5.5 \times \times 10^{10}$ N.m/rad.

3.2. Case Study *B*

The entire soil–foundation - wind turbine structure was modeled using FEM. The model used is presented in Fig. 9.

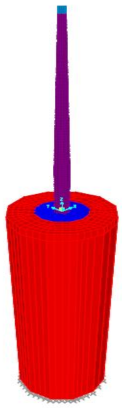

Fig. 9 – Model of the soil–foundation - wind turbine.

Table 3 presents the characteristics of the four types of foundation soils used in the analysis. The names of the soils are given after their shear wave velocity. Also the soil classes correspond to the SR EN 1998-1:2004 standard.

Table 3
Foundation Soils Characteristics

Soil type	Shear waves velocity m/s	Soil class SR EN 1998-1:2004	Poisson's ratio, ν	Density, γ N/m^3	Elastic modulus, *E* N/m^2	Shear modulus, *G* N/m^2	k_x N/m^3
V150	150	D	0.45	19,620	4,804,940	1,656,875.9	3.5×10^6
V300	300	C	0.4	20,000	13,757,818	4,913,506	6×10^6
V600	600	B	0.35	22,000	23,534,400	8,716,444	35×10^6
V900	900	A	0.3	25,000	50,000,000	19,230,769	70×10^6

From the dynamic analysis the natural frequencies of the tower considering the same type of foundation but different types of soils were determined. The variation range of the frequencies was considered to be of ±10%. Table 4 presents the results obtained from the dynamic analysis.

Table 4
Natural Frequencies and Periods of Vibration of the Model

Mode of vibration	Type of soil	Frequency Hz	Frequency +10% Hz	Frequency –10% Hz	Period of vibration s
1	V150	0.445	0.4895	0.4005	2.242
	V300	0.499	0.5489	0.4491	2.002
	V600	0.514	0.5654	0.4626	1.942
	V900	0.521	0.5731	0.4689	1.917
2	V150	1.5743	1.73173	1.41687	0.635
	V300	2.5212	2.77332	2.2690	0.396
	V600	3.084	3.3924	2.7756	0.324
	V900	3.243	3.5673	2.9187	0.308

The diagrams of resonance presented in Figs. 10,…,13 were realized using eqs. (4) and (5). The same requirement was kept namely to avoid that the first frequency, f_{f1}, belog to the variation range of the first frequency of the tower until the rotor reaches the speed of 29.18 rpm.

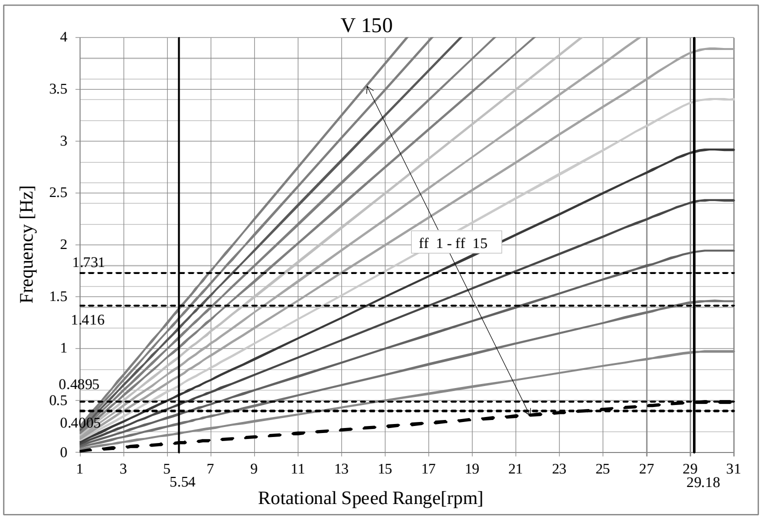

Fig. 10 – Resonance diagram for the model with V150 soil.

The resonance diagrams were performed in order to establish the minimum type of foundation soil on which this type of wind turbine can be placed.

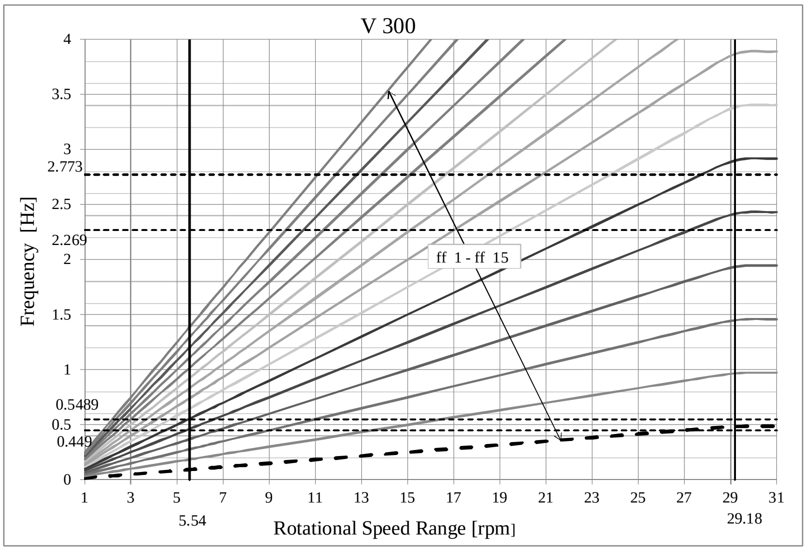

Fig. 11 – Resonance diagram for the model with V300 soil.

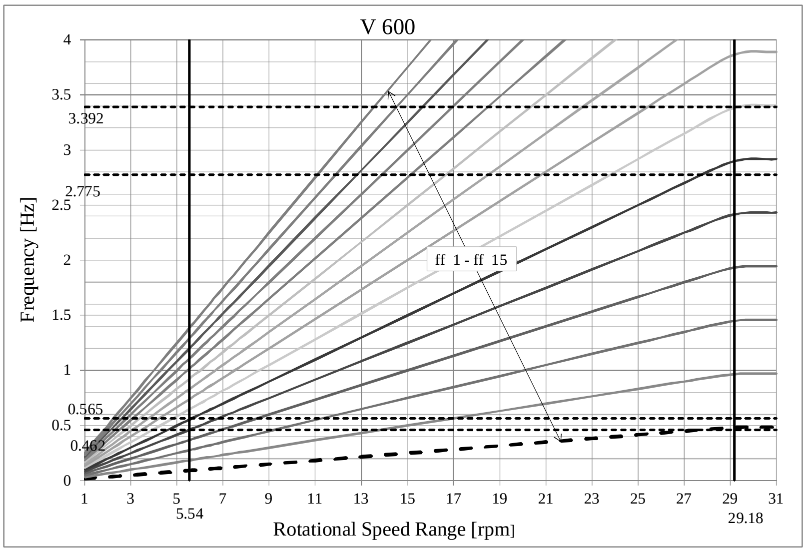

Fig. 12 – Resonance diagram for the model with V600 soil.

From the resonance diagrams it can be noticed that the V150 type of soil is the most disadvantageous because the first operational frequency of the wind turbine is entering in the resonance domain before the turbine reaches the maximum operational speed. Therefore the minimum type of soil to be used for this type of wind turbine and foundation system is V600 with the specific characteristics given in SR EN 1998-1:2004.

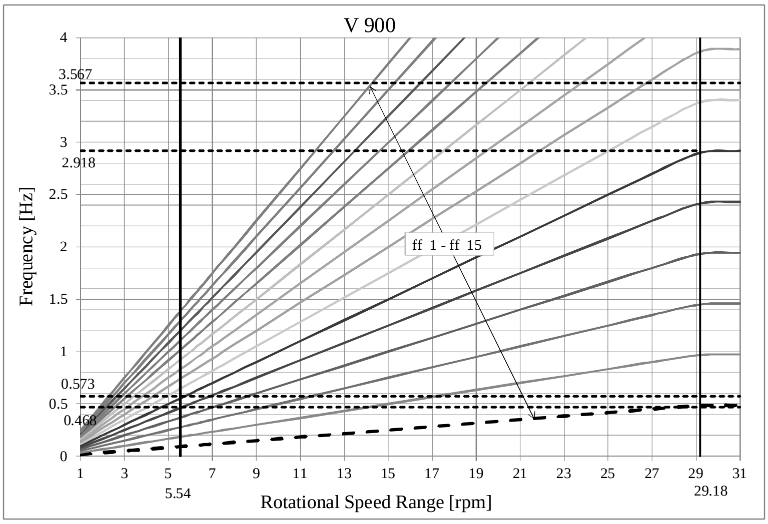

Fig. 13 – Resonance diagram for the model with V900 soil.

3.3. Comparison of the Results

It can be noticed after this analyses that by considering the soil–structure interaction the frequencies of the model are smaller in comparison to the frequencies of the model with a rigid base. This reflects also in the lower limit range of the tower's frequencies which may lead to a higher possibility that the operational frequency of the wind turbine coincide with the frequencies of the tower. Therefore care must be taken in considering the minimum allowable stiffness of the soil as for a higher safety level to be provided. Certainly, for limit values, like in the present case, the wind turbine producers are prepared to offer solutions. The limit situations of the resonance ranges can be avoided by equipping the wind turbine with a speed limitation device.

As for the methods used for modeling the soil structure interaction it can be noticed a resemblance between the results for the models with soil type V 300, V 600, V 900 and the one's with stiffness springs "Elastic 1", "Elastic 2" and "Elastic 3".

Table 5 presents a comparison between the values of the frequencies obtained in these cases.

Table 5

Comparisons Between the Results Obtained in Case A and Case B

Types of soils	Frequency, [Hz]	Types of soils	Frequency, [Hz]
Elastic1	0.505	V300	0.499
Elastic 2	0.513	V600	0.514
Elastic3	0.524	V900	0.521

The similarities between the obtained results highlight the idea that if care is taken when choosing the characteristics of the foundation soil, the results obtained using the substructure method are almost equal to those obtained using FEM. Therefore the decision of choosing the solving method for soils structure interaction is up to the experience and interpretation of the designer.

4. Conclusions

The natural modes of vibration and the frequencies of the entire soil–foundation–wind turbine system play an important role in wind turbine analysis. Based on this analysis it can be noticed that considering soil–structure interaction is a very important aspect in order to avoid entering the resonance range. By considering a rigid base in case of a dynamic analysis of a wind turbine – soil system the results can be misleading and therefore they can provide a false safety factor. Also by considering soil stiffness the entire system has smaller frequencies than considering the structure with a fixed base. This aspect is reflected in a lower limitation range of the tower's frequencies which can imply a higher possibility for the operating frequency to coincide with the tower's frequency. Therefore care must be taken when choosing the right foundation solution based on the type of soil it can be found on the construction site. The design codes and other references provide simplified computational relationships for spring stiffness as for the designer to be able to consider an elastic support. Thus, is highly important to take into account the soil structure interaction in dynamic analyses of wind turbines.

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INTERACȚIUNEA TEREN–STRUCTURĂ ÎN CAZUL UNEI TURBINE EOLIENE

(Rezumat)

Construirea turbinelor eoliene începe să se extindă şi să devină o necesitate pe teritoriul țării noastre. Întrucât România se află într-o zonă activă din punct de vedere seismic, în analiza turnului turbinelor eoliene este necesar să se ia în considerare, pe lângă acțiunea vântului, şi acțiunea seismică. O modalitate de evaluare a răspunsului structural la acțiuni dinamice o constituie cunoaşterea modurilor proprii de vibrație ale structurii. Acest aspect devine de o importanță semnificativă în analiza unei turbine eoliene deoarece este necesară evitarea intrării în domeniul de rezonanță. Pentru evidențierea efectelor interacțiunii teren–structură se utilizează, în principal, două metode: metoda pe substructuri, în care rigiditatea terenului este luată în considerare prin intermediul unor resorturi şi metoda elementului finit prin care se discretizează structura şi terenul de fundare. Se prezintă rezultatul unei comparații între rezultatele analizelor dinamice ale unei turbine eoliene cu o înălțime de aproximativ 70 m utilizând ambele metode menționatate anterior pentru realizarea analizei.