Wind Energy Systems
Albert-Ludwigs-Universität Freiburg – Summer Semester 2018

Exercise Sheet 4: Mechanics for Wind Turbine (Continued)

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Deadline: midnight before July 4, 2018
`https://goo.gl/forms/1kW0G8jtlIeo7c062`

In this exercise sheet we'll continue our preliminary study of the role of mechanics in wind turbine tower design. Here, we'll look at vibrations, and will use the Rayleigh energy method, and the Campbell diagram.

preliminary tower design (continued) **[*6 pt*]**

1. We would like to make a preliminary design of a wind turbine tower. This tower should support an un-yawed and un-tilted three-bladed wind turbine ('Turbine B'), with the following dimensions:

Table 1: wind turbine dimensions and properties for Turbine B

property	symbol	value
tower height	L	84 m
nacelle + hub mass	m_{nac}	143 tonnes
rotor radius	R	66 m **
design tip speed ratio	λ_{rated}	5
cut-in wind speed	$u_{\text{cut-in}}$	3 m/s
rated wind speed	u_{rated}	12 m/s
cut-out wind speed	$u_{\text{cut-out}}$	25 m/s

** My appologies, that the exercise was previously published with the value of 12 m.

Some other information that you might find useful is as follows:

Table 2: other potentially useful information

property	symbol	value
density of A36 structural steel	ρ_{steel}	$7.8 \cdot 10^3$ kg/m^3
Young's modulus of A36 structural steel	E_{steel}	200 GPa
yield stress of A36 structural steel	U_{steel}	250 MPa
air density	ρ_{air}	1.225 kg/m^3
surface roughness length for low crops w. occasional obstacles	z_0	0.1 m
meterological mast height	z_{Ref}	10 m
approx. drag coefficient for cylinder	C_D	1
typical wind turbine structural safety factor	f_{safety}	1.35

(a) **tower natural frequency** **[*3 pt*]**

Let's use Rayleigh's energy method to estimate the natural frequency of the tower. In this method, we assume that the strain energy from bending perfectly trades off with the kinetic energy of the tower's displacement x. We will again approximate the tower as a cantilevered beam.

Let's assume that the tower's displacement is sinusoidal in time:

$$x(t) = x_0 \sin(\omega t)$$

and that the tower remains approximately straight during its displacement.

Futher, we know that the strain energy from bending can be found as:

$$V = \frac{1}{2}kx^2, \text{ where } k = 3\frac{E_{\text{steel}} I_x}{L^3}.$$

i. What is $\dot{x}(t)$? [*0.25 pt*]

ii. What is the kinetic energy due to the nacelle displacement T_{nac}? [*0.25 pt*]

iii. What is the kinetic energy due to the displacement of the tower T_{t}? (*Hint: the tower is not massless...*) (*Hint: also, you might assume that the deflection of the tower is roughly proportional to the distance to the fixed point.*) [*0.5 pt*]

iv. What is the total kinetic energy T of the swaying cantilevered beam? [*0.25 pt*]

v. What equation can you formulate, that would implicitly define the vibration frequency ω? [*0.5 pt*]

vi. Please find ω. [*0.25 pt*]

vii. What is the natural frequency f_{nat} of the cantilevered tower? [*0.25 pt*]

viii. What is the natural frequency of each of the three potential tower designs (defined by r and τ) that you determined in Exericse Sheet 3, Problem 2b)? (*Hint: If you do not have this solution, you can use the following combinations of* (r,τ)*:* $(1.5m, 0.05m)$*,* $(3.0m, 0.015m)$*,* $(5.5m, 0.005m)$*.*)

   A. $r = 5.5$ m [*0.25 pt*]

   B. $r = 3.0$ m [*0.25 pt*]

   C. $r = 1.5$ m [*0.25 pt*]

(b) **Campbell diagram** [***3 pt***]

i. With what frequency (1P, 2P, 3P, ...) would you expect the tower to experience the following effects? What is this frequency (in Hertz), as a function of the wind turbine's rotor speed (in RPM)?

   A. 'rotor-rotation' effects, such as having unequally dirty blades? [*0.25 pt*]

   B. 'blade-passing' effects, such as tower shadow? [*0.25 pt*]

ii. Make a plot of frequency [Hz] vs rotor speed [RPM] that we will call the Campbell plot. Add the 'rotor-rotation' and 'blade-passing' frequencies into the Campbell plot. Include a 15 percent safety margin to either side of each curve. [*0.25 pt*]

iii. What is the design rotor speed (in RPM) of the wind turbine? [*0.25 pt*]

iv. Please show the design rotor speed in the Campbell plot. [*0.25 pt*]

v. Please add the tower natural frequencies corresponding to your three possible tower designs (one for each of the outer diameters 5.5m, 3.0m and 1.5m) into the Campbell plot. [*0.25 pt*]

vi. Which of the three investigated tower designs (outer diameters 5.5m, 3.0m, 1.5m) can be classified as the following? Please explain briefly.

   A. soft-soft [*0.25 pt*]

   B. soft-stiff [*0.25 pt*]

   C. stiff-stiff [*0.25 pt*]

vii. Suggest some considerations you might have when chosing between your three proposed tower designs? [*1 pt*]