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Dynamic modeling of wind turbines. Experimental tuning of a multibody model

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Abstract

This work is part of a research project funded by the Italian Ministry of the University and Research (MIUR), under the call for "National Interest Research Projects 2015 (PRIN 2015)", titled "Smart Optimized Fault Tolerant WIND turbines (SOFTWIND)". Within this project, the research unit of the University of Perugia (UniPG) aims to develop dynamic modeling and simulation methodologies and fatigue behavior evaluation ones for wind turbine as a whole. The development of these methodologies will be aimed at predicting the life of generic wind turbines, also providing important and fundamental parameters for optimizing their control, aimed at reducing the failures of these machines.
In the present paper, a small turbine, developed at the Department of Engineering of the University of Perugia, will be analyzed. The multibody modeling technique adopted and the experimental activity conducted in the wind tunnel of UniPG, needed for the tuning of the model, will be described.
The analysis of both model behavior and experimental data has allowed for the definition of a robust multibody modeling technique that adopts a freeware code (NREL - FAST), universally considered to be a reference in this field.
The goodness of the model guarantees the capabilities of the simulation environment to analyze the real load scenario and the fatigue behavior of this kind of device.

Keywords: Wind Turbines; Multi Body Simulation; Wind Tunnel Testing

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Nomenclature

n	system degrees of freedom
m	modes number
t	time vector
L	flexible body length
w	number of representative nodes of finite element model
$\boldsymbol{F_r}$	generalized active forces
$\boldsymbol{F_r^*}$	generalized inertia forces
$\boldsymbol{u_f}^i$	i-th point position of the body in the deformed configuration
$\boldsymbol{u_o}^i$	i-th point position of the body in the undeformed configuration
u_{fj}	deformation field components
$\emptyset_a$	modal shapes
q_a	natural coordinates
φ_b	shape functions
C_{ah}	interpolating polynomium coefficients
$\overline{\boldsymbol{C}}$	matrix of the interpolating polynomium coefficients
$\overline{\emptyset}^{FE}$	finite element model mode shapes

1. Introduction

This work is part of a research activity funded by the Italian Ministry of the University and Research (MIUR) of the Italian Government, under the call for "National Interest Research Projects 2015 (PRIN 2015)". The project, titled SOFTWIND (Smart Optimized Fault Tolerant WIND turbines, http://www.softwind.it/), is coordinated nationally by 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 time-frame project aims to develop intelligent control systems to minimize loads and thus to maximize the duration of large generators (Corradini et al. (2016), Castellani et al. (2017), Scappaticci et al. (2016)).

The working unit of the authors of this paper aims to develop fatigue behavior prediction techniques (Mršnik et al. (2018), Carpinteri et al. (2017), Wang et al. (2013) and Abdullah et al. (2009)) of the generic generator, also utilizing theoretical or numerical models to predict dynamic behavior and damage as detailed in Braccesi et al. (2016), and Cianetti (2012). To this aim, the activity also provides an experimental phase for the validation of simulation models and damage evaluation techniques.

In this paper, the problem of modeling and dynamic simulation of the generator is addressed. The reference software adopted is the international reference multibody (MBS) code adopted by the scientific community for modeling wind turbines: NREL FAST (Jonkman (2005) and Moriarty (2005)).

Paragraph 2 of the paper will introduce the main mechanical characteristics of a generic wind turbine. In the same paragraph, the MBS model code and code simulation logic will be schematically described and particular attention will be paid on modelling of the distributed flexibility of its main components: tower and blades.

In order to evaluate the goodness of the code both in standard and in non-classical conditions (i.e. wind tunnel simulation) a generator to be tested was identified. In view of the size of the wind tunnel available at the Department of Engineering of the University of Perugia (Italy), a micro generator was chosen which, although exempt from the PRIN project (large generators), still allows to verify the capacity of the code to simulate and apply real conditions and validate damage prediction models that will be developed. The test campaign conducted in the wind tunnel aimed at characterizing the dynamic behavior of the wind turbine (i.e. experimental modal analysis) and then addressing some tests under load at various wind pressure conditions (alias at various speed conditions). Paragraph 3 will describe the turbine and its multibody model made in FAST. In particular, the procedure to obtain the modal flexible tower model will be described.

Paragraph 4 describes the tuning of the modal tower model based on a series of numerical simulations both for finite elements (FE) and State-Space types, as shown by Braccesi et al. (2016), as well as MBS and on simple

experimental tests conducted with locked turbine.

In paragraph 5, the tests carried out in the tunnel at different wind regimes and the related simulations conducted in FAST are described. In the same paragraph, numerical and experimental results are compared and discussed. The experimental numerical comparison offered the opportunity to verify the goodness of the reference multibody code and to define a subsequent road map of the research activity.

2. Wind turbines and multibody modelling

Wind turbines are machines that allow to convert the kinetic energy of the wind, known as wind energy, into electricity. Constructively they are divided into Horizontal Axis (HAWT) turbines, the most common, and vertical axis (VAWT) ones in relation to the rotor rotation axis orientation (Holm-Jørgensen (2009)).

2.1. Wind Turbines

Horizontal axis wind turbines are the object of this activity (Fig.1). They are mainly composed of blades bent on a rotor, which is integral with a shaft that rotates at low rotation speed. The blades have a single degree of freedom: the pitch angle (see right side of Figure 1). The slow shaft through a gearbox transfers the motion to an high-speed rotating shaft connected to the generator. These components are contained within the so-called nacelle, which is connected to the tower by means of a bearing that permits the yaw rotation (see right side of Figure 1).

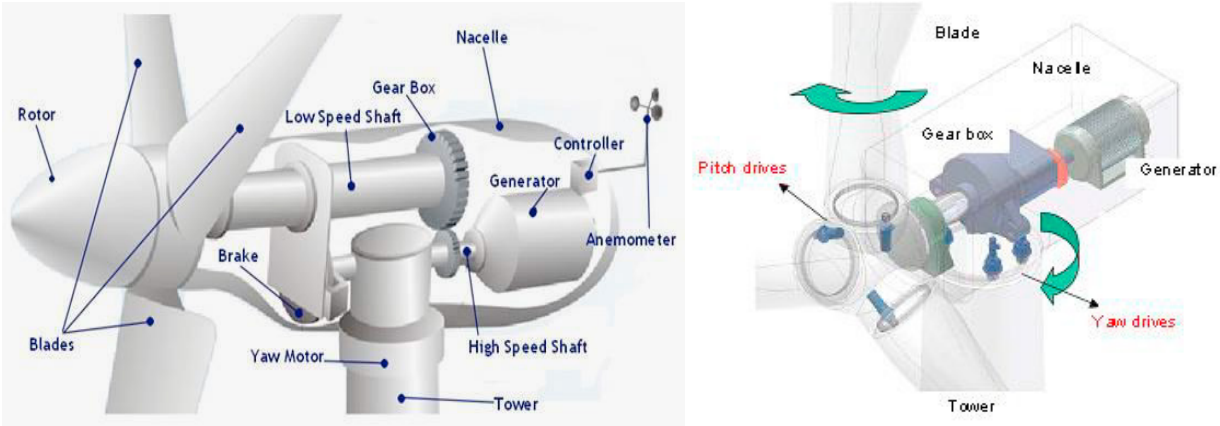

Fig. 1. Mechanical and kinematic description of an HAWT (from NREL FAST documentation (see Jonkman (2005))

2.2. Wind Turbines multibody modeling

Turbines for their kinematic simplicity are easily subjected to multibody dynamic modeling and simulation (Shabana (2005)).

The international reference software for modeling wind turbines is NREL FAST (Jonkman, Moriarty (2005)), developed by the National Renewable Energy Laboratory, owned by the United States Government that has based in Colorado. It is a freeware software shared on the web by a multitude of researcher and research organizations that, grown from a central core developed in Colorado, is continuously integrated by the community that adopts it. A general operation scheme of this development platform is shown in Figure 2 where the main stages of modeling and simulation can be identified: wind generation and simulation (Aerodyn module) (Moriarty (2005)), multibody modeling and dynamic simulation (Nrel Fast and Simulation modules). These are complemented by interfaces developed to control the generator in a user-defined modality (Simulink Control module) (Jonkman (2005)) and to generate a MBS model for the general purpose code ADAMS/Solver (MSC Software (2003)). It is also possible to linearize the generator in generic equilibrium conditions and make it available for off-line simulations.

A more accurate representation of the modeling and simulation steps is shown in Figure 3.

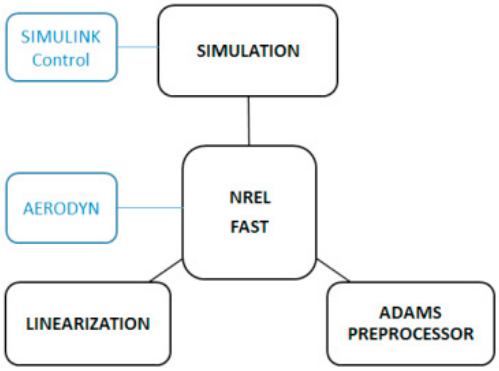

Fig. 2. Representation of MBS modelling and Simulation Platform of NREL FAST code

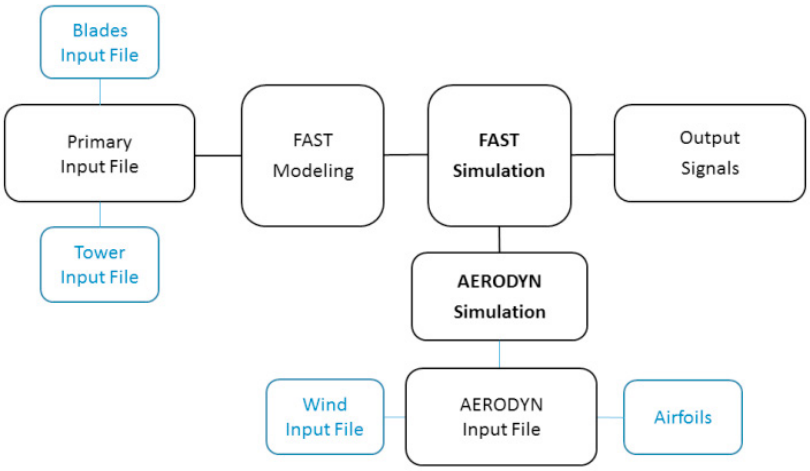

Fig. 3. Flowchart of NREL FAST modelling and Simulation steps

From a theoretical point of view, FAST modeling and simulation mode is not the classic one. Compared to commercial software that uses absolute degrees of freedom (dof), hence with kinematic congruence guaranteed by constraint equations, FAST uses only relative dofs so that it can "forget" constraints equations. It does not use energy methods (Lagrange) (Shabana (2005))for calculating motion equations, but uses Kane equations (Shabana (2005), Purushotham, (2013)). Kane's equations arise from the application of D'Alambert's principle (Shabana (2005)): the sum of the active $\boldsymbol{F}_r$ and inertia $\boldsymbol{F}_r^*$ generalized forces is equal to sero (1).

$$\boldsymbol{F}_r + \boldsymbol{F}_r^* = \boldsymbol{0} \tag{1}$$

defining with r the index of the r-th system *dof*. These equations are a system of differential equations of n equations in n unknowns (n are degrees of freedom of the system).

2.3. Flexible bodies multibody modeling

The code provides for rigid bodies modeling, but only for blades and tower, the ability to consider flexible/deformable bodies. On the contrary to the case of rigid bodies, whose configuration is defined by a maximum of 6 independent parameters, for deformable bodies it has to be considered that in general the position of

the body is defined by an infinite number of coordinates. By leaving formulas that regulate the kinematics of the flexible body, it can be asserted that the resulting motion is defined by the sum of a rigid motion and a deformation motion indicated by the deformation field described in (2):

$$\boldsymbol{u}_f{}^i = \boldsymbol{u}_f{}^i(\boldsymbol{u}_o{}^i, t) \tag{2}$$

That is, a vectorial function of a vectorial variable that associates the position at a moment t of a body point in the undeformed configuration $\boldsymbol{u}_o{}^i$ to the position of the same point in the deformed configuration $\boldsymbol{u}_f{}^i$. In this sense, infinite coordinates (those that define points position of underformed body) are needed to define the position of all the points of the deformed body.

However, for computational problems, infinite coordinates cannot be used, and finite dofs are needed. In most multibody codes, this is done by an approach that, through or finite elements (ADAMS as in Braccesi et al. (2004), SIMPACK as in Koutsovasilis et al. (2009)) or, as in FAST, analytical approach, adopts modal modeling and modal truncation: the deformation field components are expressed as a linear combination extended to a finite number of terms of time functions for function shapes (3) similar to what is encountered in the bending vibrations of solid continua:

$$u_{fj} \approx \sum_{k=1}^{l} a_{kj}(t)\, f_{kj}(x,y,z) \qquad \text{with} \qquad j = 1,2,3 \tag{3}$$

The structural model of NREL FAST has no way of importing any modal model of any number of modes and any constraint condition. The limiting but simplified hypothesis of the code which is adopted is that the tower and the blades are canteliver beams having mass and stiffness distributed.

Similarly to the vibrations of discrete systems, it is possible to express through the vibration modes the deformation in the space-time domain as a linear combination of modal shapes and of their respective natural coordinates q_a. In general, modal truncation can lead to the involvement of the sole (m) modal shapes considered fundamental for the motion:

$$u(z,t) = \sum_{a=1}^{m} \emptyset_a(z) q_a(t) \tag{4}$$

The Rayleigh-Ritz method (Shabana (2005)) allows to approximate the modal shapes $\emptyset_a(z)$ as a summatory of a set of function called "shape functions" φ_h (5):

$$\emptyset_a(z) = \sum C_{a,h}\varphi_h(z) \quad (a = 1,2\ldots m) \tag{5}$$

In FAST code, modal shapes are defined analytically by sixth degree polynomium of the following type (6):

$$\varphi_h(z) = (z)^h \tag{6}$$

Against the flexible body hypothesis always assimilated to a canteliver beam (zero displacement and rotation at the base), the first two coefficients of the sixth order polynomium are null and therefore the previous expression is reduced to the following (7):

$$\emptyset_a(z) = \sum_{h=2}^{6} C_{ah}(z)^h \tag{7}$$

Regarding modal truncation and hence the number of considered m modes for modeling flexible components in FAST, the number of modes is predefined and limited to 4 modes associated with the first two bending modes in each of the two main planes of the component: two fore-aft (FA) modes, in the vertical plane in which the longitudinal axis of the nacelle lies, and two side-side (SS) modes, in the plane normal to the previous one.

For example, if the first FA mode of the tower is considered, the previous expression (7) becomes:

$$\emptyset_{FA1}(z) = C_2 z^2 + C_3 z^3 + C_4 z^4 + C_5 z^5 + C_6 z^6 \tag{8}$$

The modal shape expressed by the polynomium must be characterized by the fact that the independent variable z is 1 at the free end (that is the independent variable must be normalized with respect to the length of the tower L) and that at the free end the value of the modal shape is also equal to 1, that is, the polynomium can be written according to the normalized abscissa:

$$\emptyset_{FA1}\left(\frac{z}{L}\right) = C_2\frac{z}{L}^2 + C_3\frac{z}{L}^3 + C_4\frac{z}{L}^4 + C_5\frac{z}{L}^5 + C_6\frac{z}{L}^6 \tag{9}$$

with the following condition:

$$\emptyset_{FA1}\left(\frac{z}{L}\right)|_{\frac{z}{L}=1} = 1 \tag{10}$$

It is obvious therefore that the sum of the coefficients C_j must be equal to the unit:

$$C_2 + C_3 + C_4 + C_5 + C_6 = 1 \tag{11}$$

From what is said the introduction of flexibility in the FAST model is reduced to the determination of the five coefficients of the polynomium approximating the modal shape.

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

Fig. 4. Representation of the test case wind turbine and of its geometrical scheme

3. Test case description

In order to evaluate the goodness of the code, especially in non-classical conditions (i.e. wind tunnel simulation),

a generator was found to be tested. In view of the size of the wind tunnel of the Department of Engineering of the University of Perugia (Italy), a three-bladed HAWT micro generator was chosen. The general characteristics of the generator are shown in Table 1 and its representation, in test configuration, in Figure 4, which also shows it geometric scheme. The Hacc parameter (not shown in Figure 4) refers to the height at which the accelerations were measured.

3.1. Multibody model

FAST multibody model is defined by the Primary Input File (Fig. 3). An example of a portion of the test case Primary Input File is represented in figure 5. It is in this file that the ability to model blades and/or tower as flexible components and to activate vibration modes (`FEATURE FLAGS`) is enabled.

In this paper, the tower modeling has followed a generalizable path adoptable for any tower and blade structural model, through the use of a generic finite elements code.

```
------------------------------------------------------------------------------
------- Primary input file -------------------------------------------------

---------------------- SIMULATION CONTROL -------------------------------------
   3        NumBl       - Number of blades (-)
---------------------- FEATURE FLAGS ------------------------------------------
  True      FlapDOF1    - First flapwise blade mode DOF (flag)
  True      FlapDOF2    - Second flapwise blade mode DOF (flag)
  True      EdgeDOF     - First edgewise blade mode DOF (flag)
  True      TwFADOF1    - First fore-aft tower bending-mode DOF (flag)
  True      TwFADOF2    - Second fore-aft tower bending-mode DOF (flag)
  True      TwSSDOF1    - First side-to-side tower bending-mode DOF (flag
  True      TwSSDOF2    - Second side-to-side tower bending-mode DOF (flag)
  True      CompAero    - Compute aerodynamic forces (flag)
---------------------- INITIAL CONDITIONS -------------------------------------
   50.0     Azimuth     - Initial azimuth angle for blade 1 (degrees)
   270      RotSpeed    - Initial or fixed rotor speed (rpm)
---------------------- TURBINE CONFIGURATION ----------------------------------
   1        TipRad      - The distance from the rotor apex to the blade tip (meters)
   0.133    HubRad      - The distance from the rotor apex to the blade root (meters)
   1        PSpnElN     - Number of the innermost blade element which is still part of
                          the pitchable portion of the blade for partial-span pitch
                          control [1 to BldNodes] [CURRENTLY IGNORED] (-)
   0.03     HubCM       - Distance from rotor apex to hub mass [positive downwind] (meters)
   0.24     OverHang    - Distance from yaw axis to rotor apex [3 blades]
                          or teeter pin [2 blades] (meters)
   0.1      NacCMxn     - Downwind distance from the tower-top to the nacelle CM (meters)
   0.13     NacCMzn     - Vertical distance from the tower-top to the nacelle CM (meters)
   1.2      TowerHt     - Height of tower above ground level [onshore]
                          or MSL [offshore] (meters)
   0.13     Twr2Shft    - Vertical distance from the tower-top to the rotor shaft (meters)
---------------------- MASS AND INERTIA ---------------------------------------
   0.7      YawBrMass   - Yaw bearing mass (kg)
  16.8      NacMass     - Nacelle mass (kg)
   6.32     HubMass     - Hub mass (kg)
   0.01     TipMass(1)  - Tip-brake mass, blade 1 (kg)
   0.01     TipMass(2)  - Tip-brake mass, blade 2 (kg)
   0.01     TipMass(3)  - Tip-brake mass, blade 3 (kg) [unused for 2 blades]
   0.18     NacYIner    - Nacelle inertia about yaw axis (kg m^2)
  0.013     GenIner     - Generator inertia about HSS (kg m^2)
  0.045     HubIner     - Hub inertia about rotor axis [3 blades]
                          or teeter axis [2 blades] (kg m^2)
```

Fig. 5. Test case FAST Primary Input File

Both the two FA modes and the two SS modes have been activated for the tower.

The finite element model (Fig.6) was made in ANSYS APDL environment by modeling the tower and the supporting structures (cross and diagonal) by beam elements to which the tower was constrained in the wind tunnel.

The suspended parts such as the rotor and the hub (nacelle) and the blades were modelled by means of a mass element (fig. 6) with appropriate mass and moments of inertia.

A procedure was developed to export modal shapes (1st and 2nd bending mode, FA and SS) and to determine of the sixth order polynomium coefficients (9), coefficients that implicitly fulfill the conditions set out in (10) and (11). Using the least square method (Rao 1990) the 5 coefficients $\overline{\boldsymbol{C}}$ (size 5 × 1) of the polynomium associated to the generic mode and to be imported into FAST can be obtained by the following relation:

$$\overline{\boldsymbol{C}} = [inv(\underline{\boldsymbol{A}}^{\boldsymbol{T}}\underline{\boldsymbol{A}})\underline{\boldsymbol{A}}^{\boldsymbol{T}}\overline{\emptyset}^{FE}] \tag{12}$$

in which $\overline{\emptyset}^{FE}$ is a vector of size w × 1 corresponding to the modal displacements (as many as the w nodes of the

principal model axis are), normalized with respect to the modal displacement of the free end $\overline{\emptyset}_w^{FE}$. That is, for the i-th node, the following applies: $\overline{\emptyset}_i^{FE} = \emptyset_i^{FE}/\overline{\emptyset}_w^{FE}$. The matrix $\underline{\boldsymbol{A}}$ instead represents a matrix, function of z (vertical) axis coordinates of the various nodes, normalized with respect to component L full length, $\bar{z}_i = z_i/L$, and of size $w \times 5$. For the generic node i, the corresponding row of the matrix is represented by the following line:

$$\underline{A}_i = [\ \ \overline{z}_i^{\,2} \quad \overline{z}_i^{\,3} \quad \overline{z}_i^{\,4} \quad \overline{z}_i^{\,5} \quad \overline{z}_i^{\,6}\ \ ] \tag{13}$$

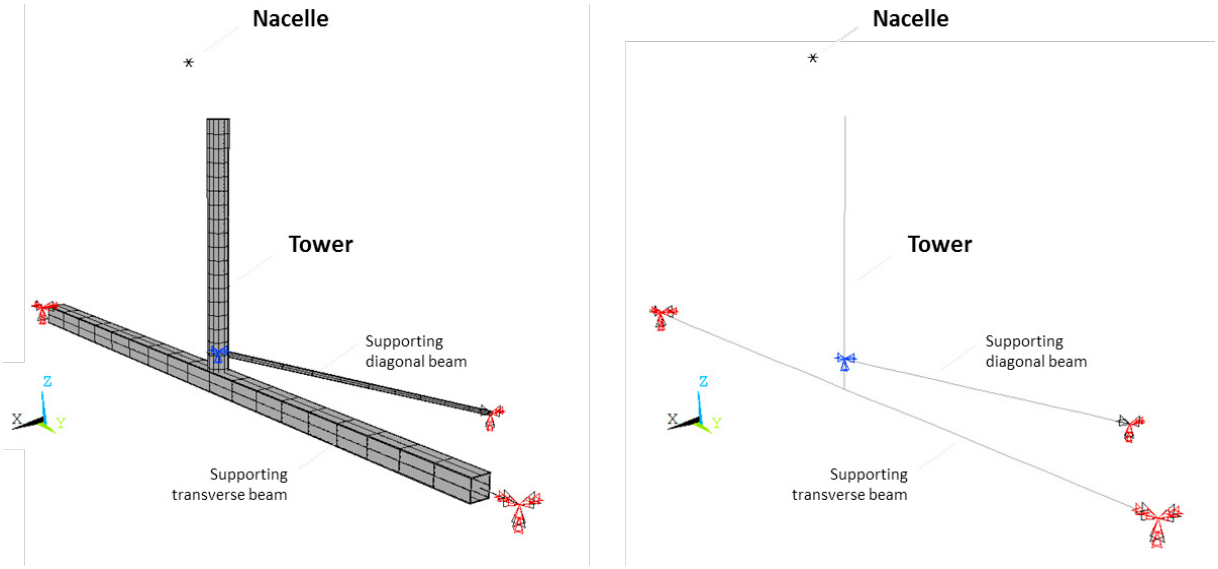

Fig. 6. FE model of Wind Turbine structure (tower, nacelle and supporting transverse beam). Shaped and wireframe representations

4. Modal model tuning

To verify that the FE model was correctly realized and eventually to tune it on the experimental behavior, a modal identification (Rao (1990), Meirovitch (2010)) was done on the wind turbine by experimental tests (hammer load condition and accelerometric measures). A first comparison was realized between the experimental results and those obtained by a modal superposition harmonic analysis realized by a consolidated state-space modeling

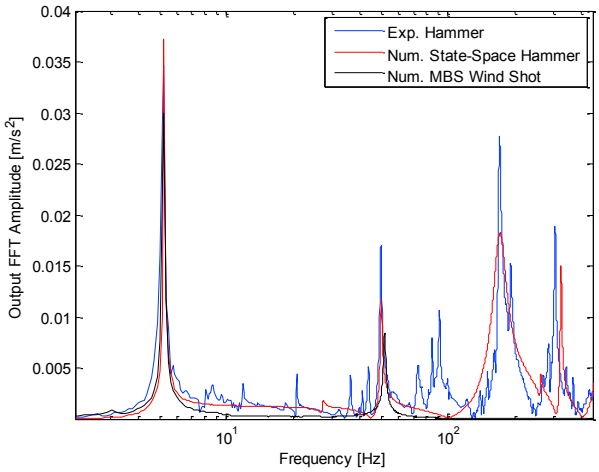

Fig. 7. Modal identification. Results comparison among experimental and numerical models (state-space and multibody)

procedure, shown in Braccesi et al. (2016), starting from the previously shown FE model. Finally, the synthesis procedure of paragraph 3 was used to obtain the polynomium coefficients for each mode. By imposing the hammer force at the tower free end and applied along x (FA) and then along y (SS) directions, the simulated and the experimental measures in terms of acceleration acquired in the same location and along the same direction have given overlapped results as it is possible to observe in figure 7. In this figure the Fast Fourier Transforms (FFT) (Rao (1990), Meirovitch (2010)) of the acceleration time histories are compared on the measured full frequency range.

Moreover, even if the load condition applied with an hammer is not simulable by FAST multibody code, the authors defined an impulsive load condition realized by a wind shot and applied on the multibody model in a configuration with the rotor considered as locked. This condition, in which the wind load was hypothesed constant along z direction, is not comparable with the hammer load one but is capable to excite all the FA modes, allowing to verify the correct introduction of the FE model modal behavior inside the MBS model. In figure 7 this result is also represented. The relative FFT is rescaled to the maximum value of the FFT obtained by experimental and state-space analyses for the hammer load condition. The results confirms the goodness of the modeling procedure of the flexible components and especially of the obtained multibody model.

Table 2. Wind tunnel load conditions

Wind speed [m/s]	Rotor velocity [rpm]
5	270
6	340
7	400
9	540
10	610

5. Wind tunnel tests and MB simulations on operating turbine

In order to verify the goodness of the model in kinematic terms or in any case regardless of the flexibility of its components, an experimental tests campaign was conducted in the wind tunnel with constant wind speed conditions and hypothesing a constant speed profile along z direction. All the tests were then replicated numerically by means of the a MBS model as shown in Castellani et al. (2017).

The wind speed conditions were acquired in the tunnel through anemometer. Anemometric stories have been considered as inputs of numerical simulations.

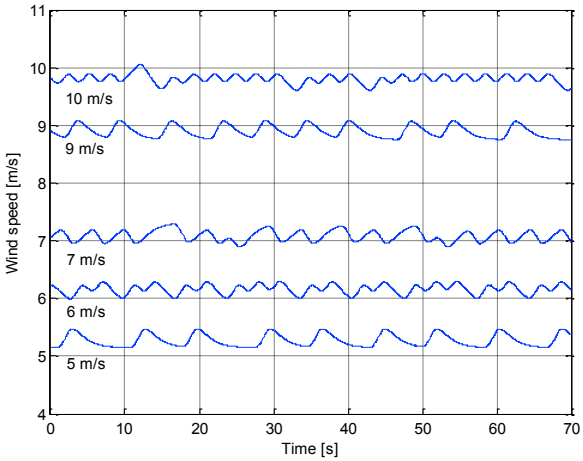

Fig. 8. Anemometer acquisitions during wind tunnel tests

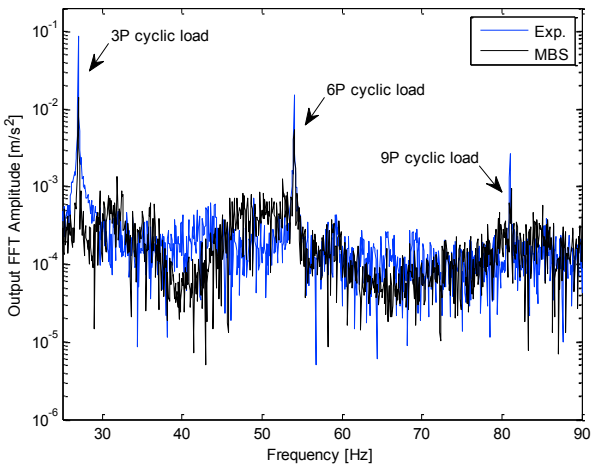

Fig. 9. Example of wind tunnel analyses result: 10 m/s wind speed

Table 2 lists the regime conditions considered in the tests and Figure 8 shows the acquired wind histories considered as inputs for the simulations.

The comparative analysis of experimental and numerical results revealed that the rotor kinematics and dynamics of motion are well represented by simulations that identify the classic load and acceleration conditions, typical of the dynamics of wind turbines. In particular, the results analysis was focused on the cyclical loads (Holm-Jørgensen (2009)), due to particular aerodynamic effects. They are cyclically present in the rotating (blade) reference system and in the fixed reference system of the tower. These loads are crucial for studying the evolution of the Fast Fourier Transform (FFT) of the experimental acceleration measurements. In the rotating reference system (for example located at the blade root) the cyclic loads are the harmonic (multiples) of the rotor angular velocity. Then there will be loads with inputs of 1P, 2P, 3P and so on (*n*P) (Dolan et al. (2016), Niebsch (2010)). In the fixed reference system (tower base), these loads, due to the presence of the three blades, translate and become multiples of three times the rotor angular velocity: it is therefore possible to see loads with frequency content 3P, 6P, 9P.

In the case of the turbine under investigation, the 1P component is visible as 3P, 6P and 9P as it is observable in Figure 9. The frequency peaks (*n*Ps) are therefore showed by the model, which is also susceptible to the conditions of tower shadow phenomenon by the blades. The frequency associated with this condition is 3P. This condition for upwind turbines is not usual and it is not foreseen by the FAST code. However, in this type of turbine, in the presence of blades placed near the tower, this phenomenon is identified and traceable, even if rarely, in the literature (Dolan et al. (2016)). The authors then modeled the turbine by using this coefficient (imposed equal to 0.65), tuned by numerical/experimental comparison (Castellani et al. (2017)), getting a MBS model confident with the real behaviour.

6. Conclusions

This work is a first step towards achieving the PRIN project main aims by providing the certification of the goodness of the simulation model that will be used to evaluate the fatigue strength of its most important components. More attention has been paid to flexible components modeling and in particular to the tower. A numerical procedure has been developed that allows to easily export and post-process the data obtainable by any FE code by obtaining the analytical representation of the main normal modes to put into the code. The results obtained confirmed the goodness of the method as well as the goodness of FAST multibody modeling, by identifying for this type of upwind turbine the need to adopt a coefficient (tower shadow) that is typically adopted for horizontal axis turbines but of downwind type.

Acknowledgements

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