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Dynamic modeling of wind turbines. How to model flexibility into multibody modelling

A. Cetrini[a], F. Cianetti[a]*, F. Castellani[a], D. Astolfi[a]

University of Perugia - Department of Engineering, via Goffredo Duranti 67, 06125 Perugia, Italy

Abstract

This work is part of a research activity inserted into "Smart Optimazed Fault Tolerant WIND Turbines (SOFTWIND)" project of PRIN 2015, funded by the Italian Ministry of the University and Research (MIUR). The need to define a robust multibody modelling procedure to realistically characterize the dynamical behavior of a generic wind turbine and to have a reduced computational burden has pushed the authors to adopt a freeware software called Nrel-FAST, that is universally considered to be a reference in the field of aeroelastic wind turbine simulations. The lightness of this software is paid in terms of modelling simplicity, which makes the modelling of wind turbines with unconventional support structures (i.e. that con not directly outlined as a fixed-beam) difficult. In this paper, some methodologies to overcome this obstacle are presented, including the use of a more powerful multibody software which, on the other hand, entails higher simulation times. In particular, the authors present a methodology based on structure stiffness-matrix reconstruction that allows, under appropriate hypothesis, to reduce a complex wind turbine support frame to a simple fixed beam so that the simulations can be done directly in FAST environment, with low computational times. The results obtained from these different approaches are compared using as test-case a small wind turbine property of University of Perugia (UniPG).

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Keywords: multibody, wind tubine, FEM

* Corresponding author. Tel.: +39-075-5853728; fax: +39-075-5853703.
E-mail address: filippo.cianetti@unipg.it

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1. Introduction

The present work is part of a research activity funded by the Italian Ministry of Education, University and Scientific Research (MIUR) in the context of the PRIN Call (Research Projects of National Interest) 2017. The project, entitled SOFTWIND (Smart Optimized Fault Tolerant WIND turbines), is coordinated at the national level by the University of Camerino and is developed by four operating units (University of Camerino, Polytechnic University of Marche, University of Lecce and University of Perugia). The three-year project aims at developing intelligent control systems aimed at minimizing loads and thus maximizing the life of large generators (Corradini et al. (2016), Castellani et al. (2017), Scappaticci et al. (2016)).

Nomenclature

n	Number of degrees of freedom
m	Mode number
t	Time vector
w	Number of representative nodes of finite element model
$\overline{\boldsymbol{F}}_r$	Generalized active forces
$\overline{\boldsymbol{F}}_{r^*}$	Generalized inertial forces
$u(z,t)$	Beam axis displacement
$\emptyset_a(z)$	Beam mode shapes
$q_a(t)$	Beam generalized coordinates
$\varphi_h(z)$	Shape functions
$\underline{C}_{ah}$	Interpolating polynomial coefficients
$\overline{\boldsymbol{F}}$	Nodal forces vector
$\underline{\boldsymbol{K}}$	Stiffness matrix
$\underline{\boldsymbol{M}}$	Mass matrix
$\underline{\boldsymbol{C}}$	Damping matrix
$\overline{\boldsymbol{x}}$	Nodal displacement
$\underline{\boldsymbol{A}}$	Flexibility matrix
u_x	Nodal displacement along fore-aft direction
u_y	Nodal displacement along side-side direction
u_z	Nodal displacement along axial direction
θ_x	Nodal rotation along fore-aft direction
θ_y	Nodal rotation along side-side direction
θ_z	Nodal torsional rotation
E	Young’s modulus
A	Beam section area
J_x	Beam side-side area moment of inertia
J_y	Beam fore-aft moment of inertia
L	Beam length
$\underline{\overline{\boldsymbol{Z}}}$	Matrix of the interpolating polynomial coefficients
$\underline{\emptyset}_{\mathrm{FE}}$	Finite element model mode shapes
$\overline{\boldsymbol{v}}$	Wind velocity vector
Δf	PSD frequency domain

The authors operative unit has as its aim the development of predictive techniques of fatigue behavior of the generic generator using theoretical or numerical models for the prediction of dynamic behavior or damage (Wang et al. (2013)).

In the context of this research activity, the software used for aeroelastic multibody modeling of wind turbines is Nrel FAST v7 (Fatigue Aerodynamics Structure and Turbulence) (Jonkman (2005) and Moriarty(2005)), which is an international reference in this field, developed at the National Rewenable Energy Laboratory which has based in Golden, Colorado (USA).

The aim of this work is to present a methodology that allows, under appropriate hypotheses, to reduce a complex support frame of a generic wind generator to a structure that can be modeled as a simple cantilever beam, as required by Nrel FAST. Although the methodology developed has its own life and can be used in various applications, this work is configured as a procedural iter, preceded by a theoretical introduction, oriented to its use within FAST environment.

Complex support structures, such as braced or tied towers, are used in those situations where the turbines, due to a non-optimal design of the tower, can reach very high levels of vibration that are mainly due to an inflection for example in the Fore-Aft direction, i.e. perpendicular to the rotor plane. This situation occurs in particular when the loads transmitted to the tower have frequency contributions close to one of the resonance frequencies of the structure. Furthermore Offshore wind turbines usually uses tripod, jacket or other kinds of complex supporting frames.

Nrel FAST implements the equations of motion by modal approach (Jonkman (2005)), schematizing the tower as a simple cantilever beam with two bending modes in the Fore-Aft direction and two bending modes in the Side-Side direction. As consequence it is impossible to study a complex structure within this code, except by modifying the Fortran algorithms of the source code. As an alternative, it is necessary to migrate into more versatile multibody simulation environments, which however generally have much higher computational costs. In this sense, therefore, the proposed method can be helpful for the simulation of the support structures directly within the FAST code.

In Section 2 of this paper the theoretical bases for the multibody modeling of wind turbines implemented in Nrel FAST are introduced. In particular, the focus is on modeling the flexible tower. The initial part of Section 3 presents the theoretical and applicative bases of the method of reduction of the complex support structure to that of the cantilever beam, highlighting its limits and strengths. This methodology can be practically carried out within a generic Finite Element Analysis environment. The procedure is also explained for the use of the method within the Nrel FAST software. The procedure has been validated by adopting a commercial wind turbine analyzed in a previous paper by authors (Cianetti et al. (2018)). In Section 4 the dynamic characterization of Nrel FAST model obtained by the proposed method is compared with those obtained by adopting detailed MBS models developed in a reference commercial code.

2. Overview of multibody modeling and simulation in Nrel FAST

2.1 Kinematics and Dynamic modeling in Nrel FAST

The kinematic and dynamic formulation implemented by the Nrel FAST code does not follow a classic approach. Within this simulation environment "relative" degrees of freedom (Lagrangian coordinates in the strict sense) and not absolute degrees are used. This avoids the writing of constraint equations that would serve to guarantee the kinematic congruence between the bodies of the system (Shabana (2005)).

The equations of motion used are called "Kane's Equations"(Purushotham et al. (2013)), which are not defined by an energetic method so are not constructed by deriving the kinetic energy and the potential energy, thus decreasing the computational burden.

Kane's Equations arise from the application of the D'Alambert principle, the generalized active forces $\overline{\boldsymbol{F}}_r$ and generalized inertia forces $\overline{\boldsymbol{F}}_{r^*}$ balance is achieved during motion (1):

$$\overline{\boldsymbol{F}}_r + \overline{\boldsymbol{F}}_{r^*} = \overline{\boldsymbol{0}} \qquad (1)$$

by defining with r the index of the $r-th$ degree of freedom of the system ($r = 1 \dots n$). These equations constitute a system of n differential equations in n unknowns.

Since the model has flexible bodies such as the tower or the blades, the inertia forces of these components and the active damping and elastic forces are defined by an integral formulation that uses distributed parameters, defined by the user in phase of pre-processing.

2.2 Flexible body implementation in Nrel FAST

The Nrel FAST code models the components of the generator as rigid bodies, except for the tower and the blades which can also be defined as flexible. In contrast to the case of rigid bodies, whose configuration is defined by a maximum of six independent parameters, the configuration of a deformable body is defined by an infinite number of coordinates.

However, for computational problems, infinite coordinates can't be used, so it is necessary to have a finite number of degrees of freedom (Shabana (2005), Holm- Jorgensen(2009)). In most multibody modeling software this is done through an approach that, through or finite elements (ADAMS, SIMPACK) or, as in FAST, analytically, adopts modal modeling and modal truncation: the components of the deformation field are expressed as a linear combination, extended to a finite number of terms, of time functions (natural coordinates) and spatial functions (modes).

FAST uses the reductive but simplifying hypothesis that the tower and the blades are fixed beams with distributed mass and stiffness. For these bodies it is possible to perform a modal truncation that only leads to the involvement of modal forms considered fundamental for the motion. In particular, referring to the case of a simple cantilever beam, defining with $u(z,t)$ the displacement of the beam axis line in only one direction (2):

$$u(z,t) = \sum_{a=1}^{m} \emptyset_a(z) q_a(t) \tag{2}$$

The Rayleigh-Ritz method allows to approximate the modal forms $\emptyset_a(z)$ as the sum of a set of functions called "shape functions"(3):

$$\emptyset_a(z) = \sum C_{a,h} \varphi_h(z) \ \ (a = 1,2 \ldots m) \tag{3}$$

In FAST environment the modal forms are defined analytically by means of sixth grade polynomials of the following type (3):

$$\emptyset_a(z) = \sum_{h=2}^{6} C_{ah} (z)^h \tag{4}$$

Regarding modal truncation, the number of modes is predefined and limited to four, associated with the first two bending modes in each of the two main planes of the component, i.e. two Fore-Aft (FA) modes and two Side-Side (SS) modes for the tower.

3. Theoretical bases and application of the method

3.1 Reference theory for the developed method

As mentioned in Section 1, this article presents a methodology that allows, under appropriate hypotheses, to reduce a complex support structure of a wind turbine to that of a simple cantilever beam in such a way as to guarantee an equivalence in static and dynamic terms. This allows simulating the reduced structure within the FAST software in an immediate way, without changing the source code. The developed method can be briefly summarized by Fig (1).

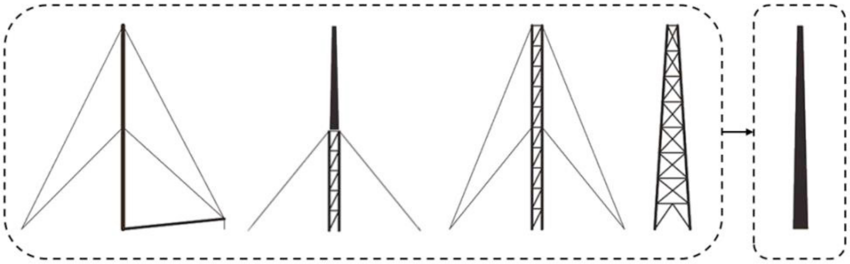

Fig. 1. Reduction of a generic Wind Turbine structure to a monopile equivalent one

Starting from the complex generator support frame, through a FEM simulation environment, the structure can be reduced to an equivalent one, corresponding to a simple fixed beam.

The procedure, even if developed for wind turbines, has a general validity and is useful to reduce whatever complex structure to a simplified one. It is applicable to both mixed-frame wind turbine, i.e. the supporting frame consists of a tower and a more complex part near the ground (jacket frame, tripod frame etc..) for which the method is applied in this paper, and completely-complex support frames such as lattice tower frames. In this process, under appropriate hypotheses, a static and dynamic equivalence is guaranteed between the two structures.

The theoretical background where this method take place is that of the Finite Elements Analysis (Rao (1990)). As known, the equation of motion that defines the dynamics of a finite element system is (5):

$$\underline{\boldsymbol{M}}\,\ddot{\bar{\boldsymbol{x}}}(t) + \underline{\boldsymbol{C}}\,\dot{\bar{\boldsymbol{x}}}(t) + \underline{\boldsymbol{K}}\,\bar{\boldsymbol{x}}(t) = \bar{\boldsymbol{F}}(t) \tag{5}$$

When the finite element system is defined by a number of degrees of freedom that is too high, it is possible to reduce the system by means of various reduction techniques, such as Guyan Reduction (Rao (1990)), which allows to define a superelement. However, the method developed in this paper does not follow the Guyan Reduction technique because FAST, as outlined in Section 3.2, requires the introduction of physical parameters referred to the equivalent structure (i.e. linear mass, flexural stiffness and polynomial coefficients for the reconstruction of mode shapes) and therefore it is useful to have a FEM model of the fixed beam equivalent structure.

As consequence the complex part of the supporting frame (for mixed structures) or the entire support structure (for complex support frames) is replaced by a cantilever beam with appropriate geometrical and inertial parameters.

This parameters has been defined in such a way as to present, for its top node, the same displacements and the same rotations, related to the Fore-Aft direction, presented by the same node of the original structure when the same loads are applied (See Fig. 2.).

To achieve this goal, defining with $u_x,\ u_y, u_z, \theta_x, \theta_y, \theta_z$ the top-node displacements and rotations of the original non-fixed-beam structure (that has to be the same of the equivalent fixed-beam) along the main axes x, y and z when unit forces and moments are applied at the tower-top node, the problem has been solved by using the inflexed beam equations known from structure mechanics (Timoshenko (1970)) that can be summarized from (6) to (11):

$$u_x = \frac{F_x L^3}{3EJ_y} + \frac{M_y L^2}{2EJ_y} = u_{x,Fx} + u_{x,My} \tag{6}$$

$$u_y = \frac{F_y L^3}{3EJ_x} + \frac{M_x L^2}{2EJ_x} = u_{y,Fy} + u_{y,Mx} \tag{7}$$

$$u_z = \frac{L}{EA} = u_{z,Fz} \tag{8}$$

$$\theta_x = \frac{F_y L^2}{2EJ_x} + \frac{M_x L}{EJ_x} = \theta_{x,Fy} + \theta_{x,Mx} \tag{9}$$

$$\theta_y = \frac{F_x L^2}{2EJ_y} + \frac{M_y L}{EJ_y} = \theta_{y,Fx} + \theta_{y,My} \tag{10}$$

$$\theta_z = \frac{L}{J_p G} = \theta_{z,Mz} \tag{11}$$

For the equations reported, the first member is known from the static analysis performed into the FEA environment and the forces and moments that appear are those transported, starting from the top node of the tower, at the top-node of the equivalent fixed beam i.e. $F = 1$, $M = 1 \cdot L = L$. However, the previous system is unsolvable for all the parameters, J_x, J_y, J_p, L and A. Therefore the parameter values that has been determined are L, A, J_p and J_y (i.e. length of the beam, area and inertia moments around the y and polar axis) such as to verify the equations (6), (8), (10) e (11).

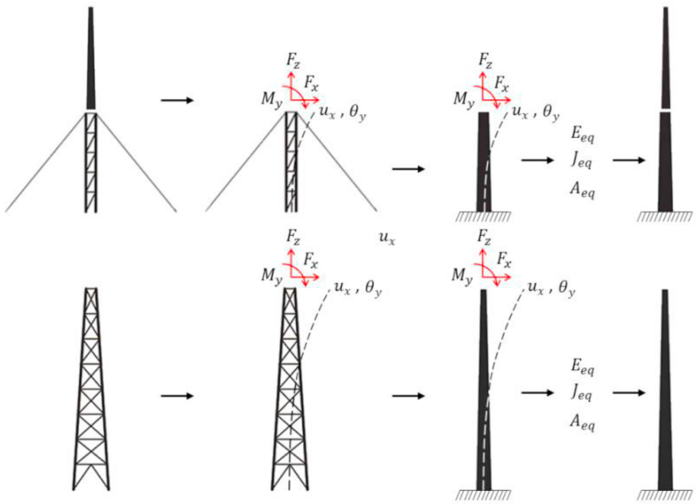

Fig. 2. How to reduce complex structure into equivalent one.

This ensures the equivalence between the original structure and the cantilever beam structure for the Fore-aft direction but not for the Side-Side direction. This approximation is not too limiting if we consider that the loads act mainly in this direction. The parameters obtained must be used as input for a "beam" element within the FEM model.

The theory described above can also be translated in order to involve the stiffness matrix, in fact the replacement of the non-beam part with the equivalent beam is essentially translatable to the creation of an equivalent stiffness matrix, in some appropriate elements, to that of the original structure. As known from Finite Element theory, the structure stiffness matrix $\underline{\boldsymbol{K}}$ statically binds the nodal displacements of the degrees of freedom of the Fem model to the corresponding forces according to formula (12):

$$\overline{\boldsymbol{F}} = \underline{\boldsymbol{K}}\,\overline{\boldsymbol{x}} \tag{12}$$

The matrix $\underline{\boldsymbol{K}}$ can be obtained, as well as automatically assembling the element stiffness matrices, also "manually" using the relation (12). In fact, if on the system under analysis it is possible to apply congruent or balanced displacement or force field and to find the corresponding binding reactions or displacements, the unknown terms of the same matrix can be obtained. Inverting the relation one arrives at Equation (13) in which $\underline{\boldsymbol{A}}$ is the "flexibility matrix", inverse of the structure stiffness matrix $\underline{\boldsymbol{K}}$.

$$\overline{\boldsymbol{x}} = \underline{\boldsymbol{K}}^{-1}\,\overline{\boldsymbol{F}} = \underline{\boldsymbol{A}}\,\overline{\boldsymbol{F}} \tag{13}$$

Equation (13) suggests that by applying a balanced force field to the system, which therefore must not be labile, constituted by a unitary force corresponding to one degree of freedom and the other zero, a corresponding displacement field is obtained that coincides with the first column of the matrix $\underline{\boldsymbol{A}}$. Thus, once the displacement field is calculated by any method, the first column of the matrix is known. Repeating this operation for all degrees of freedom (i.e. for all other columns) the matrix $\underline{\boldsymbol{A}}$ can be built and its inverse constitutes the matrix $\underline{\boldsymbol{K}}$.

The proposed method follows this approach, i.e., called i and j the degrees of freedom relative to input force and output displacement, the equivalent beam and the original structure have the same terms $\underline{A}(i, j)$ of the matrix $\underline{A}$. Finally, regarding the dynamic equivalence between the original and equivalent structure, this is so much respected the less the mass of the horizontal beam participates in the motion.

3.2 Implementation of the method in Nrel FAST environment

Once the equivalent structure has been created, a modal analysis is carried out and the mode shapes relative to the first two flexural modes in Fore-Aft and Side-Side directions are exported (Cianetti et al. (2018)).

Once the mode shapes have been exported, we must proceed, on the basis of equation (4), to determine the coefficients of the sixth-order polynomial which best approximate the fem-calculated mode shapes, and which constitute the input to the FAST tower file.

Using the method of least squares the 5 coefficients $\overline{\boldsymbol{C}}$ (of size 5 × 1) of the polynomial associated with the generic mode and to be imported into FAST can be obtained by the following relation (14):

$$\overline{\boldsymbol{C}} = [inv(\underline{\boldsymbol{Z}}^T \underline{\boldsymbol{Z}}) \underline{\boldsymbol{Z}}^T \, \overline{\emptyset}_{FE}] \tag{14}$$

Where $\overline{\emptyset}_{\mathrm{FE}}$ is a vector of dimension (w×1) corresponding to modal displacements, normalized with respect to the modal shift of the free end $\emptyset_{FE_w}$. That is, for the i-th node, the following applies $\overline{\emptyset}_{\boldsymbol{FE}_i} = \emptyset_{FE_i}/\emptyset_{FE_w}$. Instead, the matrix $\underline{\boldsymbol{Z}}$ represents a function matrix of the z coordinate values of the various nodes, normalized with respect to the component light L, $\bar{z}_i = z_i/L$. For the generic i-node the corresponding row of the matrix is represented by (15):

$$\underline{Z_i} = [\ \bar{z}_i^{\ 2} \ \ \bar{z}_i^{\ 3} \ \ \bar{z}_i^{\ 4} \ \ \bar{z}_i^{\ 5} \ \ \bar{z}_i^{\ 6}\ ] \tag{15}$$

Once the coefficients representing the four modal forms (2 FA and 2 SS) have been determined, they can then be imported into the dedicated section of the tower properties file. Furthermore, always starting from the model Fem of the equivalent structure, we must export the stiffness and inertial parameters, used within the FAST code as distributed parameters of the tower.

4. Validation of the proposed method

4.1 Test Case description

The method described in Section 3 was used to carry out simulations in FAST v7 using a mini three-blade wind turbine as test case, available at the Wind Tunnel of the Department of Engineering of the University of Perugia.

This is a variable-speed generator that follows a pre-defined power curve to maximize the extracted power.

The generator and the rotor are keyed on the same shaft without the interposition of a Gearbox. The representation of the generator is shown in Fig. 3, while many data for this machine are shown in Table 1 .

Fig. 3. Representation of the test case wind turbine and of its geometrical scheme

The support structure of the generator has been dynamically characterized by accelerometer tests carried out with instrumented hammer (Cianetti et al. (2018), Castellani et al. (2017)).

4.2 FE model reduction

As stated above, the objective of the paper is to present a method for transforming a generic support structure of a wind turbine into an equivalent cantilever beam structure.

Table 1. Test case wind turbine characteristics (see also fig.4)

Wind Turbine Parameters	**Values**	**Units**
Maximum Power	2800	W
Cut in Wind speed	3.0	m/s
Cut off Wind speed	15.0	m/s
Blades number	3	no units
Lp	1.0	m
Ht	0.98	m
Hv	0.55	m
Hacc	0.95	m
XG	0.13	m
YG	0.20	m

First of all, the Fem model of the original structure, proper to the turbine present in the wind tunnel, was built, Fig. 4, a. At this point, following the logic reported in Section 3.1, the equivalent cantilever-beam model was built, Fig. 4,b.

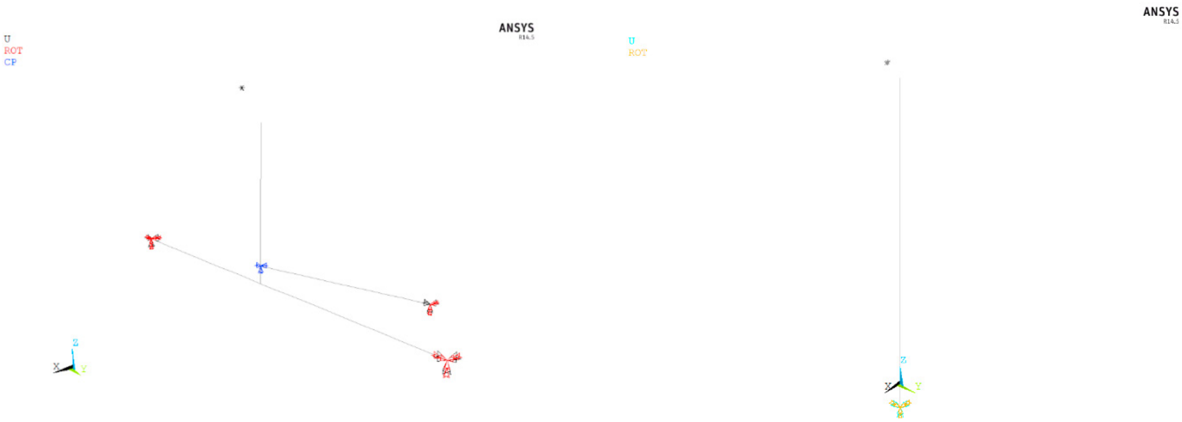

Fig. 4. (a) Original supporting frame Fem model; (b) Equivalent fixed-beam frame Fem model

Both structures are modeled with beam elements, and the Rotor, Nacelle and Blades masses and moments of inertia are represented by means of lumped masses placed above the Tower-Top.

The real support structure has been tuned with torsional springs acting in the Fore-Aft and Side-Side directions placed at the ends of the horizontal support crosspiece, in such a way as to present natural frequencies similar to those determined experimentally.

For the two structures the first four natural frequencies of the tower, two in the Fore-Aft direction and two in the Side-Side direction, are those shown in Table 2.

In Fig. 5 and Fig. 6 the displacement Frequency-Response-Functions are reported instead for the two structures compared, both in the Fore-Aft and Side-Side directions. Table 2 and Fig. 5 demonstrate that there is an excellent dynamical correspondence between the two structures for motion in the Fore-Aft plane as provided by the method. On the Side-Side direction, on the other hand, similar natural frequencies for the two structures are obtained, even if this was not foreseen by the developed methodology, as stated in Section 3.1.

Table 2. Comparison between natural frequencies of real support structure and equivalent support structure for Fore-Aft and Side-Side directions

Natural Frequencies [Hz]	**Original Structure**	**Equivalent Structure**
Fore-Aft frequency, fist mode	**5.4**	**5.8**
Fore-Aft frequency, second mode	**123.8**	**125**
Side-Side frequency, first mode	14.4	12.07
Side-Side frequency, second mode	134.4	140.9

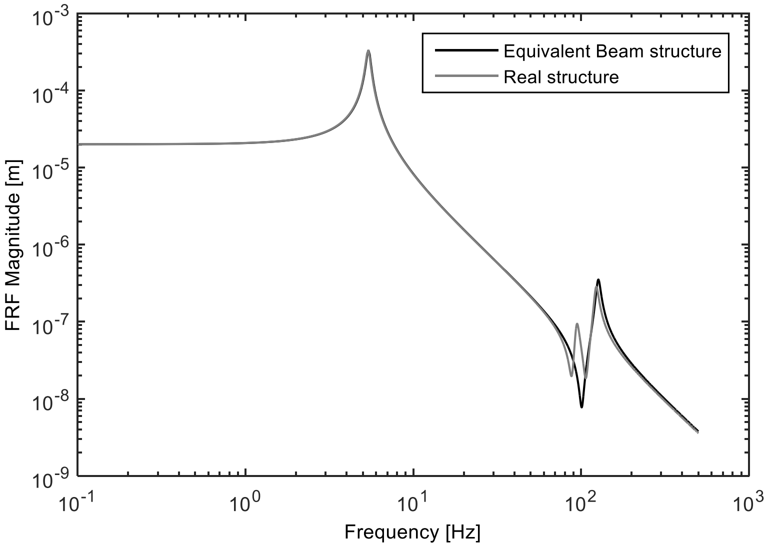

Fig. 5. Comparison between Tower-Top Fore-Aft displacement vs. Tower-Top Fore-Aft force FRFs

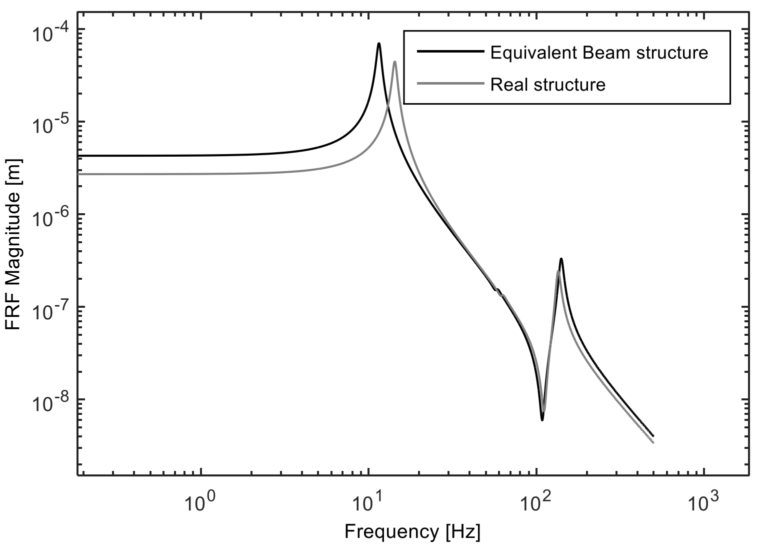

Fig. 6. Comparison between Tower-Top Side-Side displacement vs. Tower-Top Side-Side force FRFs

4.3 Method validation by multibody models

Once the equivalent cantilever-beam structure has been constructed, it is possible to build the Nrel FAST multibody model.

The structure has been introduced within the FAST code by the method reported in Paragraph 3.2. In this context a linear analysis was carried out which shows how the natural frequencies are still similar to those obtained from the modal analysis for the Fore-Aft direction, Table 3.

Table 3. Fast model natural frequencies

Natural Frequencies [Hz]	
First Fore-Aft mode	**5.5**
Second Fore-Aft mode	**125.5**
First Side-Side mode	12.5
Second Side-Side mode	140

Once the FAST multibody model with the equivalent support structure has been constructed, the process aimed at simulating the complex support structure through its equivalent structure directly inside FAST is concluded, and a wide spectrum of aeroelastic simulations can be performed.

To validate MBS modelling of complex structures into FAST, authors developed a MBS detailed model of the structure/system by adopting ADAMS/View code (Msc Software (2003)).

The wind turbine was modelled by adopting rigid parts connected each other by joints or stiffness matrix (i.e. blades) and flexible body for the principal structure (i.e. tower, crosspiece and tie).

The structure (See Fig. 4. (a)) were introduced by Component Mode Synthesis approach (Craig et al. (1968)) and then connected to other parts by joints (See Fig. 8. (c)).

To verify the fidelity of this model to the Fem complex model, a FRF was made, Fig. 7.

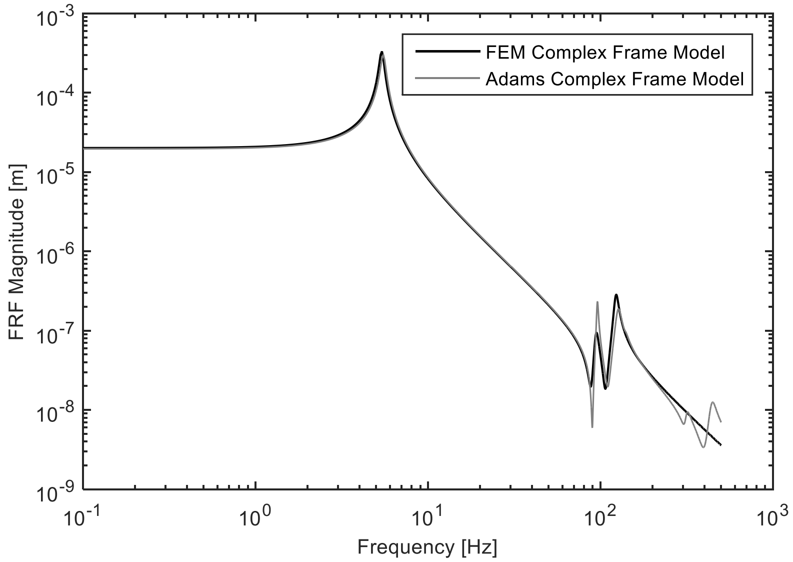

Fig. 7. Comparison between Tower-Top Fore-Aft displacement vs. Tower-Top Fore-Aft force FRFs for Adams and FEM model

The process of creating the complex Adams model just described has gone through the definition of two additional Adams models considered relevant for their simplicity.The first one, shown in Fig. 8, a, is automatically generated by the FAST software and is a lumped parameters model where the tower has been modeled with lumped masses connected by stiffness and damping matrices. The second model, Fig. 8, b, was obtained, starting from the first one, by replacing the sections of the tower with the "Craig-Bampton"(CMS) (Braccesi et al. (2004)) model of the simple cantilever beam. In particular, the latter model demonstrates how the developed method is of general interest, that is, it allows to convert a generic complex structure into an equivalent fixed beam structure that is certainly simpler to manage within the dynamic simulation software.

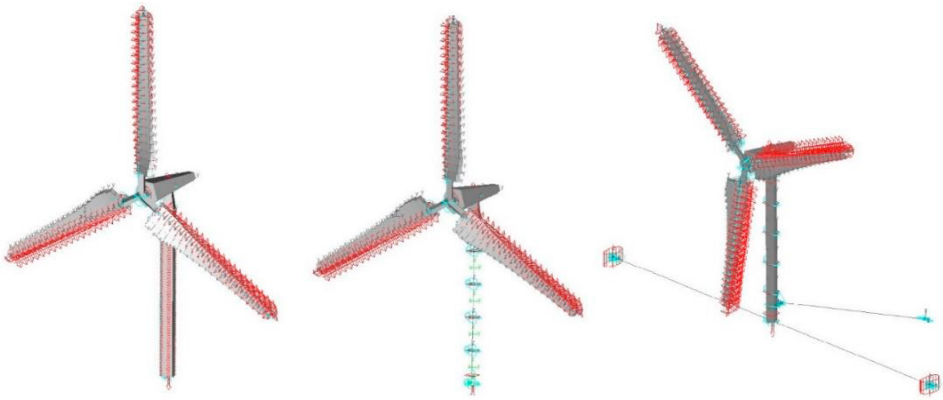

Fig. 8. (a) Lumped mass model, (b) Equivalent beam model, (c) Original structure model

All these three Adams models are dynamically equivalent to each other and show a good equivalence with the Fast model. This is shown in Fig. 9, where a comparison between the FRFs of the three Adams models and the Fast model has been done in terms of displacement vs. load. FRFs are obtained assuming the load applied at the tower top in Fore-Aft direction and measuring the resulting displacement along the same direction.

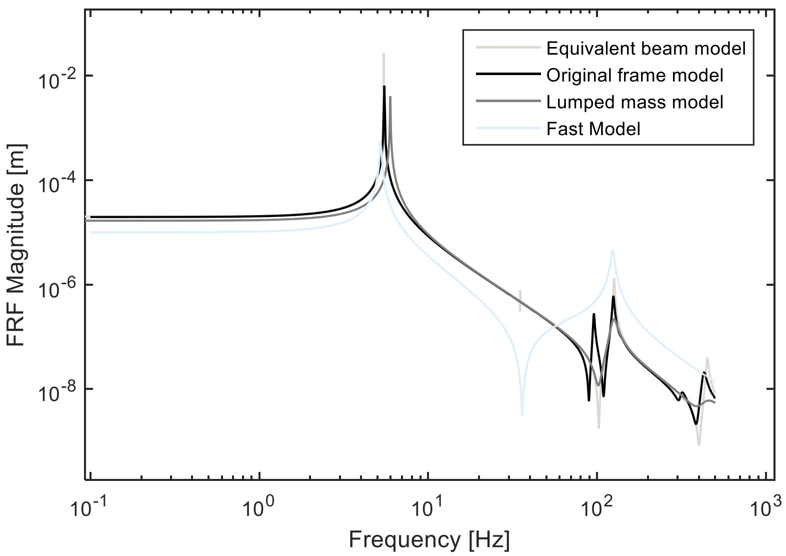

Fig. 9. Comparison between Tower-Top Fore-Aft displacement vs. Tower-Top Fore-Aft force FRFs

The observable differences between FAST FRF and Adams FRFs are probably attributable to the difficulties of implementation of the equivalent cantilever beam structure within the FAST software through the reconstruction of the polynomial modelling mode shapes.

This difficulty is given by the discontinuity of deformation between the equivalent beam part and the original beam part of the structure (See Fig. 1, right), and it is considered to be smaller if the two parts are more physically uniform.

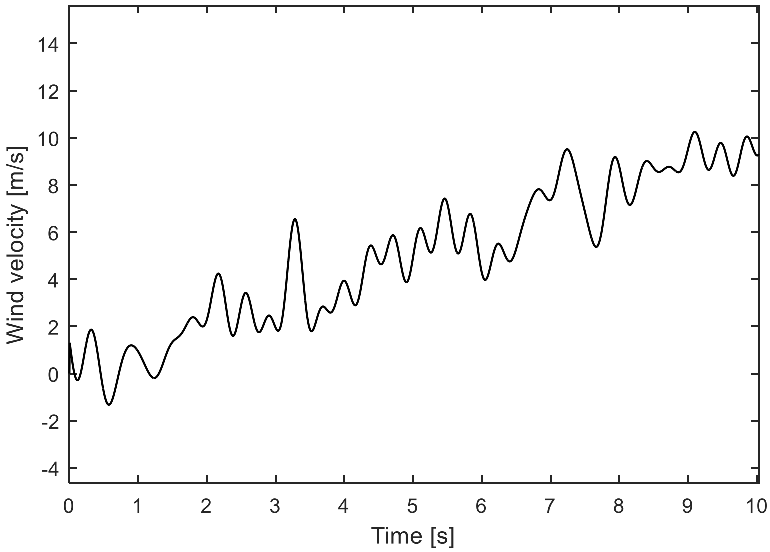

Fig. 10. Wind velocity signal used for numerical simulations

This hypothesis seems to be confirmed by the fact that the Lumped-Mass Adams model automatically generated by FAST, which does not require the introduction of modal forms by means of polynomial functions , shows a better correspondence to other Adams models. Moreover the mode of generating state matrices (i.e. concentrated force in Adams and wind distribution on the blades in Fast) can contribute to this difference. However all these results confirm the goodness and the applicability of the proposed method.

4.4 Comparison between time-marching simulations

The equivalence between the models can also be demonstrated by performing simulations over time using Aerodyn (Moriarty (2005)) to generate aerodynamic forces. In order to carry out the simulations it is obviously necessary to define the wind signal that is used as input.

In the context of this work, a routine that allows to generate a wind speed time signal that has a trend consistent with the physics of the phenomenon has been developed.

In aeroelastic numerical simulations, within Aerodyn software, wind is generally modeled analytically as a non-stationary vector field of velocity that has spatial domain defined in a plane region of appropriate size and parallel to the plane of the rotor:

$$\overline{\boldsymbol{v}} = \overline{\boldsymbol{v}}\,(\overline{\boldsymbol{x}}, t) \tag{16}$$

In performed simulations wind spatial variability is managed by defining some parameters in the wind file that the software Aerodyn uses as input. Basically these parameters define the laws with which the velocity components vary along the plane where the wind acts. The need to define a time history of speed (wind speed at the rotor height) consistent with the nature of the phenomenon has instead led to the development of the routine discussed above. The developed routine allows to build a long-term non-stationary random wind signal that is faithful to the physics of the phenomenon. This signal will be characterized by average values following a Weibull PDF around which are constructed shorter wind signals, for which the PDF is comparable as Gaussian and which can be described by three different spectral models thanks to the Power Spectral Density function: flat PSD, Von Karman PSD and Kaimal PSD (Jonkman B.J. (2012)). The long-term signal generated will be defined by a Weibull PDF and a PSD coinciding with that used to create the short-term signals that compose it. The simulations carried out have a duration of 10 seconds and so fall under the hypothesis of short term time history.

However, for these simulations it is assumed that the wind signal has a linearly increasing average value to enhance the comparison in terms of displacement between the developed models. The wind used as input has a

Gaussian PDF. In spectral content, on the other hand, it is defined by the creation of a constant PSD. i.e the Power Spectral Density assumes a constant value in a defined frequency range $\Delta f = f_{max} - f_{min}$. The wind signal used for the simulations, shown in Fig.10, is obtained considering a maximum PSD frequency of 3 [Hz] and a minimum value of 0.2 [Hz].

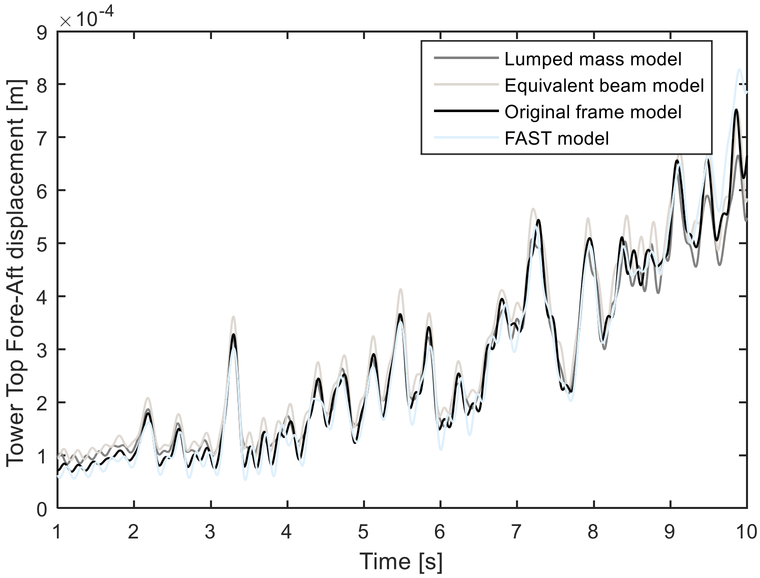

Fig. 11. Tower Top Fore-Aft displacement comparison

Fig. 11 shows the numerical results obtained by the analysis in terms of Tower Top Fore-Aft displacement without controlling the generator. The results are consistent with was previously obtained for FRFs.

5. Conclusions

This paper presents a methodology that allows, under appropriate hypotheses, to reduce a complex support frame of a wind generator (i.e. tripod frame, jacket frame, etc.) into an equivalent structure that can be modeled as a simple fixed beam.

This allows to simulate the dynamic behavior of the wind turbine using the internationally known aerodynamic simulation software Nrel FAST, that models the generator support system as a simple fixed beam.

The developed method is quite general and usable in any similar situations. To validate the proposed methodology, multibody models have been developed within the well-known commercial software ADAMS/ view.

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