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THE INFLUENCE OF SCALE EFFECTS ON THE AEROELASTIC STABILITY OF LARGE WIND TURBINES

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Abstract

This paper discusses the specific aeroelastic problems, which occur for large wind turbines. It presents an inventory and classification of current documented aeroelastic problems in the helicopter and wind turbine world, and an indication which of these documented aeroelastic problems are scale dependent. It was found that three types of instabilities deserve due attention: Flap-Lead/Lag Instability in combination with Stall, coupling of the Advancing Lead/Lag mode to the tower motion in combination with in-plane forces, as well as a possible combination of these two. A discussion of the physics of these instabilities is presented.

1 Nomenclature

A	Blade area
c	Blade chord
E	Young's Modulus
f,F	Excitation forces
g	Gravitational acceleration
I	Area moment of inertia
K_ζ	Spring constant in lagging direction
M	Blade mass
M_{lag}	Aerodynamic lagging moment
M_{flap}	Aerodynamic flapping moment
m	Blade mass per unit length
P_r	Power required
Q	Shaft torque
R	Blade radius
s	Reduced eigenfrequeny
V_{tip}	Tip speed
ζ	Lagging degree of freedom
σ	Solidity
σ_{fl}	Bending stress due to flapping
σ_{transm}	Stress in transmission
σ_{lag}	Bending stress due to weight
ψ	$= \Omega t$
Ω	Rotational speed of rotor
ω	Eigenfrequency
$\overline{\omega}$	Non-dimensional eigenfrequency

2 Introduction

The growing demand for cleaner energy has led to the development of larger, more powerful wind turbines. Current large, commercial wind turbines have diameters of 60 to 70 meters, but wind turbines with a diameter of 120 meter are already being considered for offshore applications in the future. In the past industrial wind turbines with diameters smaller than 60 meters did not appear to suffer from large aeroelastic vibration and flutter problems. However for the current size wind turbines severe aeroelastic problems have sometimes been experienced. One may expect that such problems will aggravate with increasing scale. The aim of this paper is to describe the first conclusions and results from the STABTOOL project. The STABTOOL project[1] [9] investigates these scale effects in order to understand them, to generate design rules and recommendations, and develop theoretical tools for the industry.

[1] The STABTOOL project is a joint project of the Faculty of Aerospace Engineering and the Institute for Wind Energy, Delft University of Technology, Netherlands Energy Research Foundation, Petten and Stork Product Engineering B.V., Amsterdam, funded by the Netherlands Agency for Energy and the Environment, Novem.

3 Literature Survey

In order to predict the possible instabilities in future wind turbine designs, a literature study [8] was carried out in order to make an inventory and classification of all documented aeroelastic instabilities which occurred in helicopters and wind turbines, after which they would be investigated on their scale dependency.

In this report which is available separately (see reference [8]) abstracts of all relevant reports on aeroelastic phenomena in the literature are listed.

3.1 Vibrations in general

In general vibration problems can be divided into two large groups (see Figure 3.1, Normand [4]):

- **Externally excited vibrations**, in which the structure vibrates due to external excitation motions (aerodynamic, gravity, control inputs, etc.) and in which the resulting motion depends on both the distribution of forces in space and the frequency of these forces.
- **Self-excited vibrations**, in which the structure can vibrate without being excited by external forces. The structure vibrates due to a mechanism capable of storing energy in the system, thus feeding the vibrations.

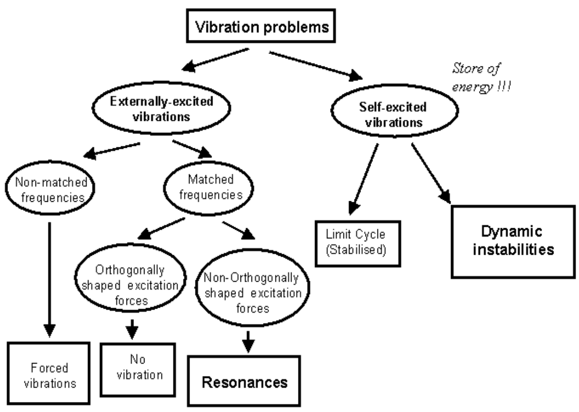

Figure 3.1 Overview of vibration problems [4].

Both classes include phenomena which can lead to structural failure: Resonance and Dynamic Instabilities. Bielawa[1] underlines that the differences between the two is that for the first, the response of the system grows linearly with time, whereas for the latter the response grows exponentially with time.

3.2 Dynamic Instabilities

It is the class of dynamic instabilities, which was the main focus of the survey available in reference [8]. Figure 3.2 [8](see end of paper) presents a classification of the instabilities reported in the literature for both helicopters and wind turbines. The instabilities are classified at two levels:

- On a first level a distinction is made between instabilities in the rotating system and instabilities caused by the interaction between the rotating and non-rotating system.
- On a second level a differentiation is made using the number of degrees of freedom involved in the instability as a criterion.

The instabilities, found in this stage, will now be further investigated, to determine whether or not these effects increase when the scale is increased.

4 Scale effects

For small to medium industrial wind turbines no huge problems have occurred. Problems observed in large wind turbines must therefore depend on scale. To obtain an insight in the effect of increasing blade diameters on the aeroelastic behaviour of wind turbines, a qualitative study into the effect of scaling was carried out.

First of all a closer look was taken on how certain parameters scale when the rotor diameter is increased. In the first column of Table 4.1 a list of these parameters is given. The starting point of this scaling exercise was to assume that the tip speed remains constant. Using this assumption the rest of the variables change in the way portrayed in the second and third column of Table 4.1.

	Square cube Law	Experience
• Tip speed	$V_{tip} = \Omega R \div R^0$	
• Rotational speed	$\Omega \div R^{-1}$	
• Solidity	$\sigma \div R^0$	
• Blade area	$A \div R^2$	
• Aerodynamic Flapping moment	$M_{flap} \div AR \div R^3$	
• Shaft torque	$Q \div P_r/\Omega \div R^3$	
• Blade mass	$M \div R^3$	$\div R^{2.6}$
• Lagging moment	$M_{lag} \div MR \div R^4$	
• Bending stress in flapping	$\sigma_{fl} \div R^0$	$\div R^0$
• Stress in transmission	$\sigma_{transm} \div R^0$	
• Bending stress due to weight	$\sigma_{lag} \div R$	$\div R$
• Eigenfrequency(flap) $\omega = \sqrt{\dfrac{EI}{mR^4}}$	$\div R^{-1}$	$\div R^{-0.8}$
• Eigenfrequency(lag) $\omega = \sqrt{\dfrac{EI}{mR^4}}$	$\div R^{-1}$	$\div R^{-1}$
• Non-dimensional eigenfrequencies	$\varpi \div \omega/\Omega \div R^0$	
• Blade chord	$c \div R$	
• Reduced eigenfrequency	$s \div \omega c/V_{tip}$	$\div R^0$

Table 4.1 Scaling of parameters [9]

4.1 Square Cube law

The second column of Table 4.1 portrays the scale dependency according to the square cube law. It is in this case assumed that all the linear dimensions, including skin thicknesses etc., scale proportional to the diameter. It is seen that material stresses in this way do not depend on scale, except the stresses due to the weight of the blades, which become relatively higher.

A second assumption is that the loads due to weight do not yet act as a design driver for the structure, so that the square-cube scaling is indeed feasible. The consequence is that deflections due to weight will increase relative to the deflections associated with other loads.

It may be seen that the position of the non-dimensional eigenfrequencies with respect to each other, as well as with respect to aerodynamic excitation frequencies is unchanged. Since the reduced eigenfrequencies also appear to be scale independent, unsteady aerodynamic effects do not change either. The consequence is, that "classical" flutter situations will not depend on the scale of the turbine.

As far as forced vibrations are concerned, it follows from the well known response diagram sketched in figure 4.1 that their amplitude - relative to the rotor scale - remains the same. An exception must again be made for the vibrations which are excited by gravity forces. Because the static deflections due to weight relatively increase, so do the vibration amplitudes associated with weight effects.

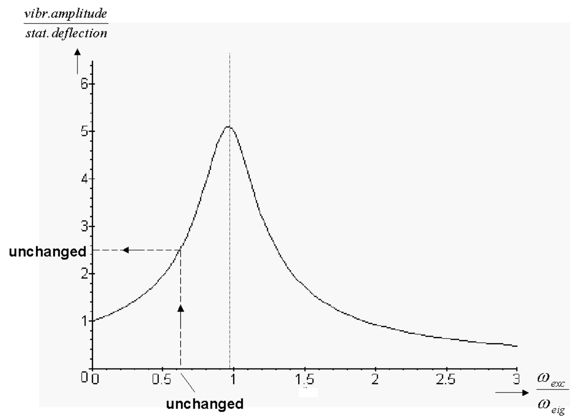

Figure 4.1 Amplitude vs. the excitations

There is one type of vibration mentioned in the literature [7] where gravity effects do play a role, but which is nevertheless not a case of merely forced vibrations. This is the so-called advancing lag-mode instability, which will now be described briefly. A further analysis is given in Chapter 6.
In the usual ground resonance diagram (e.g. a diagram like figure 5.1) the vibration frequencies are shown as observed in the non-rotating system (tower or chassis). A lead-lag vibration of a blade is observed in the non-rotating system as a mix of two frequencies, called the regressing and the advancing modes. The interaction of the tower or chassis with the advancing mode is normally stable, the reason being that the tower motion has a damping influence on the lead-lag motion. In case there is an external excitation of the lead-lag almost exactly in its eigenfrequency, the matter becomes more complicated. At a certain critical rpm, i.e. at the point where the advancing mode intersects a tower frequency, the resulting lag motion excites in turn the tower exactly in its natural frequency. Finally, there is a feed back from the tower to the lead-lag,

again in the blade eigenfrequency. At the critical rpm the phase shifts during each frequency modulation are such that nearly all the damping of the blade motion arises from the interaction between the tower and the lead-lag mode. In fact, under such circumstances the tower acts like a dynamic vibration absorber for the blade, which situation may result in violent tower motions.

A possible excitation source of the lead-lag motion may be gravity. There is one case known [7] where this phenomenon led to destructive vibrations. The reason why this phenomenon may not be considered as a pure forced resonance is, that gravity is a conservative force which cannot supply the energy to build up the large vibrations. In fact, if gravity excites the lead-lag motion, the system rpm would decrease were it not for the action of the control system which tries to keep the rpm constant. The gravity thus merely plays a catalytic role, and the energy for the vibrations is supplied by the aerodynamic or shaft torque.

Obviously, similar to other gravity effects, the advancing lag-mode instability becomes more critical when the scale of the wind turbine increases.

4.2 Scaling from an experience point-of-view

However, certain factors do not quite scale according to the square-cube law. Measurements of the blades' eigenfrequencies were carried out using representative modern blades from one family, as shown in figures 4.2 and 4.3 [10].

It can be observed from figure 4.2 that the flap frequency does not increase inversely proportional with the radius of the blade but in fact less, by an exponent of –0.8.

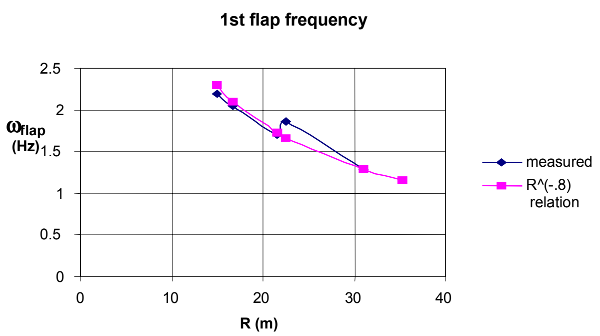

Figure 4.2 Measurement of the flap eigenfrequency [10]

However, it can be seen from figure 4.3 that the lead-lag frequency changes in accordance with the square-cube law.

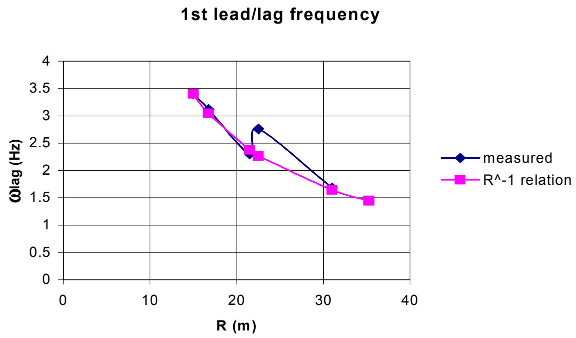

Figure 4.3 Measurement of the lead/lag eigenfrequency [10]

Figures 4.2 and 4.3 show that the flap eigenfrequency now decreases less rapidly than the lead/lag eigenfrequency with increasing blade radius, the blade eigenfrequencies will be located closer together.

This increases the risk of flap-lead/lag instability as can be seen from the generic picture of figure 4.4 [5], which shows the stability boundaries for the coupled flap-lead/lag motion. For wind turbines with smaller radii the lag frequency was 1.5 times the flap frequency but with increasing radius this ratio approaches 1.

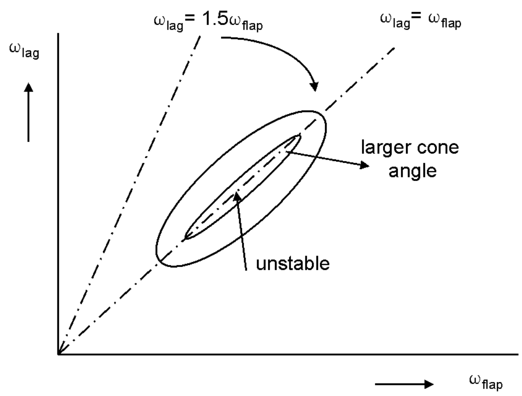

Figure 4.4 Flap-Lead/Lag Instability [5] (displaying rotating eigenfrequencies)

Ormiston and Hodges [5] have shown that for helicopters this type of instability only occurs if the rotating flap eigenfrequency is between $1.0 < \varpi < \sqrt{2}$. However, in wind turbines it was found [6,9] that this instability might occur for eigenfrequencies larger than $\sqrt{2}$, due to the influence of stall. This newly found phenomenon is explained in more detail in references [2,3].

5 Typical medium-scale wind turbine

In this section the potential instabilities due to the effects of scaling, found in the last section, will be illustrated for the case of a typical medium-scale wind turbine which has actually suffered high vibration levels. Using a similar approach to the ground resonance diagrams from the helicopter world, the interaction between the eigenfrequencies of the blade and the eigenfrequencies of the tower as function of the rotational speed for this wind turbine is displayed in Figure 5.1.

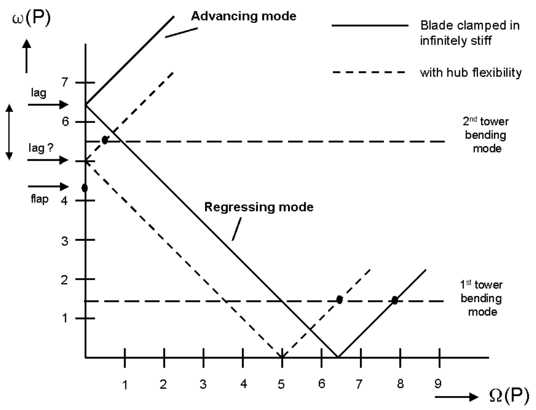

Figure 5.1 Typical Ground Resonance Diagram

In figure 5.1 the lag eigenfrequency, as 'sensed' in the non-rotating tower system, is given as function of the rotational speed. It can be seen that the lag mode splits into two branches, a so-called advancing and regressing mode.

5.1 Flap-Lag interaction

From figure 5.1 it would appear that the non-rotating flap and lag frequencies are well separated. It must be realised however, that the value of the lag eigenfrequency which is indicated in the diagram was obtained from isolated blade measurements where the blade root was clamped in almost infinitely stiff. Installed on the wind turbine the lag frequency is lower, because hub flexibility and multi-blade effects decrease the clamping stiffness. The installed situation is shown in figure 5.1 by the dotted line. The ratio of rotating lag and flap natural frequencies approaches one. According to classical theory on flap-lag instability, there is nevertheless no instability expected because the rotating flap frequency lies far above the value of 1.4 P.

In reference [3] it is explained that the situation may drastically change when stall effects influence the flap-lag coupling. Under such conditions, which frequently occur during wind turbine operation, flap-lag instability becomes possible regardless of the value of the flap frequency.

Experiments confirmed this theoretical prediction: the particular wind turbine indeed suffered from severe flap-lag vibrations during operation in partial stall.

5.2 Regressing Lead/Lag Mode

It can be observed that the regressing branch intersects with the first tower-bending mode, which would lead to the suspicion that an instability might occur. However it is well known that forces, which would cause the instability, cancel each other out. At some speed the regressing lag eigenfrequency becomes zero. After this point the regressing mode reflects and changes in phase. It then again intersects with the first tower-bending mode, causing a potential instability called 'ground resonance'. However, this instability occurs at a rotational speed, which is much higher than the normal operating speed of the turbine and is therefore not dangerous for wind turbines. It is of course a very well known instability in helicopters.

5.3 Advancing Lead/Lag Mode

Looking at the dotted line in figure 5.1 it appears that the advancing lag-mode intersects the second tower bending frequency. For the wind turbine under consideration it is not expected that gravity excitation might lead to coupled lag-tower vibrations, since the frequency of gravity excitations lies far below the natural frequency of the lag-mode.

If it would happen that any other excitation of the blade coincides with the eigenfrequency of the lead-lag motion, the wind turbine would experience large tower motions because the rpm where the second bending tower eigenfrequency crosses the advancing mode is close to the operational rpm. What in such a case would happen is analogous to the situation analysed in Chapter 6.
The blade is excited in its natural frequency, and the resulting lag motion excites the tower at a higher

frequency, which at the critical rpm is exactly the eigenfrequency of the tower. The resulting tower motion feeds back to the blade again. The phase shifts in this loop work out in such a way, that the coupled lag-tower system provides damping of the blade. The amplitudes of the blade and tower motion will tend to grow to such a value that the damping forces maintain equilibrium with the original external excitation of the blade. The inherent structural and aerodynamic damping of the lag motion and tower are small. Therefore, the coupled lag-tower motion may become relatively large in order to provide the necessary amount of damping.

In the case of the wind turbine under consideration, the flap-lag-stall phenomenon can act as a severe excitation of the blade, exactly in its lag eigenfrequency. At or near the critical rpm one would therefore expect severe tower vibrations accompanying the flap-lag-stall situation. This is what was actually observed.

6 Further analysis of the Advancing Lead/Lag mode vibrations

The vibration type considered here involves the coupling of the advancing lead-lag mode with the tower torsion mode or the second tower-bending mode. Both these latter modes are associated with large translational movements of the rotor centre, which is essential to the phenomenon. The coupling effects may result in a damping of forced lead-lag motions, in particular when the forcing is in the eigenfrequency of the blade, e.g. by gravity or flap-lag-stall instability.
Since the tower is effectively acting as a dynamic vibration absorber for the blade, undesirable tower motions may occur.

A simple single blade model as shown below in figure 6.1 will be used to explain the phenomenon. The equations of motion are discussed in the accompanying ERF paper no.66 " Energy flow Considerations, an Educational Tool to Clarify Aeroelastic Phenomena" [3].

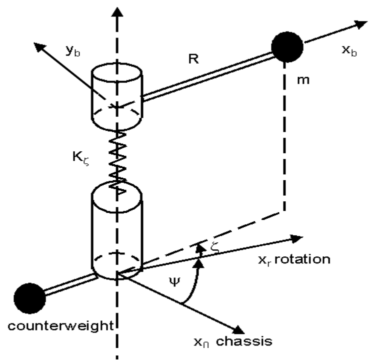

Figure 6.1 Simplified model of the rotor/tower motion [7]

Assuming that the blades are only moving in the lead-lag direction and that the advancing lead/lag mode is the problematic one for the instability, the worst resonance condition of the rotor-tower system occurs at:

$$\omega_\zeta = \Omega \qquad \omega_{ch} = 2\Omega \tag{6.1}$$

This case – although it may not correspond to the actual frequency placement - is used to qualitatively explain the occurring phenomena. Now assuming the case of sustained oscillations (the damping is high enough - either positive or negative - to keep constant amplitude oscillations):

$$\zeta = \zeta_0 \cos(\omega_\zeta t) = \zeta_0 \cos\psi \tag{6.2}$$

Describing the lead-lag as an external excitation for the tower, the effective forces on the hub due to the lead-lag motion of the blade on the rotating system are:

$$F_{x_r} = 2mR\,\Omega\dot{\zeta} = -2mR\ \zeta_0\,\Omega^2 \sin\psi \quad \text{(Coriolis)}$$
$$F_{y_r} = \Omega^2\zeta - \ddot{\zeta} = 2mR\ \zeta_0\,\Omega^2 \cos\psi \quad \text{(cf + inertia)} \tag{6.3}$$

And on the fixed system (chassis, i.e. tower + nacelle) they become:

$$F_{x_0} = F_{x_r}\cos\psi - F_{y_r}\sin\psi = -2mR\,\zeta_0\,\Omega^2 \sin 2\psi$$
$$F_{y_0} = F_{x_r}\sin\psi + F_{y_r}\cos\psi = 2mR\,\zeta_0\,\Omega^2 \cos 2\psi \tag{6.4}$$

If the system has only lead-lag motion, using (6.1) and (6.2), the motion of the blades over one period looks as shown in fig. 6.2.

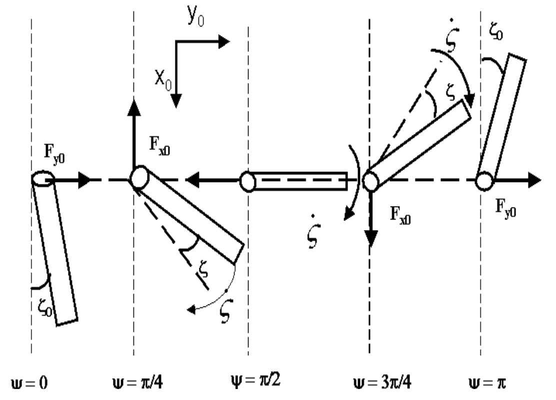

Figure 6.2 Top view of the Lead-Lag Motion of One Blade

The force acting on the chassis is rotating in the direction of the rotation of the blade, with a frequency equal to the tower frequency. This means that the blade lead-lag motion, acting in the frequency of the eigenfrequency of the tower, gives rise to a tower motion phased 90° compared to the revolving force on the tower. The response of the tower is shown in Figure 6.3. This response of the tower in turn causes a moment in lead-lag direction of the blades.

Describing the tower motion as an external excitation for the blades, the blades will move up and down with the tower with acceleration $\ddot{x}_{ch}$.

Again assuming sustained oscillations for the chassis and blade:

$$\zeta = \zeta_0 \cos(\omega_\zeta t) = \zeta_0 \cos \psi$$
$$x_{ch} = x_{ch_0} \cos(\omega_{ch} t) = x_{ch_0} \cos 2\psi \qquad (6.5)$$

D'Alembert principle will be used to determine the force on the blade due to the chassis motion:

$$f = f_0 \cos 2\psi \qquad (6.6)$$

And the motion of the system during one half revolution is now as represented in fig. 6.3.

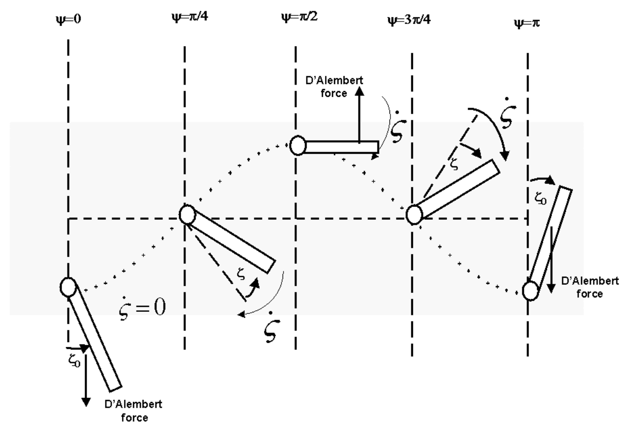

Figure 6.3 Longitudinal Tower Motion and Lead-Lag Blade Motion

The tower induced lead/lag moments on the blade appear to be in anti-phase with the lead/lag velocity. They thus represent a damping effect. Actually this is the reason why in the case of helicopters an intersection of a chassis frequency with the advancing lead/lag mode is not dangerous.

7 Conclusions

With the need for increasingly larger wind turbines, new aeroelastic problems are occurring due to the increasing scale. An inventory [8] was made which gives a good overview of the type of instabilities occurring in helicopters and wind turbines after which an investigation into scale dependency [9,10] showed that the following instabilities would worsen when larger blade radii were used:

- Flap-Lead/Lag Instability combined with Stall,
- Advancing Lead/Lag coupled to tower motion in combination with in-plane forces,
- A combination of these two.

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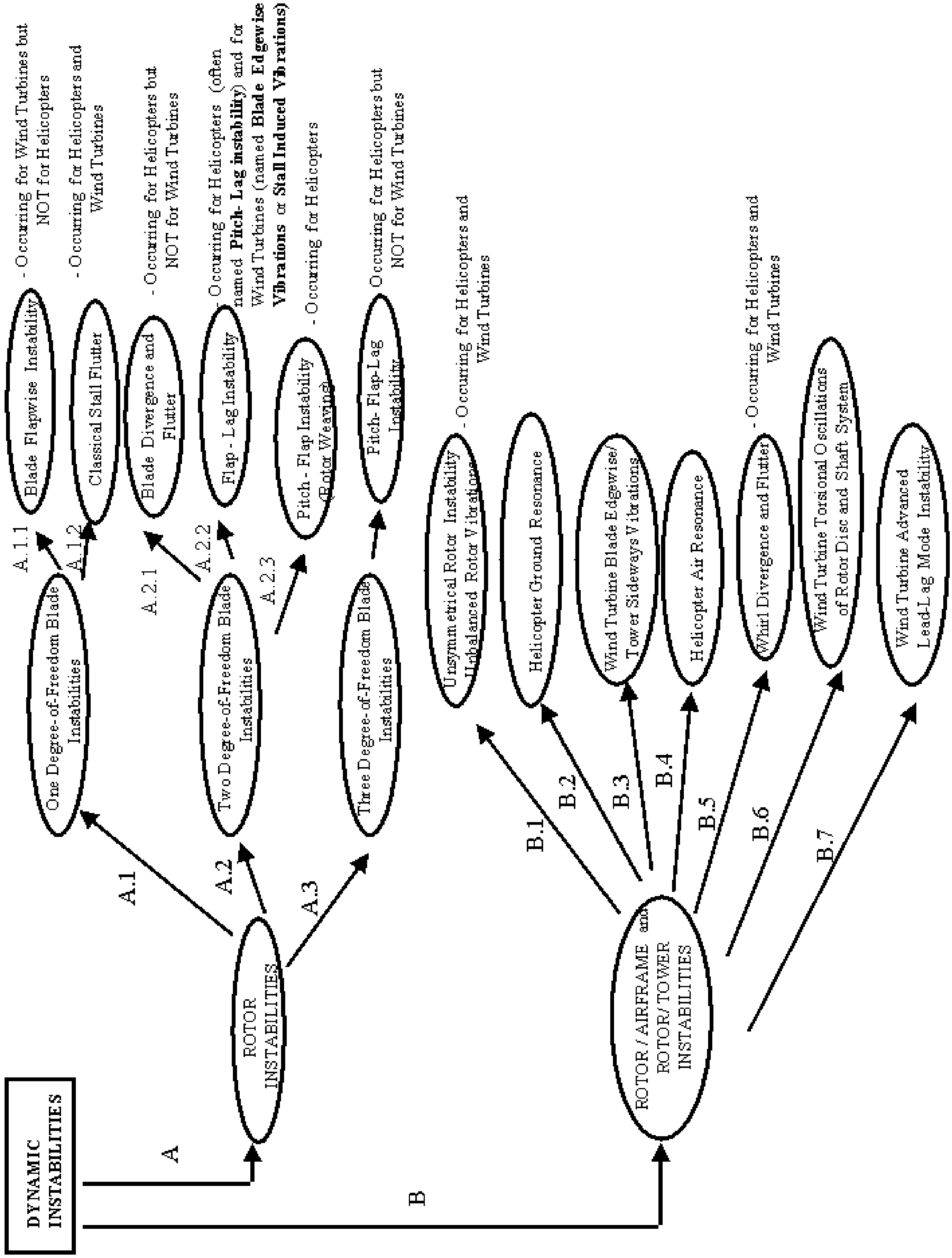

Figure 3.2 Overview of the aeroelastic instabilities found in literature and their relevance for helicopters and wind turbines [8]