Proceedings of the ASME 2019 38th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2019
June 9-14, 2019, Glasgow, Scotland, UK

OMAE2019-96721

ON DESIGN AND ANALYSIS OF A DRIVETRAIN TEST RIG FOR WIND TURBINE HEALTH MONITORING

Lorenzo Balestra*
Department of Industrial Engineering
University of Bologna
40126, Bologna, Italy

Amir R. Nejad
Department of Marine Technology
Norwegian University
of Science and Technology
NO-7491, Trondheim, Norway

Giovanni Naldi
Department of Industrial Engineering
University of Bologna
40126, Bologna, Italy

ABSTRACT

The reliability of offshore wind turbines is a key factor when estimating maintanence costs, downtime due to component failure and overall efficiency during operational life. Offshore wind turbines have limited accessibility and operate in harsh environments and, as a result, it is difficult to perform frequent checks on electrical and mechanical component. Drivetrain test rigs (DTR) are crucial to the task of: validating the design of new components to avoid early life failure, observe the behaviour of components under load over long periods of time in a controlled environment and produce a maintanence plan that minimize costs and frequency of intervention.

In this paper, after a brief introduction on the state of the art in DTR technology, is described a methodology that can be used to create an effective conceptual design for a drivetrain test rig, focusing also on the possible downscaling.

The paper starts by analyzing the benefits of the drivetrain use in the wind power industry, bringing examples of real test rigs used in industrial and academical world. Once the topic is mastered it is possible to proceed with a description of the various phases needed to obtain the conceptual design, from the definition of layout to the preliminary 3D modeling.

The test rig that is here designed, while inspired from full scale dynamometers used in the industry, is thought as a laboratory tool for academical use that can be used by students to investigate fault detection methods and health monitoring systems of wind turbines. It is also included a section dedicated to the possible techniques for downscaling the test rig, based on simple considerations of the drivetrain mechanical behaviour.

Downscaling becomes a key factor when facing the need to test turbine components of ever increasing dimensions in laboratories with limited space and budget. The definition of a procedure to create a scaled version will allow laboratories to build test rigs of smaller dimension but with a damage model for the various components still closely linked to the one in real scale. Downscaling is also a necessity when working with limited power sources, not able to recreate the conditions that the real scale turbine encounters.

The ultimate goal is to define a solid base to allow further development in the detailed design phase.

LIST OF SYMBOLS

α	Pitch angle
Γ	Downscaling factor
λ	Tip speed ratio
ω	Angular speed
ω_{n}	Natural frequency
ψ	Phase angle
ρ	Air density
A	System's oscillation amplitude
c	Damper coefficient
$c_1; c_2 \ldots$	Manufacturer coefficients (equation 2)

*Address all correspondence to this author.

f	Ordinary frequency
$f(t)$	Generic excitation
k	Elastic modulus
m	System's mass
r	Rotor radius
t	Time
v_1	Wind flow velocity

INTRODUCTION

With the rapid growth of wind energy production in many countries across the globe extensive measures have been taken to ensure the reliability of wind turbines. The new technology has achieved such a level of quality, that wind turbines obtain a technical availability of 98 percent - for land-based turbines. This means that an average wind turbine (WT) will be inactive for around one week per year for repairs and maintenance [1]. To counterweight this good results, we can observe a trend in the increasing distance between the shore and the wind farms location [2], reducing visual and noise pollution but rendering maintanence increasingly difficult and costly.

To operate in these conditions it is required to have an extensive knowledge of all the components installed on the wind turbine and in particular how, when and why they fail, in particular at system level [3]. It is also required to have a reliable condition monitoring system (CMS) in place to know in advance if a component is undergoing unusual stresses and will be prone to failure before the scheduled maintanence occurs. Test rigs are the high value tool that allows us to gain the above mentioned knowledge on the components and validate a monitoring system while safely working in a controlled laboratory environment. The purpose of this tool is to keep downtime to a minimum and avoid extra-ordinary and high cost maintenance interventions.

Drivetrain test rigs in particular include some of the components with the highest downtime per failure, like generator and gearbox, averaging 5.77 days/failure [4]. This means that an unseen failure in the drivetrain could almost double the average downtime of the turbine. With this data on hand it is clear that providing an effective conceptual design for a test rig to be used in an academic environment is vital. This test rig should be able to replicate operational condition of the wind turbine in difficult environments and be able to test components for long periods of time and under usual and unusual loads. This will allow students working in the laboratory to gain the necessary knowledge on how a drivetrain test rig work, perform experiments and maybe further develop the test rig itself. This design should be realized with a parametric strategy in mind, allowing the construction in full scale when the budget and the facility allow it, or of a downscaled version if needed, based on the similarities between the dynamical behaviour of the real scale and the scaled version. The final goal of the finished test rig is to give students the chance to validate the design of components, studying early life failure and work on fault detection and finally fault prediction during operational life.

BENEFITS OF THE DRIVETRAIN TEST RIG

It is easy to understand why is convenient to extensively test the offshore wind turbine components indoor for big manufacturers when we see at the effects of a failure in the drivetrain component. Considering that, to maximize the energy yield per unit installed the turbines can reach up to 12 MW, the size of the components grows with the size of the turbine creating difficulties in case a part needs to be replaced. The access to the turbine might also not be guaranteed because of weather or sea condition, leaving the turbine not operational for long period of time. With large turbine financial losses from not generating becomes significant and downtime needs to be kept to a minimum. Test rigs provide the means to solve the reliability prior deployment leading to [5]:

1- Minimizing maintenance costs.
2- De-risking turbine deployment.
3- Enhancing investment attractiveness.

Having established the advantages of this tool we can continue analyzing the state of the art in DTR technology in wind power industry.

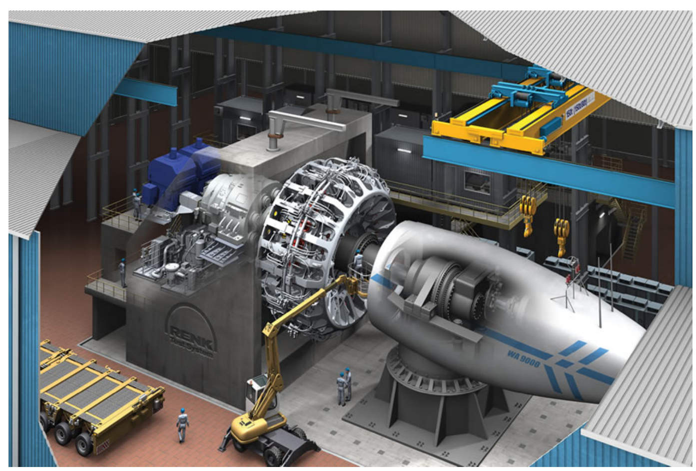

FIGURE 1: Rendering of Clemson University 15 MW wind turbine test rig with prototype nacelle connected [6]

STATE OF THE ART IN DRIVETRAIN TEST RIG TECHNOLOGY

During the last two decades multiple manufacturer and research laboratories have developed drivetrain test facilities of

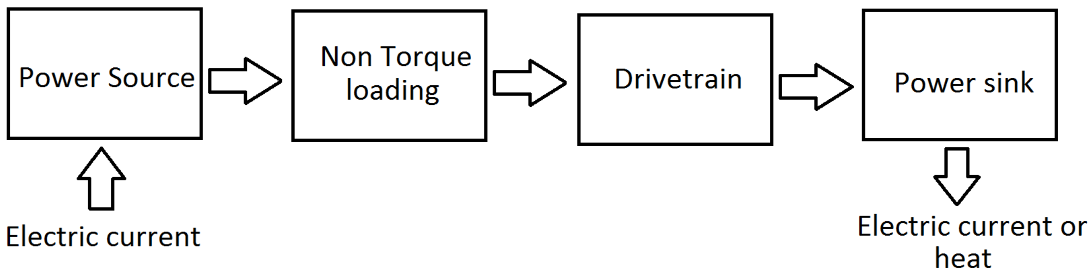

FIGURE 2: Block scheme of a drivetrain test rig main subsystems

different size and complexity. Through the analysis of these designs it is possible to take a look at the most common shared solutions and use them into the conceptual design phase.
The first test rig taken into consideration is the one installed at Clemson University in South Carolina.
This test rig is rated for a power of 15.7 MW and can be connected directly to the full scale nacelle assembly to test new prototypes of large turbines. The development of this incredibly large test rig, the biggest in the world when presented in 2013, is due to an increase in the demand for larger, more efficient and reliable wind turbines that can maximize the energy yield per unit installed, especially for offshore applications . Other relevant test rigs can be found at NREL laboratories in Boulder, Colorado, where are located, among others, three test rigs rated for 225 kW, 2.5 MW and 5 MW. These test rigs share multiple technical solutions with the one at Clemson University while in a smaller package, allowing the manufacturers to test smaller models of turbine for onshore application.
After analyzing the layout of these DTRs, from the smallest to the biggest size, it is clear that the most widespread configuration is the one including an electric power source, a non-torque loading system and, if needed, a gearbox. We can now take a look at each subsystem separately.

1. **Power source**: the prime mover of the test rig is, for the most part, an AC induction motor coupled with a variable frequency drive (VFD) with full regeneration capacity.
2. **Non-torque loading** consists of an hydraulic system able to control the remaining five degrees of freedom of the main shaft. This allows the operator to load the wind turbine drivetrain system with the movements and shears that it experiences during real world operation.
3. **Drivetrain** Necessary to transform the low speed-high torque input from the power source to low torque-high speed output for the generator.

The shaft out of the non-torque loading is then connected with a special flange to the prototype that needs testing.

CONCEPTUAL DESIGN OF THE DRIVETRAIN TEST RIG

Using the knowledge gained on DTRs, it is now possible to define the procedure analyzing the creation of an effective conceptual design for this complex systems.
The test rig selected for development has a main difference from the one listed before, as it is not simply comprised of the components to be connected to the already existing nacelle, but includes also a prototype drivetrain mounted on a test bench. The purpose of this DTR is not to test existing drivetrain prototypes for the industry but rather to study fault detection models and health monitoring systems inside universities and research laboratories. This tool will allow students to master the knowledge on test rig operation and develop tools that can, one day, maybe transferred to full scale multi megawatt test facilities
The work started defining the type of turbine and drivetrain that would be represented by the test rig. The final choice was the drivetrain of a variable speed, variable pitch (VSVP) wind turbine, consisting of main shaft, bearings, brake, gearbox, high speed shaft and generator. This type of drivetrain is broadly used in the industry [7] and includes all the components that need to be investigated for critical failures.
The first step is to model the test rig with a reference to a full scale turbine, in this case a 1 MW HAVT, and then analyze the downscaling process by calculating the downscaling factor Γ.
The second step in this process is to break down the drivetrain in four macro subsystem: power source, drivetrain, power sink, monitoring system; so that each subsystem could be studied individually channeling the resources on one main aspect at a time. The condition monitoring system and the analysis on the sensors needed on the drivetrain are briefly considered, leaving the study to be developed in the detailed design phase.
Each subsystem of *figure 2* is broke down and studied component

by component in the next subsections. This process is necessary because each systems includes many different components, both mechanical and electrical, each serving a specific function vital to the test rig operation.

Power source subsystem

The power source subsystem (PSOS) consists of all the components needed to simulate the effects given by the rotor during the turbine operation. The primary mover of this subsystem is the variable speed drive (VSD), connected to an AC induction motor producing high speed-low torque output.
The VSD can operate on a single operational point, with a constant value of torque and rotational speed, or follow a profile created between discrete points representing variable wind speeds during hours, days or any span of time needed. To control the variable speed drive it is necessary to build a software tool containing the relation between wind flow velocity, torque and rotational speed on the main shaft. This tool has been implemented in Matlab studying wind turbine basic operations [8] [9] and introducing specific parameters such as diameter of the rotor, coefficient of lift and more from a real wind turbine model.
The ”wind emulator” idea revolves around operation between cut in speed and cut off speed, when the turbine is not put in parking condition. The $Cp-\lambda$ curves for each blade pitch angle α are loaded among the data and used to find value for Cp (Coefficient of power) that maximizes the efficiency in specific operational conditions. By inputting the wind flow velocity (v_1) in (1) we can calculate the value of λ (tip speed ratio).

$$\lambda = \frac{2\pi f r}{v_1} \tag{1}$$

This value is then used to find the respective maximum Cp using the curves. It is necessary to take into account the limitations on the value of Cp given by the turbine’s design.

$$Cp(\lambda,\alpha) = c_1(c_2\frac{1}{\Lambda} - c_3\alpha - c_4\alpha^x - c_5)\mathrm{e}^{-c_6\frac{1}{\Lambda}} \tag{2}$$

$$\frac{1}{\Lambda} = \frac{1}{\lambda + 0.08\alpha} - \frac{0.035}{1+\alpha^3} \tag{3}$$

$$P = \frac{Cp(\lambda,\alpha)\rho\pi r^2 {v_1}^3}{2} \tag{4}$$

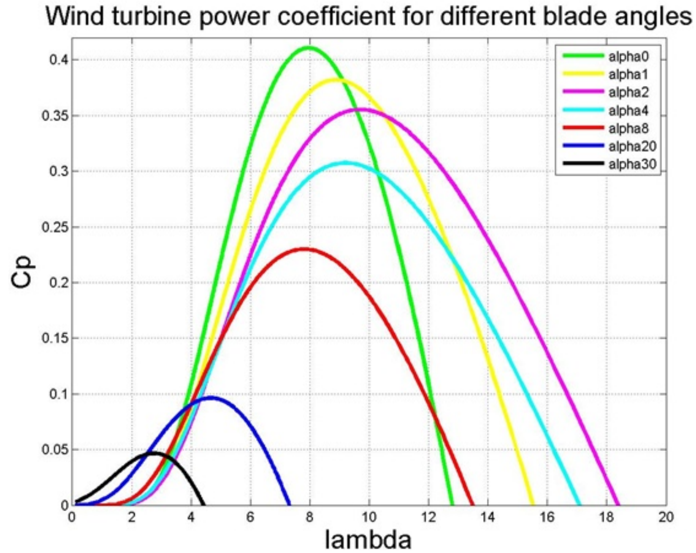

FIGURE 3: Example of $Cp-\lambda$ curves [10]

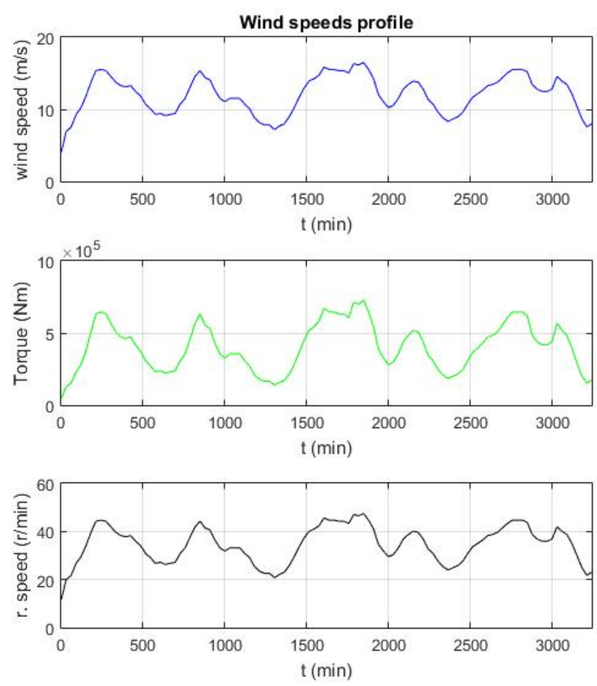

FIGURE 4: Wind load profile obtained with ”wind emulator” for 2 days long simulation on the test rig using the data from a US shores wind farm site.

When the power output calculated using (4) [11] exceeds the rated power of the turbine the process is reiterated until a viable value of Cp, generating the required power is found. Once obtained the power output it is possible, taking into account the efficiency of the drivetrain and generator, to calculate the torque and the rotational speed needed on the main shaft during testing. The entire subsystem essentially replicates the control of the VSVP turbine starting with the wind speed as input and having torque and rotational speed of the main shaft as a result. Defining the operational point of the motor for each wind speed allows the operator to input personalized wind load profiles, to test specific torque loading conditions on the drivetrain.
Once defined the main source of power and the input of the PSOS, the type of transmission was defined, linking the motor and the main shaft. As the test rig purpose is to test components that can will eventually be damaged, it was chosen to place the AC motor out of the driveline. The motor is connected to the driveline with a belt transmission, with either one or two pulley stages depending on the downscaling factor. This solution allows the slipping of the belt when a critical failure occurs on the driveline, without damaging the motor.

Non-torque loading mechanism

This components serves a key role in the drivetrain test rig, simulating the off axis loading produced by the rotor on the main shaft and bearings [12]. The version represented in *Figure 5* is the fourth version of the design of this component and has been chosen to be the the one that best suits our needs. The basic requirement for this system are controllability and simplicity.

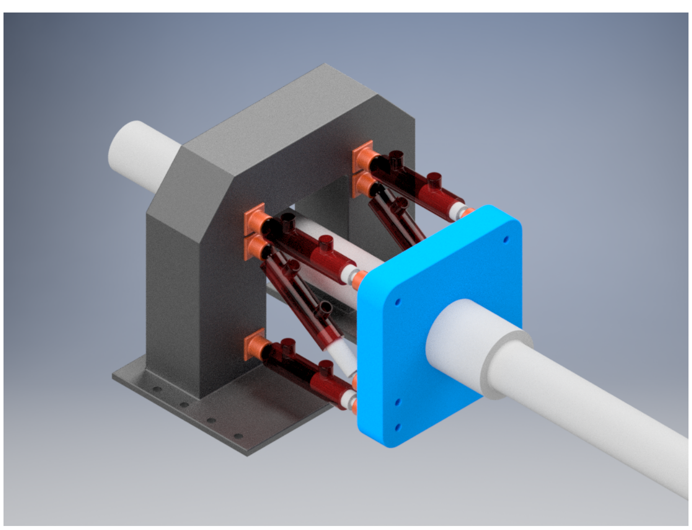

FIGURE 5: Conceptual design of the non torque mechanism

As we can see this system includes a fixed frame (represented in grey), three couples of pistons (in red), a mobile plate (represented in blue). Four pistons out of six have an axis parallel to the one of the main shaft, while two are installed at an angle. This non torque mechanism is able to control the 4 degrees of freedom of the plate:

1- F_z: Radial force due to the weight of the rotor.
2- F_x: Axial force due to the force of the wind pushing the rotor.
3- Moments M_y, M_z given by shear wind or incorrect orientation of the nacelle during transitory conditions.

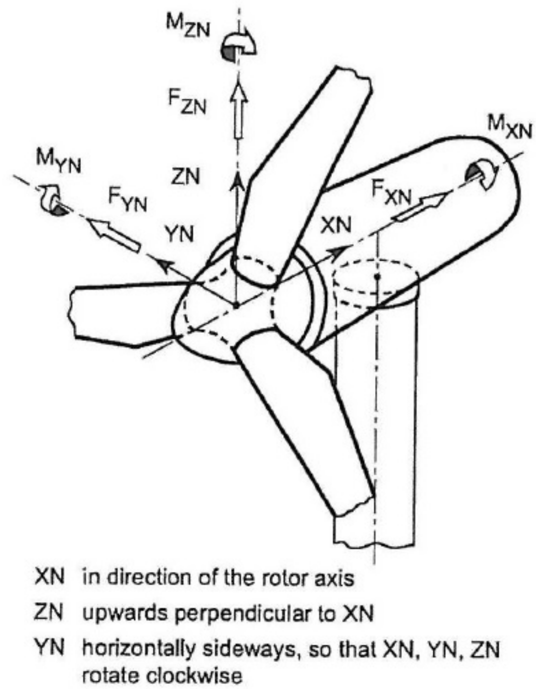

FIGURE 6: Effects on the rotor of the real wind turbine [5]

The connection between the pistons, the frame and the plate is made with spherical joints. While the early designs revolved around the idea of having a plate moving with six degrees of freedom with an octaedral layout for the pistons, the layout here presented is much simpler to control but the trade off is that it is not possible to obtain force along the y axis.
The effect M_x is given by the power source subsystem completing the list of loads that is possible to generate using

this test rig. It is important to mention that the plate includes who bearings inside to allow the rotation of the shaft inside the hole of the plate. These bearings should be able to withstand the previously listed loading with an high factor of security, not to influence the effect on the bearings that need to be tested on the test rig. This design is not to be intended as a sized version but purely as a concept design developed following a kinematic analysis, with the detailed design phase left to further development.

Power sink subsystem

To realize an effective power sink subsystem for this test rig three possibilities were identified. These options are interchangeable and have to be selected according to budget, dimensions of the laboratory and the presence of preexisting infrastructure like an evaporation tower for cooling or pipelines to supply water.

The first option is to connect the output shaft of the GB (high speed shaft) to a Doubly-Fed Induction Generator (DFIG) similar to the one used in real turbines [13]. The DFIG is then connected to a resistive load bank, simulating the grid [14] and cooled through a heat exchanger. This option gives us the system closest to the one operating in the real turbine and can be used for fault detection and condition monitoring of the generator; the drawback is that this layout is reliant on an indirect measurement for mechanical torque either obtained either with strain gauges or observing the power output of the generator.

The second consist in the adoption of an eddy current break as resistive load instead of an electrical generator. This option requires an adequately sized cooling system for the brake and does not allow for the study of generator related faults with the test rig while allowing for an accurate reading of mechanical torque on the shaft. This solution is therefore preferred when the focus is specifically on the drivetrain mechanical components and not on the electrical machines of the system.

The third option mixes solutions from both previous options, including a DFIG, but replacing the electrical load given by the load bank with a mechanical load. The DFIG is connected to an electric motor and a brake, either elecrical, hydraulic or mechanic depending on the scale value adopted. With this layout it is possible to control the load on the generator by acting on the brake controls and allowing the operator to perform fault detection on the generator. As in solution one we have to rely on a different system for measuring mechanical torque.

Condition monitoring system

Once finalized the conceptual design of the test rig, the remaining main task was to develop a layout for the condition monitoring system. This system would be active while conducting activities on the test rig and is needed both as a feedback for the test rig control system and as a platform to collect data for analysis. The ultimate goal is to validate the design of a compact condition monitoring system that can give relevant results both in a laboratory environment but also if installed on the real system. This system needs to include:

1- **Accelerometer**: to measure vibration on drivetrain component. While the ideal system is balanced a fault in the system will inevitably create unbalances on the driveline.
2- Microphone: gear meshing failure, bearing failure, generator failure produce noises on specific frequencies that can be recognised by strategically placed microphones.
3- Voltmeter/amperometer: measures variation in tension and current from what is expected according to the model of the PSIS, indication a generator failure.
4- Thermometer: to monitor the oil temperature of the GB. If out of optimal range can indicate friction problems or many cases of GB fault.
5- Strain gauges: for all measurements related to the strains on the shafts and the measurements of torque along the drivetrain.
6- Encoder: to accurately measure angular position and velocity of the two shafts.

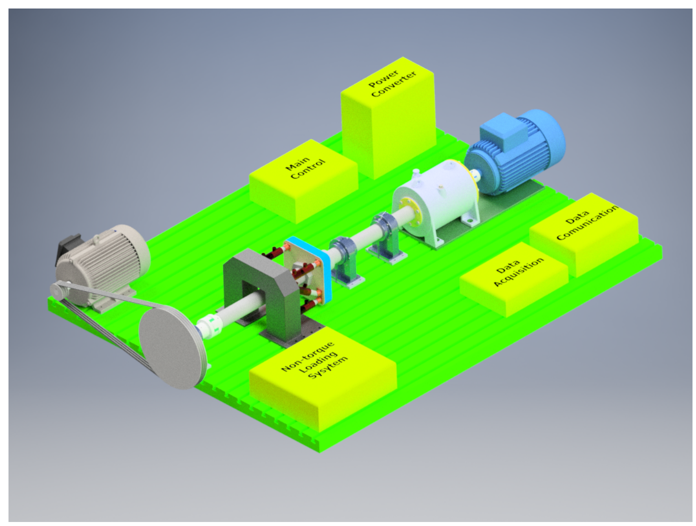

FIGURE 7: Preliminary design of the test rig

SCALING THE TEST RIG

The final phase of this project takes into consideration the possibility of downscaling the test rig of a defined scale factor Γ

to reduce the size of the system and the budget needed for the built.
The downscaling process of a complex system like this one has to be divided in three main parts considering geometrical similarities, kinematics similarities and dynamical similarities. While the first is obtained by just reducing the dimension of the components by a defined factor, the other two need to be obtained through a process of simplification and modeling of the system, with the goal of defining the simplest model possible, still representative of the test rig. Observing the dynamical behaviour of the DTR, it is possible to assume, for downscaling purposes, that the drivetrain can be modelled into the second order 1DOF system under an harmonic loading. The total number of DOFs are two, but can be studied independently along the axis Y, Z. The response of the system can be represented as *(5)* with $f(t)$ as a general time varying excitation having the unit of displacement/time [15].

$$m\ddot{z}(t)+c\dot{z}(t)+kz(t)=f(t) \tag{5}$$

By introducing the damping factor ζ and the natural frequency ω_n it is possible to express (5) as (7).

$$\omega_\mathrm{n}=\sqrt{\frac{k}{m}};\ \zeta=\frac{c}{2\sqrt{km}} \tag{6}$$

$$\ddot{z}(t)+2\zeta\omega_\mathrm{n}\dot{z}(t)+{\omega_\mathrm{n}}^2z(t)=\frac{f(t)}{m} \tag{7}$$

In our case, where the components are rotating around an axis, $f(t)$ can be written using the Fourier series as (8).

$$f(t)=\sum_{j=0}^{p}f_\mathrm{j}\cos(\omega_\mathrm{j}t+\beta_\mathrm{j}) \tag{8}$$

The most appropriate model that has the behaviour described above is the spring mass dampener system. In this case through dynamical simulation it is necessary to find the value of ω representing the real system to define the ratio $\overline{\omega}$ as (9) [16] [17].

$$\overline{\omega}=\frac{\omega}{\omega_\mathrm{n}} \tag{9}$$

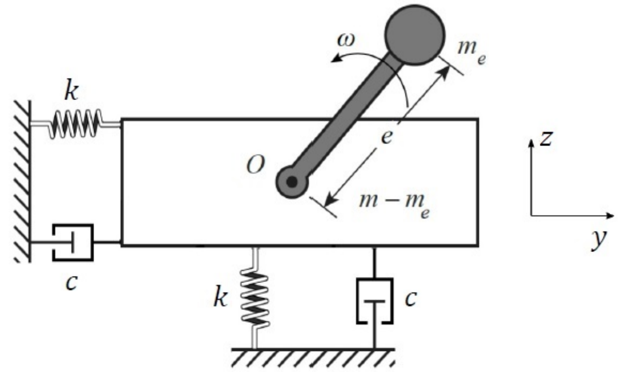

FIGURE 8: Dynamical model representing the test rig

The steady state motion amplitude is, thus:

$$|Z(i\overline{\omega})|=A|G(i\overline{\omega})| \tag{10}$$

$$|G(i\overline{\omega})|=\frac{1}{\sqrt{(1-\overline{\omega}^2)^2+(2\zeta\overline{\omega})^2}} \tag{11}$$

The idea is to use the ratio between the $|G(i\overline{\omega})|_\mathrm{real}$ relative to the real scale and $|G(i\overline{\omega})|$ relative to the downsized version to define the factor Γ.

$$\Gamma=\frac{|G(i\overline{\omega})|_\mathrm{real}}{|G(i\overline{\omega})|} \tag{12}$$

This factor can be used to downsize the components while maintaining the downscaled system linked to the full scaled one. We can also notice that, while during normal operation we make the assumption that the system is balanced and modelled as mentioned above, when some component is damaged it will be possible to observe an increase in the representative value of the m_e that describes the influence of a new imbalance over the normal behaviour of the test rig.

$$z=\frac{m}{m_\mathrm{e}}e\frac{\overline{\omega}^2}{|G(i\overline{\omega})|}\sin(\omega t-\psi) \tag{13}$$

$$y=\frac{m}{m_\mathrm{e}}e\frac{\overline{\omega}^2}{|G(i\overline{\omega})|}\cos(\omega t-\psi) \tag{14}$$

The goal is to have the system response (13) (14) of the full scale test rig and of the downscaled version as close as possible. This may be obtained through dynamical simulations or though mathematical iterations once defined all the parameters relative to the real system.

CONCLUSION

The development of a conceptual design for a small drivetrain test rig focused on academical use is a necessary step in giving students, currently analyzing wind turbine operations, the proper knowledge on these systems. While this paper just scratches the surface of what is a huge project, the hope is to established the basic knowledge for a solid further development into the detailed design phase. The ultimate goal would be the construction of a scaled down modular test rig, able to validate the design of components and monitor model gearboxes, generators, bearings and many other components of offshore wind turbines.

With a test rig representative of the real scale turbine also in the condition monitoring department, will allow the laboratory operators to study fault methods and develop software tools for projects or exams that explore the reduction of the costs of maintenance and in the end build a predictive model for the fault cases.

REFERENCES

[1] Berthold Hahn, Michael Durstewitz, Kurt Rohrig *Reliability of Wind Turbines* Institut fr Solare Energieversorgungstechnik (ISET), Verein an der Universitt Kassel e.V., 34119 Kassel, Germany.

[2] *Windenergie report Deutschland 2016* Fraunhoder-Institut fur windenergie und energiesystemtechnil IWES.

[3] A.R. Nejad, T. Moan *On model-based system approach for health monitoring of drivetrains in floating wind turbines* DOI: 10.1016/j.proeng.2017.09.182, 2017.

[4] S. Faulstich, B. Hahn, P. J. Tavner *Wind turbine downtime and its importance for offshore deployment* DOI: 10.1002/we.421, 2010.

[5] Stuart Herbert *Ensuring Reliability for Offshore Wind* EWEC 2010

[6] Tina Casey *Zombie ARRA Funds Turn South Carolina Into Wind Powerhouse* CleanTechinca, November 22nd, 2013.

[7] Rafal Gawarkiewicz, Filip Wasilczuk, Michal Wasilczuk *Drivetrain of a Wind Turbine* Politechniki Gdaskiej, Machine Dynamics Research 2015, Vol. 39, No 2, 8395.

[8] Tony Burton, David Sharp, Nick Jenkins, Ervin Bossanyi *Wind energy handbook* Wiley.

[9] Erich Hau *Wind turbines* Springer.

[10] Sharmin Shams Ferdausi, Jahan Ara Arju *Effects of parameters variation on wind power generation* Power, Electronic Systems, Applications and Resources on Electrical and Electronic Project-Thesis

[11] *Wind Turbine Control Methods* `http://www.ni.com/it-it/innovations/white-papers/08/wind-turbine-control-methods.html`

[12] Ju Seok Nam, Young Jun Park, Seung Je Jo, Heung Sub Kim, Sung Bo Shim *Development of a gearbox test rig with non-torque loading capacity* Journal of Mechanical Science and Technology 30 (4) (2016) 1713 1722.

[13] K.W.E. Cheng, J.K. Lin, Y.J. Bao, X.D. Xue *Review of the wind energy generating system* , APSCOM, 001-007, 2009

[14] S. S. Kaddah, K. M. Abo-Al-Ez, T. F. Megahed, M. G. Osman *Impact of Renewable Resources Forecasting on Unit Commitment Solution of Egyptian Electric Grid* International Journal of Scientific and Engineering Research Volume 6, Issue 8, August 2015.

[15] Haim Baruh *Applied Dynamics* CRC Press, Published December 12, 2014.

[16] Qingkai Han, Jing Wei, Qingpeng Han, Hao Zhang *Dynamics and Vibration Analyses of Gearbox in Wind Turbine* Springer.

[17] Jitendra Kumar Sasmal *Condition Monitoring of Wind Turbine Gearbox by Vibration Analysis* Department of Mechanical Engineering, Maulana Azad National Institute of Technology Bhopal (MP), India.